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APPLICATION OF GROUNDWATER MODELING IN REMEDIAL ACTION DEVELOPMENT*

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Summary

The development and implementation of a remedial program usually is a costly process. Available scientific and engineering data should be used to optimize the investigation program which will lead to the development of a cost-effective remedial action. As part of the scope of the Remedial Investigation (RI), the data needs and significance of the key parameters as related to the final remedial design should be assessed and determined to obtain necessary data in a timely and cost-effective manner. Properly verified groundwater computer models are powerful tools for both identifying data gaps which must be filled before an appropriate design can be prepared and for assessing the significance of site features on the problem and solution. These models can be used effectively during both the RI and Feasibility Study (FS) phases. In the RI phase, the models can be used for optimization of field and laboratory testing programs and in data analysis to assess adequateness of the field investigation and provide basic data for a risk assessment. In the FS phase, the models can be used to evaluate the effectiveness of various remedial alternatives.

1. Introduction

Presently, many abandoned and certain active hazardous waste sites pose risks to both human health and the environment. Public pressures and corporate liability control, along with numerous stringent regulations and legislative orders, have created a need for the cleanup of contaminated groundwater. Various regulations such as the Resource Conservation and Recovery Act (RCRA), the Underground Storage Regulations, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the Superfund Amendment Reauthorization Act (SARA), the Safe Drinking Water Act (SDWA), the Clean Water Act (CWA), and others require the control and management of surface and groundwaters.

In most cases, this control and management mandates an assessment of the nature and extent of contamination and risk associated with contaminated

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groundwater. If a site requires remediation, remedial alternatives are developed, and the most suitable one is selected for the detailed design and implementation. The implementation of groundwater control and cleanup might involve a combination of containment, waste removal, groundwater extraction, and treatment options. The level of effort during assessment and cleanup will depend on the type of project, nature of contamination, and applicable regulations.

SARA and other regulations place an emphasis on risk assessment for selection of the remedial alternatives and cleanup levels. The risk assessment requires an understanding of spatial and temporal variations of groundwater quality and quantity for different remedial alternatives. The alternatives which produce short- and long-term acceptable risk levels are selected for future consideration. From among these alternatives, the cost-effective remedial action is selected.

The critical link between the source of contamination and potential receptors is the transport pathway; in this paper, groundwater flow. Ground water computer models are powerful tools in risk assessment processes, including identification of the pathways and determination of the rate, magnitude, extent, and duration of the chemical constituents at critical receptor locations. In such modeling, a calibrated model is developed to substantiate the interaction between the source and the receptor via the groundwater pathway. Solute transport models are then used to predict magnitude and time-varying concentrations of contaminants at various receptor locations resulting from the source(s). The uncertainties in prediction because of the variation in basic input data are addressed by a parametric analysis. During parametric analysis, the values of input data are varied and the effects of their variation on model results are evaluated. This logical approach provides a technically sound method to develop the cost-effective plan to remediate contaminated groundwater resources and restore the aquifer to an acceptable condition.

In this paper, the type and application of groundwater models are presented. The major parameters and elements required for assessment and design of remedial alternatives are also discussed. Afterwards, case studies representing the application of the models are explained and, finally, conclusions are presented.

2. Type and features of groundwater models

Groundwater models have been used extensively to understand the phenomenon of groundwater movement under various hydrogeologic and boundary conditions. These models range from simple sandbox models to sophisticated three-dimensional numerical codes. In general, groundwater models can be categorized into three different groups:

- analog models,

- physical models,
- mathematical models.

2.1 Analog models

Analog models are among the earliest models developed for ground water investigations. The two most notable, which are commonly utilized by numerous investigators, are the viscous flow analog (Hele–Shaw analog or parallel-plate analogy) and electric analog [1].

Hele–Shaw models. Hele–Shaw models are well-known devices for two-dimensional ground water flow investigations. These models have been discussed by numerous authors such as Lehr [2,3] and Bear [1]. They are based on the similarity between the differential equations governing saturated flow in a porous media and those describing the flow of viscous liquid in two closely-spaced parallel plates. These models have been used for horizontal and vertical two-dimensional flow conditions and have been successfully utilized to simulate various changes in hydrogeological conditions, including such problems as artificial recharge, drainage, seepage through impervious and low-permeable lenses, well spacing, and presentation of miscible and immiscible flow. Scale factors for vertical and horizontal spatial analogs have been established to project the observed conditions in the laboratory to the actual field conditions. Applications of the Hele–Shaw analog model are as follows:

- The vertical Hele–Shaw analog model is able to directly simulate an abrupt interface between two liquids and, hence, also a phreatic surface. A camera is often used to record the results. The streamline of different kinds can be made visible by adding dyes. The analog gives us the special purpose model for solving problems of steady flow involving stationary or moving interfaces. The flow domain, subject to certain restrictions, may be homogeneous or anisotropic.
- The horizontal plane analog model can simulate ground water flow for two-dimensional horizontal conditions. Various layers including a semi-impervious layer can be incorporated in the model. It could simulate pumping from two-layered confined aquifers with artificial recharge. This model has similar disadvantages as the vertical model.

Electric analog models. Electric analog models are powerful tools for simulating ground water flow in porous media. These models are based on the similarity of governing equations for flow in porous media and currents in electrical systems. These are special purpose models which have been used to simulate various hydrogeologic conditions for different geometrical and hydrogeologic conditions [4]. Difficulty in using the analog models is associated with establishing a well representative of the site conditions with varying aquifer thickness, boundary and condition, etc. The process is relatively tedious and requires an experienced individual to set up the model.

2.2 Physical models

Physical models are good representations of the natural porous media domain. They are a true model in the sense that both prototype and model involve flow and solute transport through porous media. The two types of these models will be discussed in this section.

Sandbox model. A sandbox model is built with a ridged watertight container, or box, and is filled with a porous matrix sand, powdered or crushed glass, or glass beads. It consists of one or more fluids, supply systems, and measuring devices [5]. The geometry of the box corresponds to that of the investigation flow domain. The sandbox model is used extensively because of its special features that permit studies of flow phenomena such as microscopic structure of the saturated and unsaturated flow domain, miscible displacement, hydrodynamic dispersion, and immiscible displacements. The sandbox models are usually used to simulate flow under confined conditions. These models are relatively simple to use; however, one should take care to establish proper boundary and initial conditions corresponding to the actual site setting. Unlike analog models, there is no need to prove the existence of an analogy between the sandbox model and the prototype as both involve flow-through porous media. Bear [1] presents various scales to translate the sandbox model results to actual field representations.

Laboratory models. Laboratory models are physical models which are used for determining the hydrogeologic and geologic properties of porous media [6] and can be used to simulate the long-term effects of the interactions between waste and pathways [7]. A schematic of a column test system is shown in Fig. 1. In these tests, representative field samples are placed in triaxial cells. Initially, the hydraulic conductivity of the soil samples is measured with tap (fresh) water or standard 0.01 N $CaSO_4$ solution. Subsequent to the hydraulic conductivity reaching a constant value, the waste permeant is introduced into the system and the concentration of the contaminant or chemical constituents is measured with respect to time at the effluent exit points. The hydraulic head in the laboratory can be increased by order of magnitude to accelerate the chemical constituent migration rate. The flow rate and concentration of the chemical constituents of interest are then measured and plotted versus time. Because of the increased laboratory hydraulic gradient, usually an hour of laboratory simulation represents 50 to 100 hours of the field condition. Using a scale factor [7], it is possible to predict the changes of hydraulic conductivity and concentration for the field conditions in a relatively short time. Another advantage of the column test is the determination of the retardation factor,

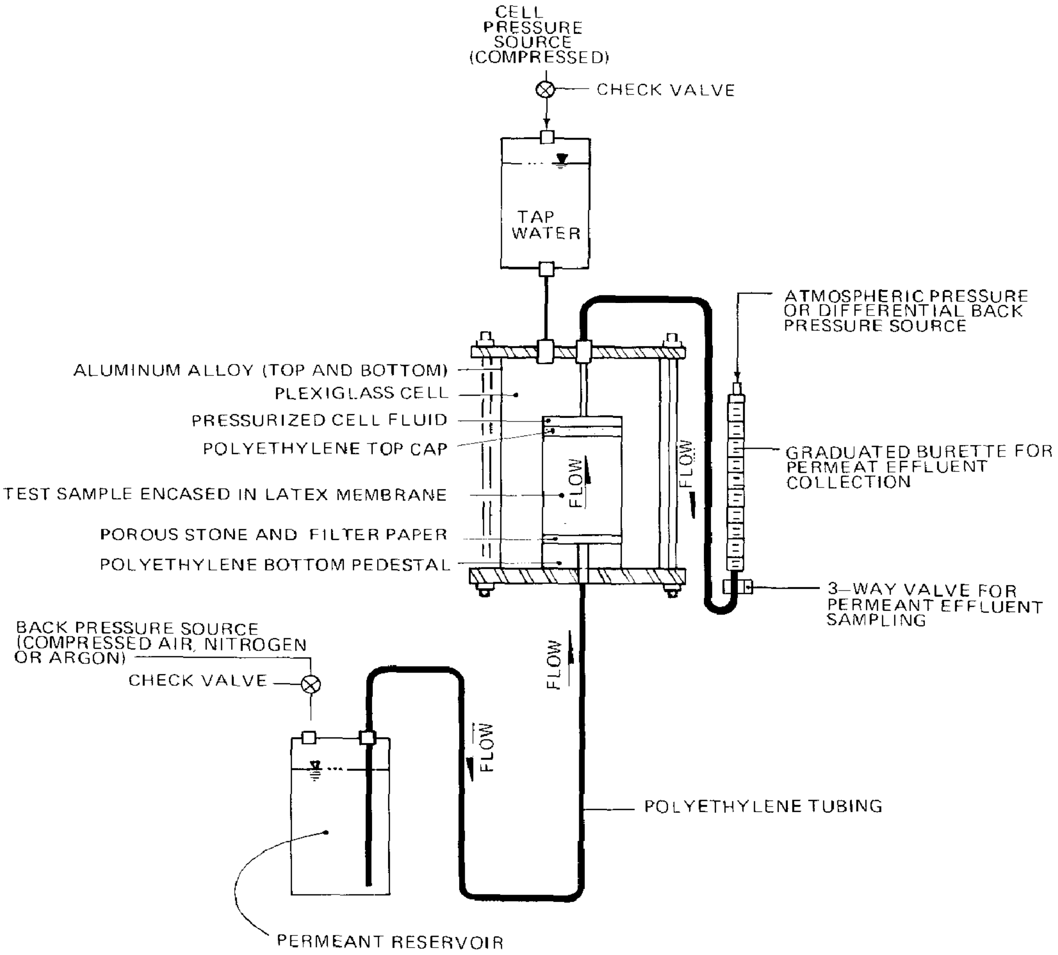

Fig. 1. Schematic of a constant head column test system.

which is a measure of the relative chemical constituents migration rate compared with fresh water.

Column tests have also been used to predict the achievable cleanup level and the cleanup period. Using fresh water, solvent, or surfactants as an influent, it is possible to develop a laboratory program to determine the contaminant removal rate. Similarly, the concentration of the chemical with respect to time is plotted and compared with the pore volume displacement. After completion of the test, the soil samples from the columns are used for analysis to determine the residual chemical constituent remaining in the soil.

Soil simulation. Another notable physical model is field simulation. The field measurement of the aquifer yield, i.e., pump test [8], represents an actual simulation of the field condition, with limited assumptions that are inherent in other methods of modeling. Field simulations are relatively expensive and time consuming. Furthermore, as with other simulations, the inherent difficulty of selecting representative site conditions may result in the misinterpretation of the field test.

2.3 Mathematical models

Mathematical models have been used extensively in the assessment of hydrogeologic and geologic parameters and also in the prediction of changes in hydrogeologic setting and ground water quality under various applications [8]. Mathematical models can be divided into two major categories:
- closed form or analytical solutions,
- numerical solutions.

Closed form solutions. The governing equations of ground water flow and solute transport are well established in the literature such as in Bear [1] and Freeze and Cherry [4]. Under simplified assumptions and boundary conditions, it is possible to solve the governing equations through a closed form or analytical solution. Examples of these solutions are the well or one-dimensional dispersion equations. These models have been used extensively in assessing hydrologic parameters and estimating the rate of flow and contaminant transport. Additionally, these simplified solutions have been used in parametric studies to determine the effect of parameter variation on model results. These models have also been utilized to verify the performance of numerical models. Apart from these applications, analytical models can be used to calculate flow and solute transport parameters under field and laboratory conditions.

Numerical models. Numerical models have been used in the last two decades for both environmental assessment and design. The most commonly used numerical models are finite-element and finite-difference computer codes. Features of these models have been discussed and summarized in various applications such as those by Wang and Anderson [9], Huyakron and Pinder [10], and the U.S. Environmental Protection Agency (U.S. EPA) [11]. Numerical models simulate ground water flow and solute transport in porous media and have wide applicability in defining remedial options and environmental impacts. With these programs, it is possible to develop site-specific models representing the site hydrogeology and ground water flow and solute transport conditions. With these models, various hypotheses such as boundary conditions and variations in hydrogeologic parameters including hydraulic conductivity, thickness of the different geological units, and intercommunication within the various aquifers can be tested. These tests provide an understanding of the sensitivity of the investigation results to various site-specific parameters and document the effect of these parameters on vertical and horizontal contaminant migration within the various aquifers.

A wide range of computer programs have been developed and are available as discussed in van der Heijde et al. [12], and Kinzelbach [13]. The range includes simple one-dimensional flow or solute transport to complex two- or three-dimensional models capable of incorporating complex site geology, special features such as multiple wells or geologic discontinuities, and boundary conditions. These programs can be solved by hand calculator, microcomputers, or mainframe computers, based on the type of the program and the complexity of the models. Depending on the complexity of the site conditions and accuracy requirements, one or a combination of several models may be used.

2.4 Advantages and disadvantages of various models

As we follow the development of ground water modeling during the last several decades, we see the emphasis shifting from analog models toward laboratory and mathematical models. This shift in emphasis is partially due to the complexity of various remedial actions, accessibility of computers, and the requirements for traceable documentation of the modeling. Therefore, labora-

TABLE 1

Advantages and disadvantages of laboratory models

Advantages

- Tests actual earth materials to determine physical parameters
- Enables the collection of waste permeant for chemical testing by column permeability testing
- Allows "accelerated" testing of earth materials to determine effect of contaminants upon physical properties by simulating long-term behavior
- Provides direct verification of physical properties for constructed earth materials such as for slurry walls and clay liners
- Enables direct measurement of ground water/earth material interaction
- Allows the determination of the effect of different chemicals upon earth materials
- Allows "bench-scale" modeling of remedial alternatives

Disadvantages

- Tests "best" samples; for example, hydraulic conductivity tests are typically performed on homogeneous samples free of defects such as cracks or voids
- The correlation from laboratory results to *in situ* behavior is probably not known or, at best, inadequately demonstrated
- May require several months to complete testing such as long-term simulation of slurry wall materials
- Unless a sufficient variation of samples is available to model the *in situ* variability, a large-scale extrapolation of laboratory results to in situ behavior must be made
- May be very difficult to obtain samples to determine variation in physical properties, such as horizontal versus vertical permeability
- It may be difficult to simulate *in situ* conditions for "bench-scale" modeling; the correlation to actual conditions may at best be an estimate

TABLE 2

Advantages and disadvantages of field simulation

Advantages
- Allows the direct measurement of *in situ* properties and their spatial variation
- For constructed earth materials, a test fill can be built to model the actual construction of a clay liner which, in turn, allows the direct measurement of properties such as hydraulic conductivity under actual conditions
- Provides direct measurement of *in situ* conditions

Disadvantages
- The control of field simulation can be very complex and difficult
- *In situ* parameter measurement in a borehole may provide results which are influenced in an unknown manner by *in situ* conditions
- The numerical computation of results may be limited by known "closed form" solutions which do not model the exact case or require the use of sophisticated numerical models for better estimation
- *In situ* simulation must consider many variables, including "second order" effects such as barometric pressure

TABLE 3

Advantages and disadvantages of closed form solution models

Advantages
- Provides "exact" solution to model
- Enables direct comparison with other mathematical solutions
- Provides a solution which is recognized in the technical community
- If derivations are not required as part of the solution, the application of the solution should be straightforward
- The effect upon the result of the variation of a single parameter can generally be isolated
- Allows the use of a "simplified" solution to obtain approximate results which can be used for defining the type of modeling to be used for more complex calculations or to define the remedial alternative to be more fully modeled
- They can be used to determine flow and solute transport parameters under laboratory or field conditions
- It may be possible to combine various solutions to more closely model the physical case

Disadvantages
- Typically, there is the necessity of simplifying the *in situ* conditions because closed form solutions do not model complex physical conditions. This results in:
  a. simplified stratigraphy,
  b. different boundary conditions,
  c. simplifying the variation in physical properties
  At best, the effect of simplification of the in situ conditions upon the result can only be estimated
- There are a limited group of solutions available
- There may be restrictions in the range of parameters the solution will accommodate. The range of parametric variations may be set as part of the mathematical solution, and any ranges must be known by the user
- If the derivations of equations are required as part of the solution, the mathematics may be complex

TABLE 4

Advantages and disadvantages of numerical models

Advantages

- Enables modeling of the *in situ* spatial conditions better than closed form solutions
- Would enable the simulations of several different remedial alternatives using the same spatial model
- Allows the variation of physical properties to determine the effect of a parameter upon the results
- Enables the solution of physical models for which closed form solutions do not exist
- The reporting of results can be coupled with graphic presentation

Disadvantages

- All numerical solutions are approximations of the theoretical basis for the solutions; the limitations of the numerical method must be known
- Developing the model presumes sufficient knowledge of the *in situ* conditions
- To justify the use of numerical techniques requires detailed knowledge of physical parameters and their variation
- Changing of the model to accommodate spatial or boundary value variations may be difficult
- Requires more experienced person to set up and execute the model

tory and mathematical models have become the more common tools for the assessment of remedial alternatives and performing parametric studies. The advantages and disadvantages of various models and their range of application for remedial programs are presented in Tables 1 through 4. It should be noted that for a particular type of model, a specific item may be both an advantage and a disadvantage. In this paper, the case study examples are limited to application of the column test and mathematical models.

3. Model selection

3.1 Source, pathway and receptor relationship

In the evaluation of remedial measures. Three major components — source, pathway and receptor — play major roles:

- Source — The type of chemical constituents and their chemical and physical properties.
- Pathways — The hydrogeological and geological characteristics of the pathways and rate and extent of migration of contaminants.
- Receptors — The nature and location of receptors and the present and future contamination levels at the receptors.

The critical link between the source and receptor is the transport pathway; in this paper, ground water flow. The relationship between the source/pathway/receptor and various model types which are used in defining release, transport, and risk characterization is depicted in Fig. 2. Geochemical analysis determines the geochemical properties of the chemical constituents and mass

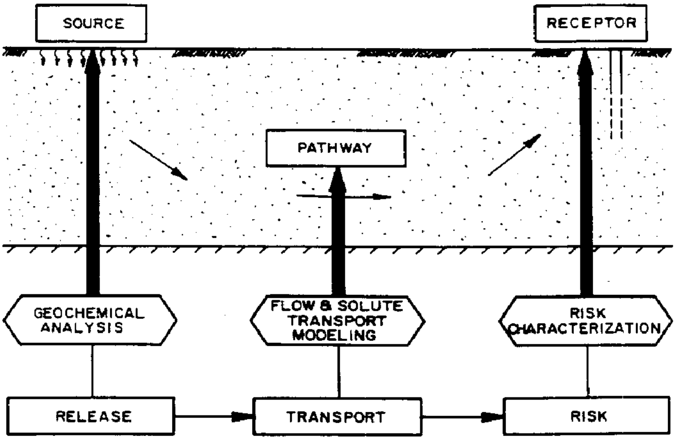

Fig. 2. Overview of model applications.

TABLE 5

Correlation between ground water model output and risk assessment input parameters

Ground water input parameter	Ground water model output	Risk assessment input parameter
Contaminant source (type, location)	Source loading Migration rate Ground water quality	Chemical of concern Chemical concentration
Ground water quality	Extent of plume	Chemical concentration
Ground water level	Ground water flow Direction and rate	Pathway
Hydraulic conductivity	Rate of migration	Receptor location Chemical concentration
Aquifer thickness	Flow rate	Receptor location Chemical concentration
Pumping well or recharge points	Flow rate and direction	Pathway Chemical concentration
Retardation or biodegradation factor	Rate of migration Chemical concentration	Chemical concentration
Dispersion coefficient	Spreading chemical constituent	Chemical concentration

loading of the chemical to the aquifer. The analysis also provides information regarding retardation or biodegradation factors. The geochemical analysis is usually performed concurrently with flow and solute transport modeling. It provides input to the source determination and solute transport modeling. The determination of the rate, magnitude, extent, and longevity of the chemical constituents at the critical receptor locations is the key consideration in the development of a remedial action plan.

Flow and solute transport models (ground water models) provide information regarding pathway characteristics and spatial distribution of chemical constituent concentration. The correlation between the ground water models and risk assessment input parameters is presented in Table 5. Risk models use the results from ground water flow models to characterize the risk to human health and the environment.

3.2 Model selection consideration

Model selection and use are subjective processes and no clear guidance has been established. However, there is general agreement that ground water models are powerful tools for data interpretation and remedial alternatives effectiveness assessment. The following should be considered for the selection of ground water models:

- What is to be determined?
  - Contaminant transport.
  - Ground water flow rate.
  - Methods of remediation.
- How complex is the hydrogeologic regime being studied?
- Are the available data adequate for the study needs?
- Would additional data significantly enhance the results of the analysis considering economics, ability to measure, and representativeness of the measurement?
- Considering the regime of the study area, is a "complex" model justified rather than a "simple" model?
- How sensitive are the results of the model to variations in physical parameters? If a parameter is changed, is there a direct proportional change in the modeling results?
- Has similar investigation/modeling been performed which could be used to reduce the modeling effort?
- What is the sensitivity of the remedial cost to the model certainty level?

3.3 Model usage

Geochemical models for remedial design are generally used when the geochemical properties of the chemical constituents are not well defined or when more than one contaminant is involved. In both cases, laboratory simulation has provided an excellent data base for the determination of cleanup time and method of remediation. Present interest to bioremediation has also resulted in the usage of the laboratory model for treatment design and evaluation of the effectiveness of the remediation.

Ground water models can be very simple or complex, depending on site conditions, complexity of the hydrogeological setting, and the degree of sophistication required.

These models can be used during various phases of the remedial alternative development. The initial usage of such a model is a parametric study and definition of data gaps with the resulting optimization of field exploration and sampling programs. During this period, preliminary data are used to simulate the present site hydrogeological setting (based on known and assumed values). The values of the key parameters are varied, and their effect on the horizontal and vertical migration of the contaminants is assessed. As a result of these simulations, the key parameters and specific locations for data collection are identified.

These models also assist in determining the level of precision and, hence, the most appropriate methods for measurement of the hydrogeological and geochemical characteristics of the geological units of interest. For example, if the model result appears to be very sensitive to the hydraulic conductivity of a given unit, proper attention is required, such that hydraulic conductivity values are measured within the necessary precision. On the other hand, if a parameter such as storage coefficient has no major significance in the result of the analysis, the parameter might be eliminated from further consideration or field testing. The result of the preliminary hydrogeological simulation could be the identification of the location of the field exploration borings, the type of information necessary, the data to be gathered, and the significance of these data in the final analyses.

Similar procedures are used in assessing remedial alternatives. Various remedial alternatives are tested by the model and the most effective remedial alternatives are selected for subsequent economic analysis.

4. Case studies

In the previous sections, the types and features of ground water models were discussed. In this section, representative case studies showing the application of laboratory and mathematical models are presented.

4.1 Case study – laboratory column test

The following case study is a combination of selective test results which were used to evaluate line suitability and expected migration rates of solutes from the example linear material [7]. Column tests were conducted to evaluate the long-term performance of a clay liner proposed for use in a waste disposal facility. The soil specimen tested was a clayey silt to which 4% bentonite, by dry weight, was added. The admixture was compacted to 95% of Modified Proctor maximum dry density at optimum water content to represent the probable compactive effort of field placement. The compacted density was 2.04 g/cm^3.

The reference hydraulic conductivity was determined, using site ground water, to be 1.0×10^{-8} cm/s (flow rate of approximately 0.4 ml/h) with a hydraulic gradient equal to 258.

The column influent waste permeant had the following characteristics:

1 pH 2.0
2 Specific conductance, 23 000 μΩ/cm at 25°C.
3 Available acidity, 7500 mg/l calcium carbonate equivalent ($CaCO_3$).
4 Sulfate, 10 000 mg/l.
5 Chloride, 45 mg/l.

A summary of hydrologic data for the impoundment includes the following:

1 Thickness of liner, 30 cm (1 ft).
2 Impoundment fluid elevation, 300 cm (10 ft).

Results of the long-term column test are illustrated in Figs. 3 and 4. Zero time on these figures represents the time when the waste permeant initially reached the soil column.

The test was terminated after a steady-state hydraulic conductivity of the soil column and breakthrough of the chemical species of interest were achieved.

As shown in Fig. 3, the flow rate varies from initial values of 0.40 ml/h to final steady state of 0.65 ml/h. These rates yield hydraulic conductivity ranging from 1.0×10^{-8} to 1.7×10^{-8} cm/s. These values indicate that hydraulic conductivity increased somewhat, but not significantly. In addition, the hydraulic conductivity reached a steady-state value and, in the long-term, major changes are not anticipated.

The accumulated laboratory time of the chemical breakthrough curves (Fig. 4) can be multiplied by the corresponding time scale (that is, 60 for this ex-

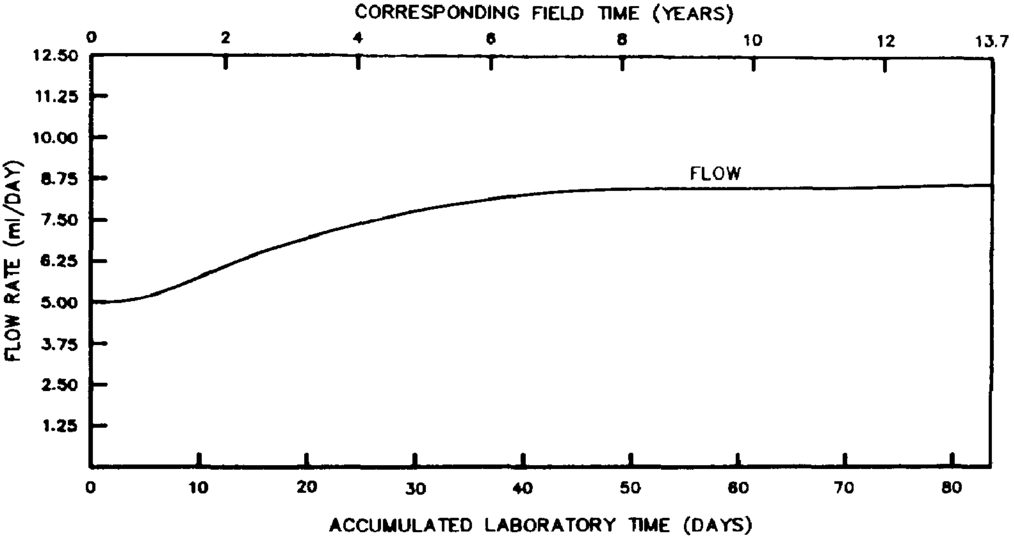

Fig. 3. Flow rate vs. accumulated laboratory and corresponding field time.

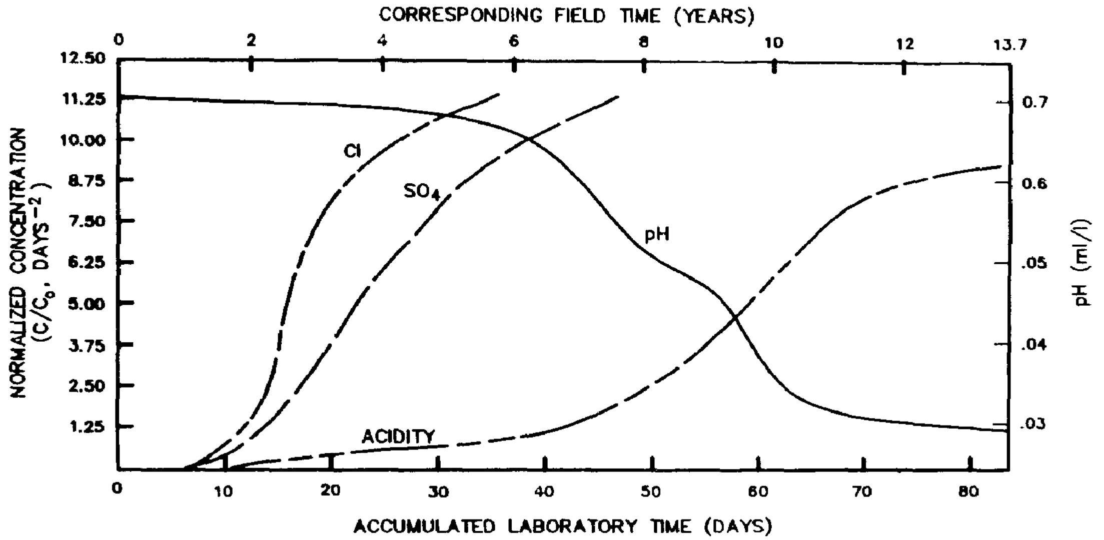

Fig. 4. Normalized concentration vs. accumulated laboratory and corresponding field time.

ample, Djafari and Wright [7]) to represent the equivalent concentration profile beneath the facility for various times. For example, after 380 hours of laboratory testing, the chloride concentration reached one-half the concentration of the point source. This time corresponds to 60×380 = 22 800 hours (2.6 years) of field time. Similar calculations can be made for other chemical species under consideration. The actual concentration of each species can be obtained by multiplying its normalized concentration by its point source (impoundment) concentration, respectively.

Another point of interest is the evaluation of the pH curve. The pH of the effluent is initially 7.1 (Fig. 4) and decreases to pH 3.0 after 1700 test hours. However, it remains above pH 6.0 until 1060 hours. This laboratory time corresponds to 1060×60 = 63 600 hours (7.26 years) of equivalent field time. Because most heavy metals do not significantly migrate above a pH of 6.0, the concentration of pH-dependent species, such as iron, would not significantly increase beneath the clay linear during this period.

Another example of the laboratory column test is the determination of contaminated soil cleanup time, as a result of ground water withdrawal and treatment remedial options. Field soil samples were saturated with site-representative aqueous leachate in the column test apparatus. The leachate contained ethylene dichoride (EDC), perchlor or tetrachloroethylene (PERC), and trichloroethylene (TCE). The sample was then flushed with fresh ground water and the concentration of these chemicals with time was plotted (Fig. 5). Using the scale factor, it was possible to convert the laboratory measurement results to field conditions and, hence, to determine the effectiveness of the planned ground water remediation.

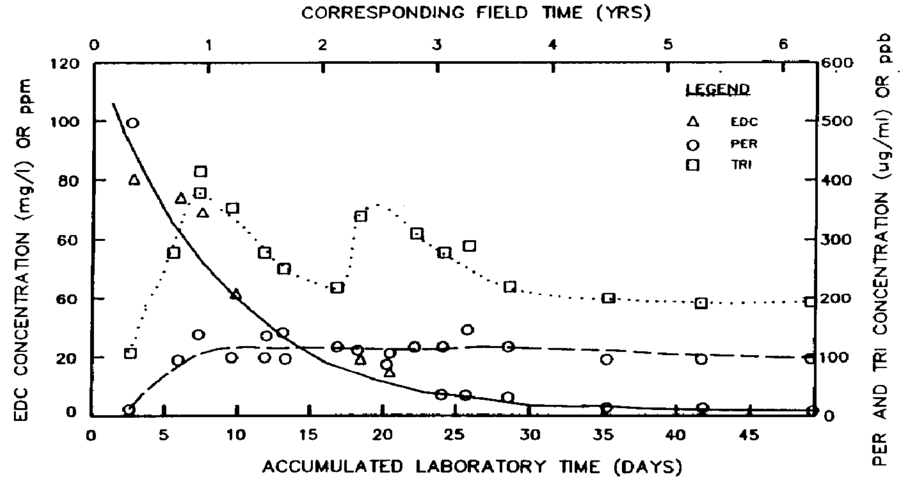

Fig. 5. Desorption profile of DEC, PER, and TRI in laboratory and corresponding field conditions.

4.2 Case study - closed form solution

During the early screening of the remedial alternatives for a Superfund site, it was necessary to determine the effectiveness of the extraction well(s) on the withdrawal of the contaminated ground water and on hydraulic control. The aquifer was unconfined with an average thickness of 35 feet and hydraulic conductivity of 4×10^{-2} cm/s. For preliminary assessment, the Theis program [14] was used. In the parametric analysis, flow rate was varied and drawdown versus time curves for various times was plotted (Fig. 6). It was determined that a flow rate of 50 gallons per minute would provide the optimum result. The computation was quick and it was possible to make numerous calculations in a short time.

Another practical application of closed form solutions is the use of such solutions in the numerical model verification. An example for a case study is the use of STRIP1B [15] to verify the GEOFLOW [16] computer code. GEOFLOW is a finite-element flow and solute transport code. The example problem is a two-dimensional system. A line source with a constant concentration is simulated in a uniform velocity field. A schematic of the problem and input data along with comparison of analytical and numerical models for normalized concentrations versus distance is shown in Figs. 7 and 8, respectively.

4.3 Case study - numerical modeling

Following is a summary of a case study representing the application of numerical modeling in selecting the appropriate remedial alternative for a site with a ground water contamination problem.

Past operations at a chemical facility resulted in soil and ground water contamination. The contaminants included DDT and several chlorinated and

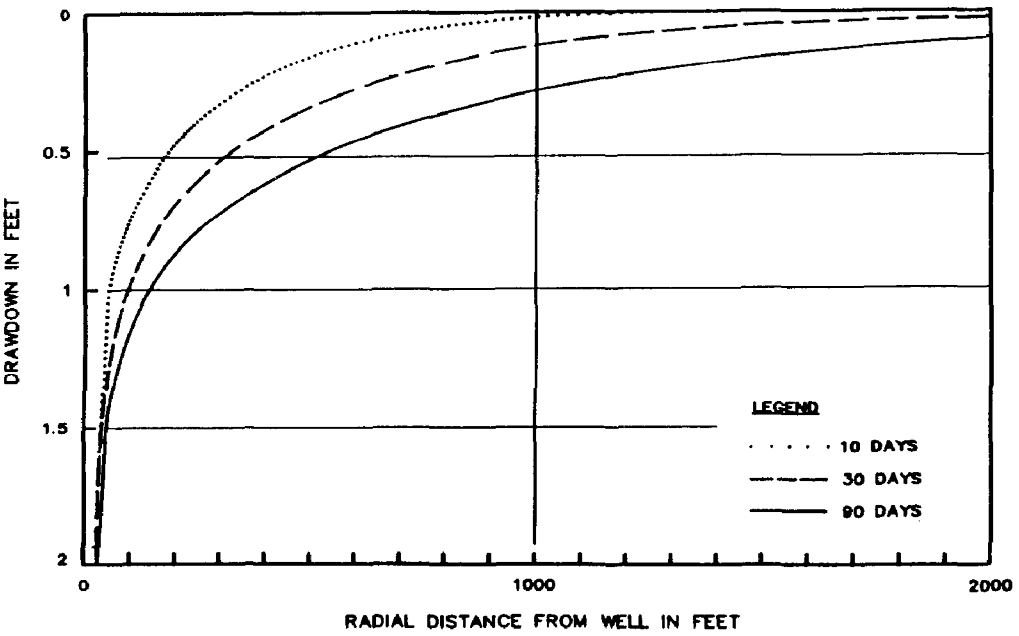

Fig. 6. Drawdown vs. distance.

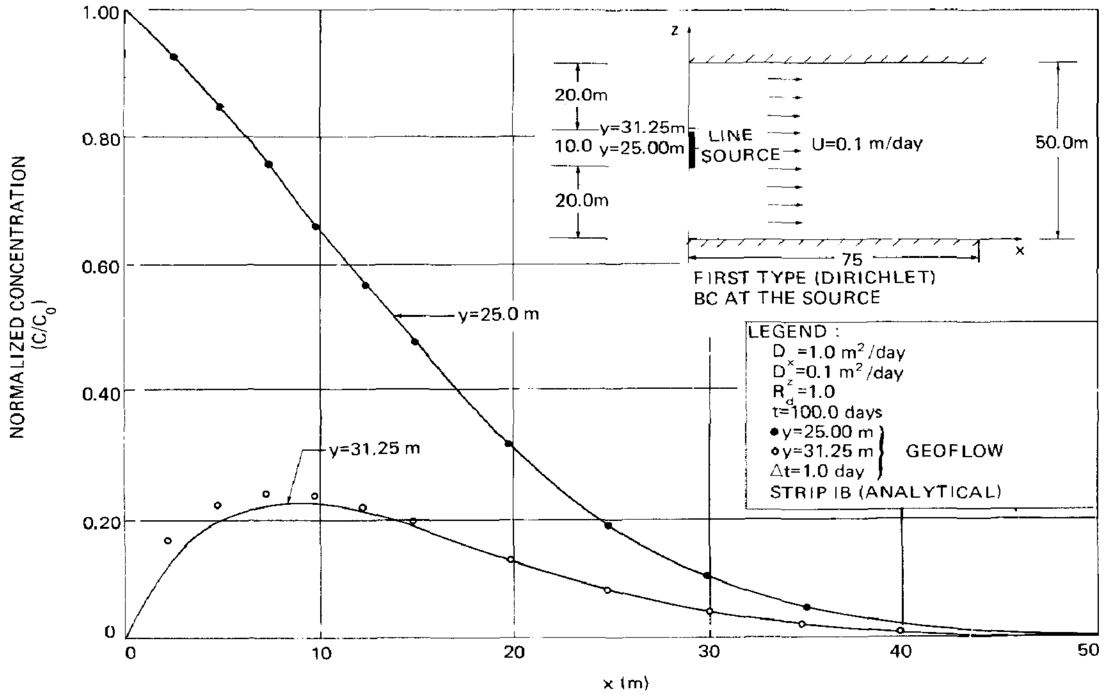

Fig. 7. Comparison of numerical and analytical models results normalized concentration vs. *X*-distance.

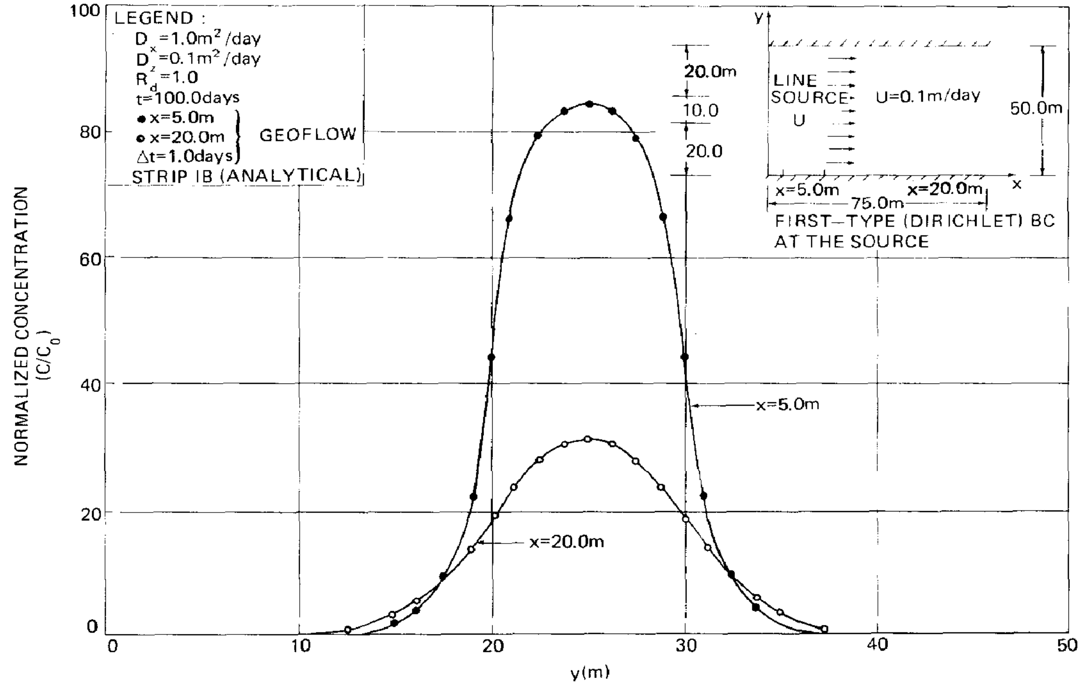

Fig. 8. Comparison of numerical and analytical models results normalized concentration vs. *Y*-distance.

nonchlorinated organics. A review of the characteristics of the site contaminants indicated that DDT and volatile organics could be used as the key indicators for the establishment of appropriate site cleanup levels. The extent of the above compounds at the site is shown in Fig. 9. The major components of the alternatives include recovery well systems, partial source removal, and no action.

To determine the effectiveness of each alternative, it was decided to develop a two-dimensional horizontal flow and solute transport model. The GEOFLOW [16] computer program was used in the development of the model. Known parameters such as hydraulic conductivity and a retardation factor were input to the model. The model then solved unknown parameters such as ground water level and chemical constituent concentrations.

A typical geologic cross section of the site is depicted in Fig. 10. The water-bearing formation consists of sand and gravel mixed with clay and silty clay in anisotropic conditions. The hydraulic conductivity of the formation varied from 3.5×10^{-3} cm/s (10 ft/day) to 5.3×10^{-2} cm/s (150 ft/day). The aquifer was unconfined and its thickness varied from 3 m (9 ft) to 7 m (22 ft).

Initially, the model was calibrated by matching the measured water levels with those generated by the model. Several trials were necessary to obtain a

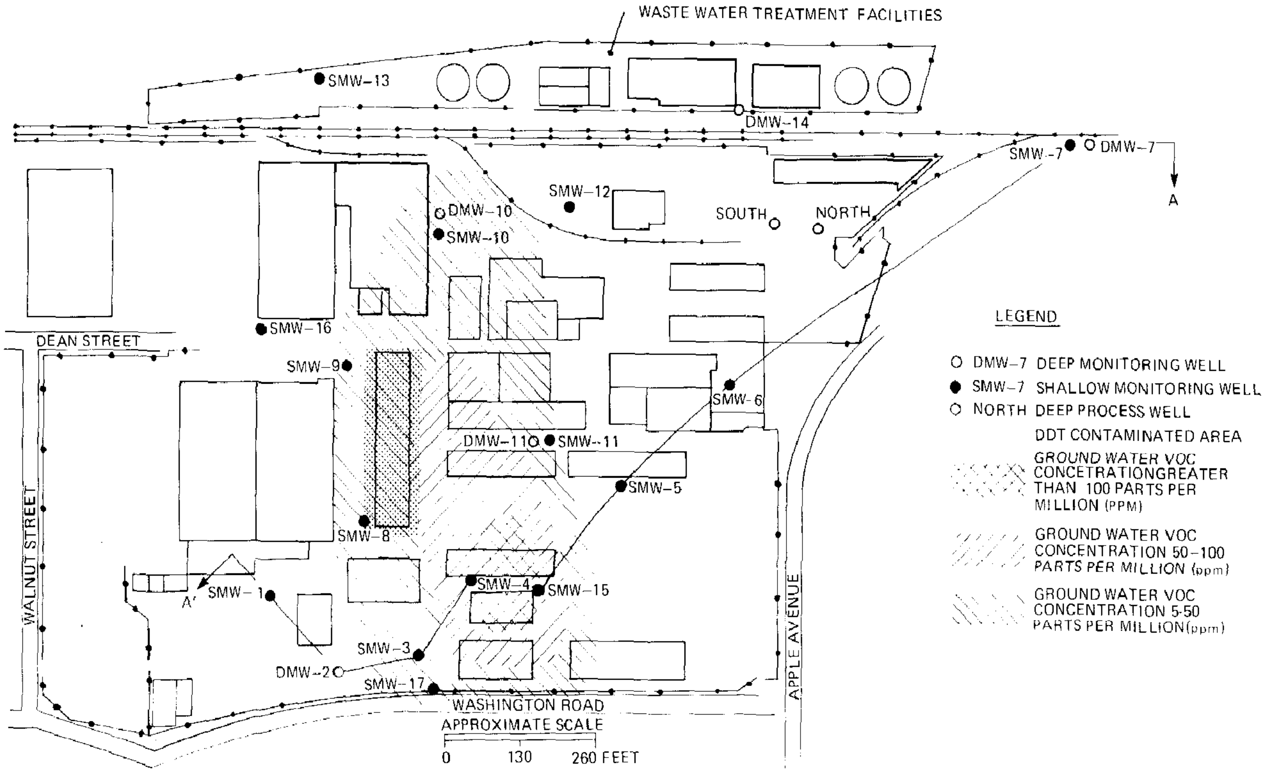

Fig. 9. Site conditions and contaminated areas.

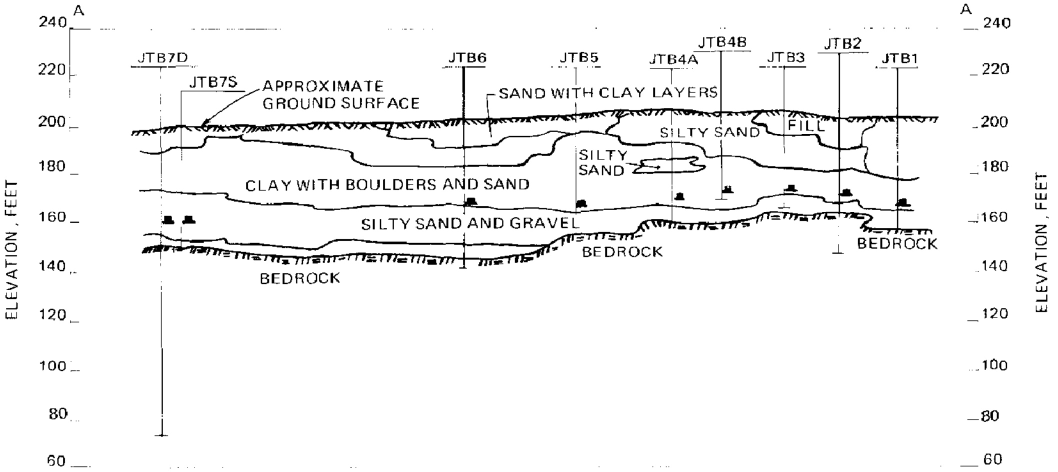

Fig. 10. Hydrogeologic profile (A–A′).

reasonable match. Subsequent to model calibration, various alternative components, such as capping, partial or total waste source removal, purge well systems, slurry wall, and other options, were systematically tested. The modeling provided the prediction of short- and long-term changes in ground water flow direction and concentrations of chemical constituents as a result of various remedial actions. The model results for the various remedial alternatives were evaluated as to their effectiveness in controlling off-site contaminant migration and cleanup period. Economic calculations were made on alternatives which satisfied the remedial action requirements. After reviewing the results of the analysis, the most cost-effective remedial alternative (Fig. 11) was recommended for implementation.

5. Conclusions

Numerous analog, physical, and mathematical ground water models are available to assist in selection of the prudent and cost-effective remedial alternative. They are powerful tools for identifying data gaps, planning field exploration, planning development, performing environmental impact assessments, and evaluating the cleanup options. Ground water models can be used in determination of the pathways characteristics and calculations of the rate, magnitude, extent, and duration of the chemical constituents at critical receptor locations.

In selecting an appropriate model, it is necessary to understand the types of available models, their applicability, benefits, and limitations. In most cases, a simplified analytical model will be sufficient for remedial alternative evaluation. On the other hand, for a site with various features and complexity, it

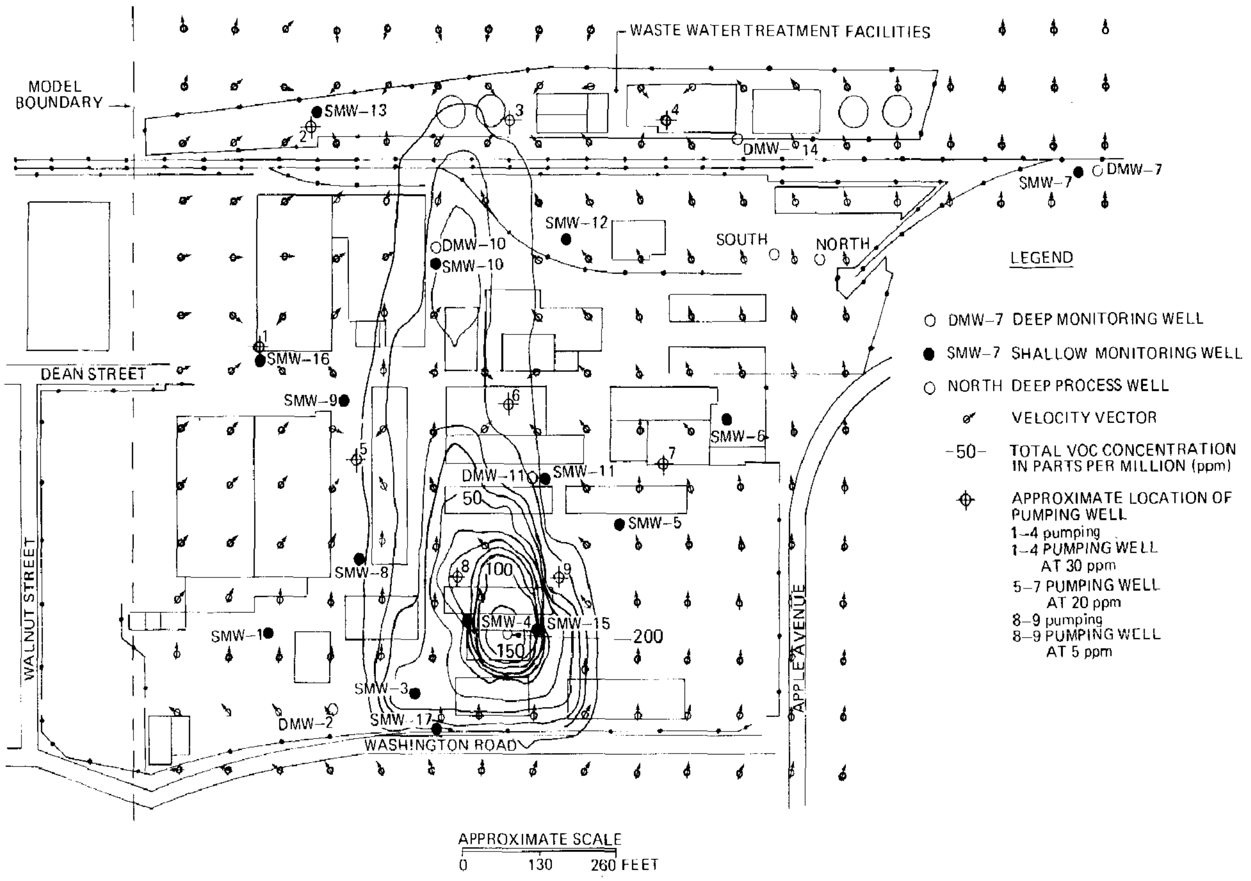

Fig. 11. Recommended remedial alternative.

may be necessary to use mathematical models for alternative selection and laboratory models for cleanup time and cleanup level determination.

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