United States Department of the Interior

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EMS TRANSMISSION 8/8/06
Instruction Memorandum No. NV-2006-065
Expires: 9/30/07

To: Field Managers, Nevada

From: State Director, Nevada

Subject: Groundwater Modeling Guidance for Mining Activities

The use of groundwater models at mine operations is widely practiced for analyzing water resource impacts, mine operations, and mine closures. Groundwater-flow and fate and transport models have been utilized to evaluate numerous hydrogeologic conditions. Groundwater flow models are used to calculate the groundwater flow rate, quantity, and direction of movement of groundwater through aquifers and confining units in the subsurface. Fate and transport models estimate the association/disassociation of concentrations of chemicals in groundwater, and evaluate the rate of movement, concentrations, and pathways.

Purpose

The use and protection of water resources is an important environmental and economic issue. As mining has the potential to have significant quality and quantity impacts to the State of Nevada water resources, it is important and necessary that the Bureau of Land Management (BLM) adequately address water resource concerns through National Environmental Protection Act (NEPA) analysis as an integral part of Plans of Operation (POOs) approvals. Groundwater and fate and transport models are useful tools to aid in the NEPA evaluation of potential impacts from mining.

It is necessary that the BLM adequately address water resource concerns in the review of all proposed Mining POOs conducted under 43 CFR Subparts 3802 and 3809 - Surface Management Regulations. The goals of this policy are:

- To ensure the continued health of the land and water resources
- To ensure the use of good science in making informed decisions
- To collaborate with appropriate Federal, State, local and tribal agencies and other interested parties

Policy

This guidance is intended to focus specifically on groundwater modeling, conceptual design and evaluation processes. The Nevada BLM Groundwater Modeling Guidance for Mining Activities requires that groundwater resource investigations involving groundwater modeling, at a minimum, meet protocols outlined in this policy. This guidance will ensure that a consistent approach is followed for groundwater modeling studies and reports required to meet POO and NEPA standards.

It is also the policy of the Nevada BLM to collaborate with the appropriate State regulatory agencies, specifically, Nevada Department of Conservation and Natural resources (NDCNR), Division of Environmental Protection (NDEP) and Division of Water Resources (NDWR). In certain situations, BLM may evaluate potential impacts at a level of detail or breadth of analysis that exceeds State requirements. For example, the BLM might require a detailed groundwater model analysis associated with each mining alternative as proposed within the NEPA document. Such departures should be coordinated with the appropriate State agency.

Implementation

This Instruction Mermorandum should be followed when developing groundwater investigative studies in support of NEPA documents and POO approvals. Attachment 1 "Nevada Bureau of Land Management Groundwater Modeling Guidance for Mining Activities" is intended as a flexible document to aid in meeting requirements of this policy. Also included is a glossary of useful terms pertinent to groundwater hydrology and modeling and a table of relevant references on groundwater modeling.

Contact Person

Questions concerning this policy and the attached guidance document should be directed to Dr. Tom Olsen, BLM Nevada State Office, Division of Minerals Management at (775) 861-6451.

Signed by:	Authenticated by:
Ron Wenker	Pam Collins
State Director, Nevada	Staff Assistant

1 - Attachment
  1 - Nevada Bureau of Land Management Groundwater Modeling Guidance For Mining Activities (30 pp)

Separate Cover:
Figures 1 - 14

Nevada Bureau of Land Management
Groundwater Modeling Guidance
For Mining Activities

The following guidelines are provided to facilitate the implementation of the Nevada Bureau of Land Management (BLM) Groundwater Modeling Guidance for Mining Activities conducted under 43 CFR subparts 3802 and 3908 Surface Management Regulations. The guidance document is intended as a flexible document specific to water resource protection, and all sections of this document may not apply to every mining operation. For example, there may be projects where the mining will not intercept the water table or saturated zone. In such an instance, groundwater modeling may not be necessary. If there is any indication of potential mine operation/water resource conflicts, the proposed activity should be evaluated by the BLM, in coordination with the State and the mining company.

1.0 Use

The use of groundwater flow models is widely accepted in the field of environmental hydrogeology. Models have been applied to evaluate numerous hydrogeologic conditions associated with mining projects. In addition, groundwater models have been applied to predict the fate and transport of contaminants for risk evaluation purposes. This guide is intended to assist BLM staff specialists, contractors and mining companies in the evaluation and development of work plans that propose to utilize groundwater models, and to aid BLM staff specialists in the assessment of models that have been developed for mine dewatering, water management, remedial design, developing performance monitoring, and risk assessment.

The guidance document describes the following general concepts:

- Use of groundwater flow and transport models for saturated flow conditions
- Level of hydrogeological characterization needed to develop a model
- Different types of models
- Modeling procedures
- Appropriate degree of model documentation
- Model submittal procedures
- Need for verification sampling

It is not the purpose of this document to provide BLM staff specialists with a detailed examination of groundwater modeling procedures, or of particular groundwater models. A number of technical terms are used throughout this guide when describing numerous aspects of groundwater modeling. A glossary of these and other widely used modeling terms and their definitions are contained in Appendix 1. A list of selected references, which provide more specifics on the concepts presented in this guidance, is presented in Appendix 2.

2.0 Groundwater models

Models are conceptual descriptions or approximations that describe physical systems using mathematical equations, they are not exact descriptions of physical systems or processes. The applicability or utilization of a model depends on how closely the mathematical equations approximate the physical system being modeled. To evaluate the applicability or utilization of a model, it is appropriate to have thorough understanding of the physical system and of the assumptions applied in the derivation of the mathematical equations. A specific discussion of the assumptions and derivations of the equations that are the basis of different groundwater models is beyond the scope of this guide.

Groundwater models describe groundwater flow and fate and transport processes using mathematical equations that are made on specific simplifying assumptions. These assumptions generally involve the direction of groundwater flow, geometry of the aquifer, heterogeneity or anisotropy of the sediments or bedrock within the aquifer, and contaminant transport mechanisms and chemical reactions.

Groundwater models are useful investigation tools that hydrologists, hydrogeologists, engineers, and water resource specialists can use for mine project assessment, such as:

- Evaluation of regional groundwater resources
- Designing a groundwater monitoring network
- Evaluating mine dewatering projects
- Evaluating water disposal proposals
- Tracking the possible migration pathway of groundwater contamination
- Assessing environmental risk
- Evaluating pit lake recovery
- Evaluating design of hydraulic containment and pump-and-treat systems

It is important to have a general understanding of both groundwater flow and fate and transport models to ensure that applications or evaluation of these models can be performed correctly.

2.1.1 Groundwater Flow Models

Groundwater flow models are used to evaluate the rate and direction of movement of groundwater through aquifers and confining units in the subsurface. These calculations are referred to as simulations. The simulation of groundwater flow requires a thorough understanding of the hydrogeologic characteristics of the mine operation or area to be modeled. The hydrogeologic study should include a complete characterization of the following:

- Extent and thickness of aquifers, confining units, and structural controls
- Hydrologic boundaries that control the rate and direction of movement of groundwater

- Hydraulic properties of the aquifers and confining units
- A description of the horizontal and vertical distribution of hydraulic head throughout the modeled area for initial conditions, steady-state conditions and transient conditions when hydraulic head may vary with time
- Distribution and amount of groundwater recharge, pumping or injection of groundwater, leakage to or from surface water bodies

The outputs from the model simulations are the hydraulic head and groundwater flow rates that are at equilibrium with the hydrogeologic conditions defined for the modeled area. Figure 1 shows the modeled flow field for a test site at which pumping from a well creates changes in the groundwater flow field.

Through the process of model calibration and verification that is discussed in later sections of this guide, the values of the different hydrogeologic conditions are varied to reduce any disparity between the model simulations and field data, and to improve the accuracy of the model. The model can also be used to simulate possible future changes to hydraulic head or groundwater flow rates as a result of future changes in stresses on the aquifer system.

2.1.2 Fate and Transport Models

Fate and transport models simulate the movement and chemical change of contaminants as they move with groundwater through the subsurface. Fate and transport models require the development of a calibrated groundwater flow model that has based on field data. The model simulates the following:

- Movement of contaminants by advection and diffusion
- Removal or release of contaminants by sorption or desorption
- Spread and dilution of contaminants by dispersion
- Chemical changes of the contaminants by chemical reactions that may be controlled by biological processes or physical reactions

Besides a thorough hydrogelogical investigation, the simulation of fate and transport processes requires a complete characterization of the following:

- Horizontal and vertical distribution of average and linear groundwater velocity determined by a calibrated groundwater flow model or through determination of direction and rate of groundwater flow from field data
- Boundary conditions for the solute
- Initial distribution of solute
- Location, history and mass loading rate of chemical sources or sinks.
- Effective porosity
- Soil bulk density
- Fraction of organic carbon
- Water partitioning coefficient
- Density of fluid

- Longitudinal and transverse dispersivity
- Diffusion coefficient
- Chemical decay rate

The outputs from the model simulation are the contaminant concentrations that are in equilibrium with the groundwater flow system, and the geochemical conditions defined for the model area. Figure 2 shows the simulation migration of a contaminant at a test site.

As with groundwater flow models, fate and transport models must be calibrated and verified by adjusting values of the different hydrogeological or geochemical conditions to reduce any disparity between the model simulations and field data. This process may result in a re-evaluation of the model used for simulating groundwater flow if the adjusted values of geochemical data do not result in an acceptable model simulation. Predictive simulations may be made with a fate and transport model to predict the expected concentrations of contaminants in groundwater as a result of a remedial action.

2.2 Types of Models

The equations that describe the groundwater flow and fate and transport process may be solved using different types of models. Certain models may be exact solutions to equations that describe very simple flow or transport conditions and others may be approximations of equations that describe very complex conditions. Each model may also simulate one or more of the processes that govern groundwater flow or contaminant migration rather than all of the flow and transport processes. An example is the particle tracking model MODPATH, which simulates advective transport of contaminants, but does not account for other fate and transport processes. In selecting a model for use at a site or area, it is necessary to determine whether the model equations account for the specific processes occurring at the site or area. Every model, whether it is a simple analytical model or a complex numerical model, can have applicability in hydrogeological and remedial investigation.

2.2.1 Analytical Models

Analytical models are an exact solution of a specific groundwater flow or transport equations. The equation is a simplification of a more complex three-dimensional groundwater flow or solute transport problem. Analytical models are typically steady-state and one-dimensional, although selected groundwater flow models are two dimensional, and some contaminant transport models assume one-dimensional groundwater flow conditions. An example of output from a one-dimensional fate and transport analytical model (Domenico and Robbins, 1985) is shown in figure 3.

Because of the simplifications associated with analytical models, it is not possible to account for field conditions that change with time or space. This includes variations in groundwater flow rate or direction, variations in hydraulic or chemical reaction properties, changing hydraulic stresses, or complex hydrogeologic and chemical boundary conditions.

Analytical models are best used for:

- Designing data collection plans prior to beginning field activities
- Initial site or area assessments where a high degree of accuracy is not needed
- An independent check of numerical model simulation results
- Sites or areas where field conditions support the simplifying assumptions associated with an analytical model

2.2.2 Numerical Models

Numerical models are able to solve the more rigorous equations that describe groundwater flow and solute transport. These equations usually describe multi-dimensional groundwater flow and solute transport, but there are one dimensional numerical models. Numerical models use approximations to solve the differential equations describing groundwater flow or solute transport. The approximations require that the model domain and time be discretized. In the discretization process, the model domain is represented by a series of grid cells or elements, and time of the simulation is represented by time steps or increments. A simple example of discretization is presented in Figure 4. The curve represents the continuous variation of a parameter across the model space or time increment. The bars represent a discrete step-wise approximation of the curve.

The accuracy of numerical models depends on the model input data, the size of the space and time discretization, and the numerical method used to solve the model equations. Numerical models have the capability to represent a complex multi-layered hydrogeologic system. This is done by dividing the framework into discrete cells or elements. An example of representing a multi-layered aquifer system in a numerical model is shown in Figure 5.

Besides complex three-dimensional groundwater flow and solute transport problems, numerical models can be used to simulate very simple flow and transport conditions, that can be as easily simulated using an analytical model. Additionally, numerical models are generally used to simulate problems that cannot be accurately described using analytical models.

2.2.3 Inverse Models

Groundwater flow and groundwater fate and transport models try to predict behavior of groundwater and groundwater contaminants. However, model predictions are not exact, one of the reasons is the heterogeneity of the subsurface soils and rock which are usually not well known throughout the entire model domain. Use of inverse models improve evaluation of prediction reliability because the results yield not only parameter estimates and head and flows simulated for the stresses of interest, but also confidence intervals for estimated parameters and the heads and flows, which are used to explain the reliability of the model results.

The main benefit of inverse modeling is the capability to automatically calculate parameter values that produce the best fit between observed and simulated hydraulic heads and flows. Secondly, other benefits are, 1) improved model calibration, 2) identifying data needs, 3) better estimates and predictions help support model studies. Additionally, the uncertainty and correlation of estimated parameters can be improved through automated calibration.

3.0 Groundwater Model Development Procedure

3.1 Hydrogeologic Characterization

Good characterization of the hydrogeological conditions at a site or area is necessary in order to understand the importance of flow and solute-transport processes. It is important that a thorough site characterization be completed. This level of characterization requires more site-specific field work than just an initial assessment, including more monitoring wells, water samples, water levels, and an increase in the number of laboratory and field parameters. Without appropriate site characterization it is not possible to select a model or develop good calibrated model, the following hydrogeological information must be available in a characterization process:

- Topographic data, to include surface water elevations
- Regional data, to include subsurface geology
- Surface water bodies and measured stream discharge data
- Geologic cross sections from soil borings and well logs
- Measured hydraulic head
- Well construction diagrams and soil boring logs
- Estimated hydraulic conductivity, from aquifer tests
- Location and estimation of flow rate of groundwater sources or sinks
- Identification of chemicals of concern in contaminant plume*
- Vertical and horizontal extent of contaminant plume*
- Mass loading or removal rate for contaminant sources or sinks*
- Direction and rate of contaminant migration*
- Identification of downgradient receptors
- Organic carbon content of sediments*
- Geochemical field parameters (e.g. dissolved oxygen, Eh, pH, etc.)*

*required only by fate and transport models

These data must be presented in map, table, or graph format in a report documenting model development.

3.2 Model Conceptualization

Model conceptualization is the process where data describing field conditions are gathered in a systematic way to describe groundwater flow and contaminant transport processes at a site or area. The model conceptualization helps in determining the model approach and which model software to use.

Questions that should be asked during conceptual model development include, but not limited to:

- Are there adequate data describing the hydrogeology?
- In how many directions is groundwater moving?
- Can the groundwater flow or contaminant transport be defined as one, two or three dimensional?
- Is the aquifer system made up of more than one aquifer, and is vertical flow between aquifers significant?
- Is there recharge to the aquifer by precipitation or leakage from a river, drain, or infiltration system?
- Is groundwater leaving the aquifer by seepage to surface water bodies, flow to a drain, or extraction well?
- Does it seem that the aquifer's hydrogeological characteristics remain? uniform or do or does the geologic data indicate considerable variation?
- Have boundary conditions been defined around the modeling domain, and what is the basis?
- Do groundwater flow or contaminant source conditions remain the same, or do they change with time?
- Are there receptors located down-gradient of the contaminant plume?
- Are there geochemical reactions taking place in onsite groundwater and are the processes understood?

Other questions related to site-specific conditions may be asked. This conceptualization step must be completed and described in the model documentation report.

3.3 Model Software

After hydrogeological characterization of the site or area has been completed, and the conceptual model developed, computer model software is selected. The selected model must be capable of simulating conditions encountered at the site or area. The following guidelines should be utilized in evaluating the appropriate model:

Analytical models should be used where:

- Field data indicates that groundwater flow or transport processes are relatively simple
- An initial assessment of hydrogeological conditions or screening of remedial alternatives is needed

Numerical models should be used where:

- Field data indicate that groundwater flow or transport processes are quite complex
- Groundwater flow directions, hydrogeological or geochemical conditions, and hydraulic or chemical sources and sinks vary with space and time

One dimensional groundwater flow or transport model should be used where:

- Initial assessments where the degree of aquifer anisotropy and heterogeneity is not known
- Sites where a potential receptor is immediately downgradient of the contaminant source

Three-dimensional flow and transport models should be used where:

- Hydrogeologic conditions are well know
- Multiple aquifers are present
- Vertical movement of groundwater or contaminants is vital

The reasoning for selection of appropriate model software should be discussed in the model documentation and report. The selection of the appropriate model software program for a project is the responsibility of the modeler. Any groundwater flow or fate and transport model software may be used provided that the model code has been tested, verified, and documented. However, it is recommended that the model developer contact the BLM at the beginning of the investigation to discuss the model software.

3.4 Model Calibration

Model calibration consists of changing values of the model input parameters to better match field conditions within acceptable criteria. This requires that field conditions at the site or area be adequately characterized. The lack of adequate characterization results in a model that is calibrated to a set of conditions that are not representative of actual field conditions. Calibration processes typically involve calibrating to steady-state and transient conditions. In steady-state simulations, there are no observed changes in hydraulic head or contaminant concentration with time for field conditions being modeled. Transient simulations involve the change in hydraulic head or contaminant concentrations with time. These simulations are needed to reduce the range of variability in the model input data where there are numerous choices of model input data values that can result in similar steady-state simulations.

At a minimum, model calibration should include comparisons between model-simulated conditions and field conditions for the following data:

- Groundwater flow direction
- Hydraulic head

- Hydraulic gradient
- Water mass balance,
- Contaminant migration rates *
- Contaminant concentrations *
- Degradation rates *
- Migration direction *

*required only for fate and transport models

These comparisons should be presented in maps, tables, or graphs. Simple graphical comparison between measured and computed heads is shown in Figure 6. In this example, the closer the heads fall on the straight line, the better is the goodness-of-fit. Typically, the difference between simulated and actual field measurements should be less than 10 percent of the variability in the field data across the model domain. An example of a plot showing residuals for monitoring wells is shown in Figure 7. The appropriate reasoning for establishing acceptable quantitative calibration target residuals and residual statistics for analyzing model error depends on several factors: the degree of natural heterogeneity, complexity of boundary conditions, location, number and accuracy of water level measurements, and the model purpose. The acceptable residual should be a small fraction of the difference between highest and lowest heads across the site or area and be based on:

- Magnitude of the change in heads over the model domain
- Ratio of the Root Mean Square (RMS) error to the total head loss should be small
- Head differential for the residual mean and standard deviation, and for the ratio of the standard deviation to total head change

After calibration, the coefficient of variation as well as the difference between calibrated targets and simulated heads and fluxes should be presented in the model documentation report.

The modeler must not adjust model input data on a scale that is smaller than the distribution of field data. Such a process is referred to as "over calibration," resulting in a model that looks calibrated, but has been based on a dataset that is not supported by field data.

3.5 History Matching

A calibrated model utilizes specific values of hydrogeological parameters, sources and sinks and boundary conditions to match field conditions for specific calibration time periods. The choice of the parameter values and boundary conditions used in the calibrated model is not unique, and other combinations of parameter values and boundary conditions may provide similar model results. History matching uses the calibrated model to reproduce a set of historic conditions. The process has been referred to as model verification. The most common history matching process consists of reproducing an observed change in hydraulic head or solute concentration over a different time period (see Figure 8). The best processes for model verification are ones which use the calibrated model to simulate the aquifer under stressed conditions. The process of model verification may result in the need for further calibration adjustment of the model. After a model has successfully reproduced measured changes in field conditions for both the calibration and history matching time periods, it is ready for predictive simulations.

3.6 Sensitivity

The sensitivity analysis is a process of varying model parameters over a reasonable range (range of uncertainty in values of model parameters) and observing the relative change in model response (see Figure 9). Generally, the observed changes in hydraulic head, flow rate or contaminant transport are noted. At a minimum, the following parameters should be considered in the sensitivity analysis: hydraulic conductivity, recharge, dispersivity*, and porosity. Other inputs such as boundary conductance and heads that are likely to effect computed heads, groundwater flow rates and mass flux of contaminants may be varied as appropriate. The reason for the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data. Sensitivity of one model parameter relative to other parameters is also shown. Sensitivity analyses are also utilized to determine the direction of future data collection activities. Data for which the model is relatively sensitive to would require future characterization, as opposed to data for which the model is insensitive to.

*required only by fate and transport models.

3.7 Predictive Simulations

A model may be used to predict some future groundwater or contaminant transport conditions. The model may also be used to assess remediation alternatives, such as hydraulic containment, pump-and-treat systems, and to assist in risk analysis. To be able to perform these works, the model, must be reasonably accurate, as demonstrated during the calibration process. Even a well calibrated model is based on oversimplifications and uncertainties. For this reason, model predictions should be provided as a range of possible outcomes that reflect the uncertainty in model parameter values. The range of uncertainty should be similar to that applied to the sensitivity analysis. Figure 10 shows the range in computed heads at the calibration targets for a particular point in time resulting from varying a model parameter over a range of uncertainty. Figure 11 shows hydraulic heads predicted for a future time period in response to changing stresses on the aquifer system. Likewise, the range in predicted heads should be presented so that good decisions may be made regarding the groundwater resource. Figure 12 shows a well head protection area for public water-supply. These simulations show a range of hydraulic conductivity values over time and distance. Figure 13 shows a simulated contaminant concentration down-gradient of a source area.

Model predictive simulations may be used to estimate the hydraulic response of an aquifer, the migration pathway of a contaminant, and the concentration of a contaminant at a point of compliance at some future point in time. As an example, the design of mine dewatering system may be based on predictive model simulations. A model may be used to predict the pumping rate needed to dewater a mine, as well as, water quantity during the dewatering process.

Predictive simulations are based on the conceptual model developed for the mine operation or site, the values of the hydrogeology or geochemical parameters used in the model, and the equations solved by the model software. Models are calibrated by adjusting values of the model parameters until the model response closely reproduces field conditions within some acceptable criteria to try to minimize model error. Given the uncertainty in model input parameters and the corresponding uncertainty in predictive simulations, model input values should be selected which result in a conservative simulation. Site-specific data may be used to support a more reasonable conservative scenario and also limit the range of uncertainty in predictive models. Figure 14 shows an example of the growth of model error over time for predictive a simulation.

4.0 Performance monitoring

Groundwater models are used to predict the future conditions of groundwater, and concentrations of contaminants in groundwater. The accuracy of a model prediction relies on successful calibration and verification of the model for determining groundwater flow directions, groundwater quantity, groundwater quality, transport of contaminants and chemical reactions. As a result, performance monitoring is required to compare future field conditions with the model predictions. Monitoring data will provide the necessary information to both compare and update model predictions, so that the model can be improved and become more accurate with time.

As previously mentioned, groundwater model simulations are an approximation of the actual system behavior and monitoring of field conditions are necessary to assess error in model predictions. As a result, performance monitoring is required as a means of physically measuring the actual behavior of the hydrogeologic system and demonstrating compliance with environmental and mining statutes. Groundwater model simulations are estimates and may not be substituted in place measurement of field data. Examples of the applications of groundwater and contaminant transport modeling requiring performance monitoring would include, but not be limited to the following:

- Groundwater and surface-water interface mixing zones that can potentially impact human receptors and sensitive ecological habitat
- Mine dewatering, that could potentially impact water rights and groundwater systems
- Water discharge and disposal that could potentially impact human receptors, ecological habitat and localized aquifer systems
- Hydraulic containment systems that have certain physically measured geochemical and hydraulic head criteria that measure the success of a remediation

The degree of performance monitoring required at a mine operation or site depends on the conditions or actions that have been simulated and the associated level of risk to groundwater systems, ecological habitat, and the environment. As an example, mine dewatering would require extensive groundwater monitoring for hydraulic head levels, groundwater quantities, chemistry, and surface-water systems, through a monitoring well system and monitoring program. Another example would be hydraulic containment of a contaminant plume by a pump-and-treat system that would require extensive monitoring of hydraulic heads and groundwater quality, through a monitoring well system and a water sampling program.

5.0 Documentation of Models

A groundwater model developed for a mine operation or site, either an analytical or numerical model, should be described in sufficient detail so that the model reviewer can determine the appropriateness of the model for the mine operation or site or problem that is simulated. The submittal of a model documentation report and model dataset is required. A suggested format for this report is contained in the following sections. Groundwater modeling documentation must detail the process by which the model was selected, developed, calibrated, verified and utilized. The model documentation report must include the following information:

- Description of the purpose and scope of the model application
- Hydrogeologic data used to characterize the project
- Documentation of the source of all data in the model whether acquired from published sources or measured or calculated from field or laboratory tests
- Model conceptualization
- Model applicability and limitations
- Model approach
- Documentation of all calculations
- Summary of all calibration, history matching and sensitivity analysis results all model predictive simulation results as a range of probable results given the range of uncertainty in values of model parameters.

The format of the report should include the following sections:

- Title page
- Table of contents
- List of figures
- List of tables
- Introduction
- Objectives
- Hydrogeologic characterization
- Model conceptualization
- Model software selection
- Model calibration
- History matching

- Sensitivity analysis.
- Predictive simulations or use of the model for evaluation of alternatives
- Recommendation and conclusions
- References
- Tables
- Figures
- Appendices

5.1.1 Tables

The following is a list of tables that should appear within the body of the model documentation:

Well and boring data including:

- name of the wells or borings
- top of casing elevation
- well coordinate number
- well screen interval
- hydraulic head data
- elevation of bottom of model
- hydraulic conductivity or transmissivity
- groundwater quality chemical analyses
- aquifer test data
- model calibration and verification results showing comparison of measured calibration targets and residuals
- results of sensitivity analysis showing the range of adjustment of model parameters and resulting change in hydraulic heads or groundwater flow rates

Other data, not listed above, may lend itself to presentation in tabular format. The aquifer for which the data apply should be clearly identified in each table.

5.1.2 Figures

The following is a list of the types of figures (maps or cross sections) which should be included in the model documentation report:

- Site map showing soil boring or well locations and site topography
- Regional location map with topography
- Geologic cross sections
- Map showing the measured hydraulic-head distribution
- Maps of top and /or bottom elevations of aquifers and confining units
- Maps showing structural control
- Map of areal recharge
- Model grid with location of different boundary conditions used in the model.
- Simulated hydraulic-head maps

- Contaminant distribution map(s) and/or cross sections showing vertical distribution of contaminants (for fate and transport modeling)
- Map showing simulated contaminant plume distribution (for fate and transport modeling)

Other types of information, not listed above, may be presented in graphic format. Figures that are used to show derived or interpreted surfaces such as layer bottom elevations and hydraulic-head maps should have the data used for the interpolation also posted upon the figure. As an example, measured hydraulic-head maps should identify the observation points and the measured hydraulic-head elevation. Likewise, the simulated hydraulic-head maps should locate the calibration target points and the residual between the measured and modeled data.

All figures should provide the following information:

- North arrow (for maps)
- Date of figure preparation
- Title bar
- Scale bar
- Legend

All maps or cross sections should be drawn to scale with an accurate scale clearly displayed on each figure. When appropriate, all figures should be the same scale. Figures that apply to specific aquifers should be clearly labeled.

5.1.3 Additional Data

Additional data may be required to be presented in the model documentation report. Examples of additional data are as follows:

- Additional studies work plans providing for the collection of additional data where model simulations indicate data deficiencies
- Groundwater monitoring plans/recommendations to collect data needed to verify model predictions.

Other data may be required, depending on the conditions of the project or site. These additional subjects should be addressed within the body of the report. This may include additional figures and tables, or report sections.

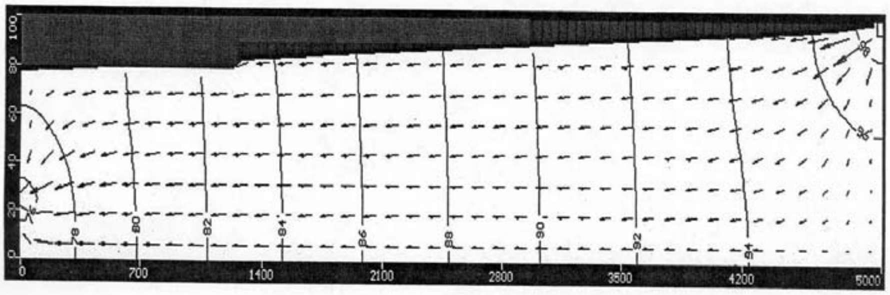


Figure 1. Simulated groundwater flow vectors and hydraulic head.

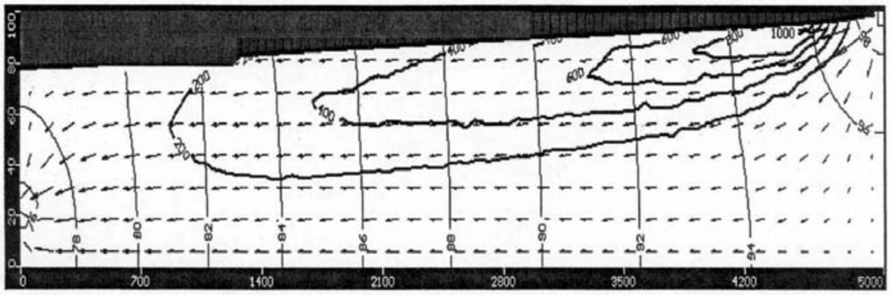


Figure 2. Simulated contaminant plume migration.

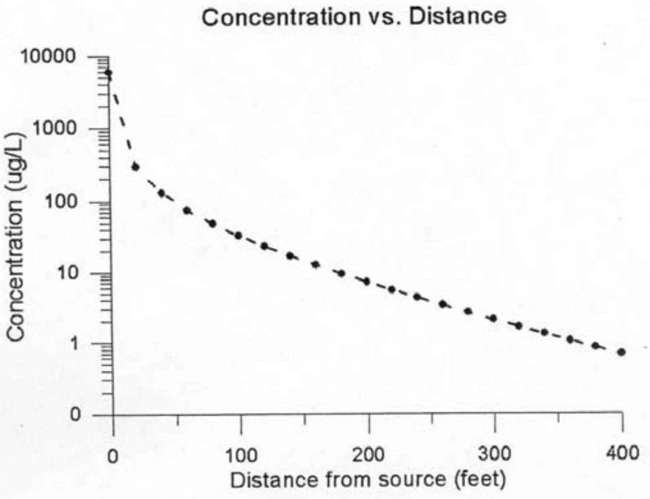


Figure 3. Results from one-dimensional fate and transport model.

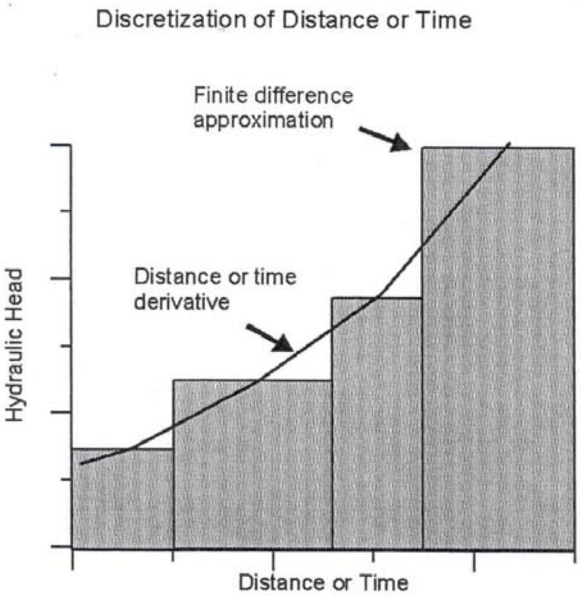


Figure 4. Example of discretization process.

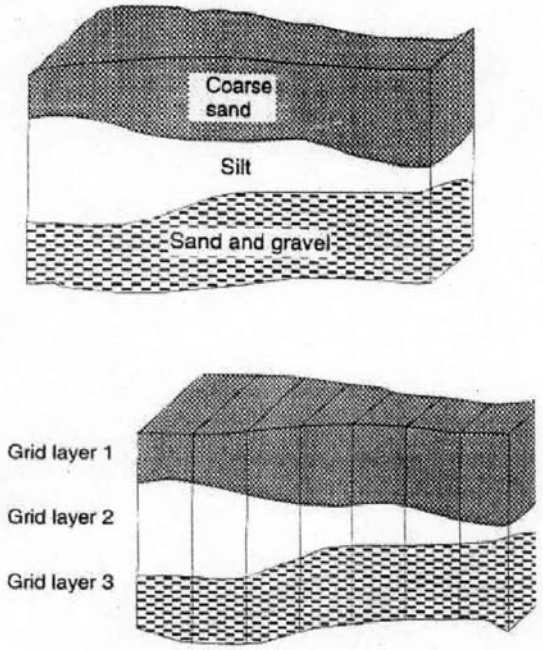


Figure 5. Example of discretization of complex hydrogeological conditions by a numerical model.

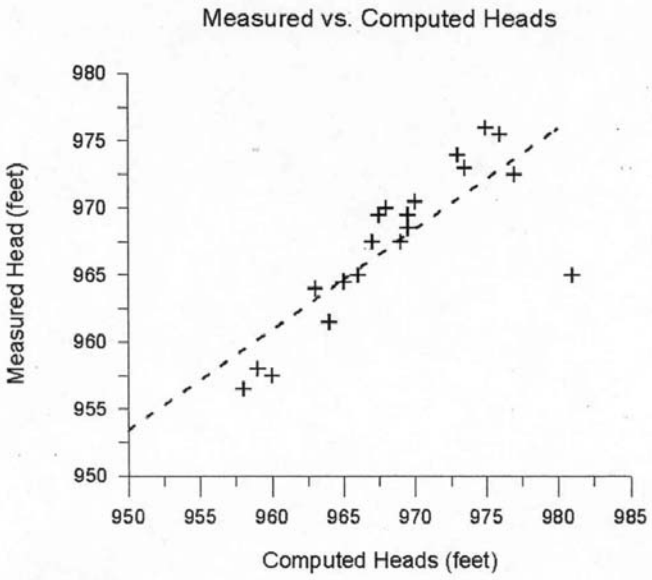


Figure 6. Comparison between measured and computed hydraulic heads.

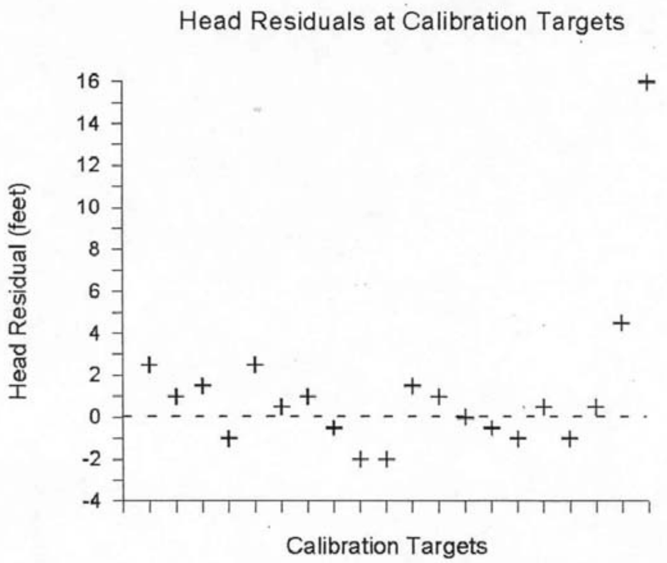


Figure 7. Residuals from comparison of measured and computed heads at calibration targets.

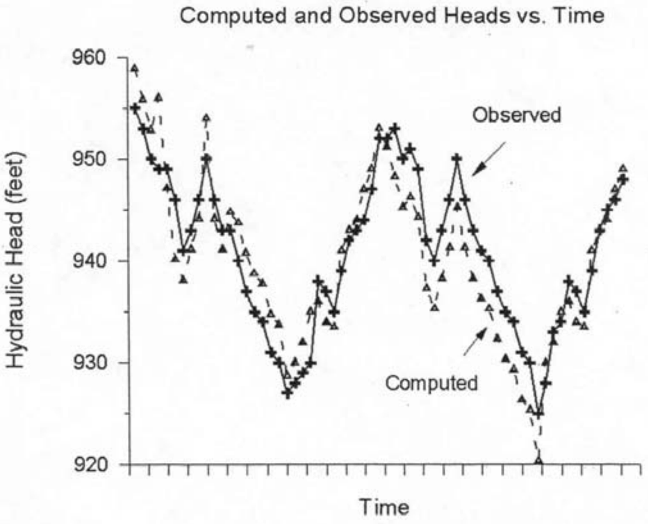


Figure 8. Comparison between computed and observed heads with time.

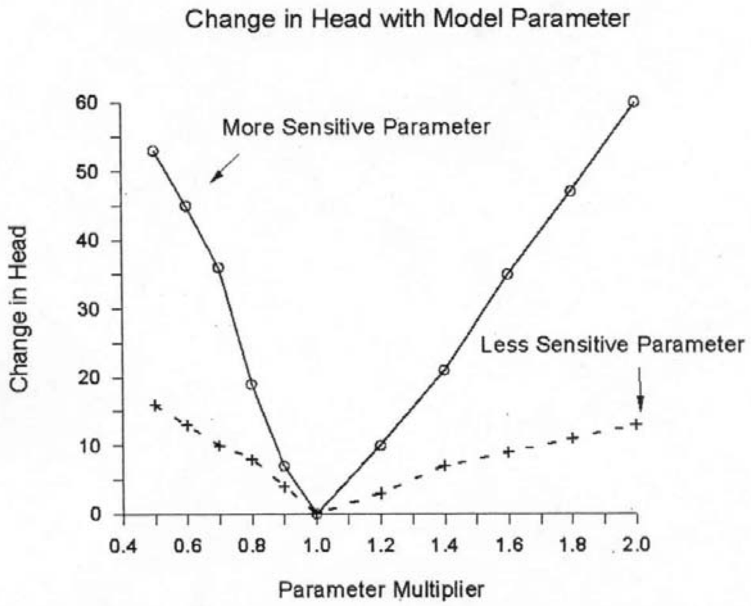
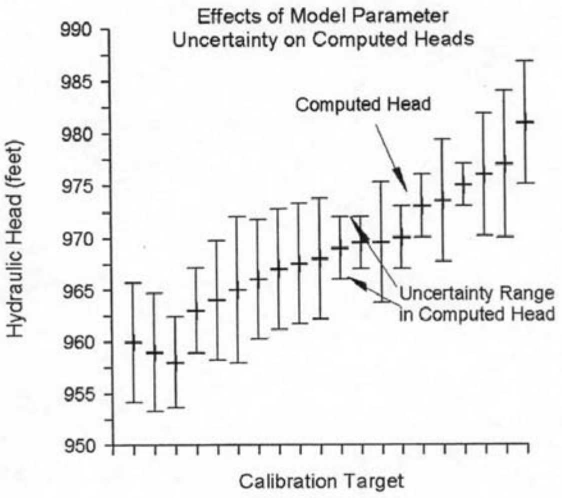


Figure 9. Simulated change in hydraulic head resulting from change in parameter value.



- Figure 10. Simulated uncertainty in hydraulic heads at calibration targets.

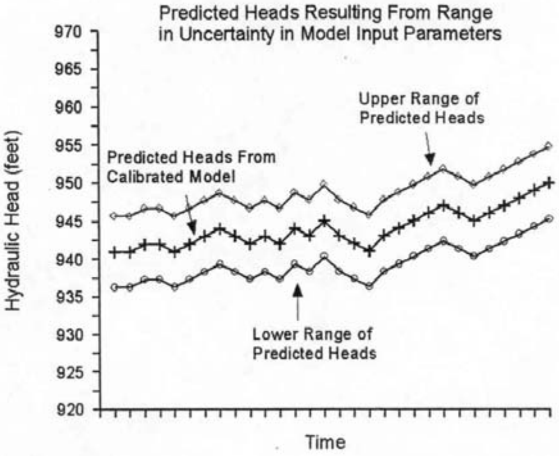


Figure 11. Predicted range in hydraulic heads.

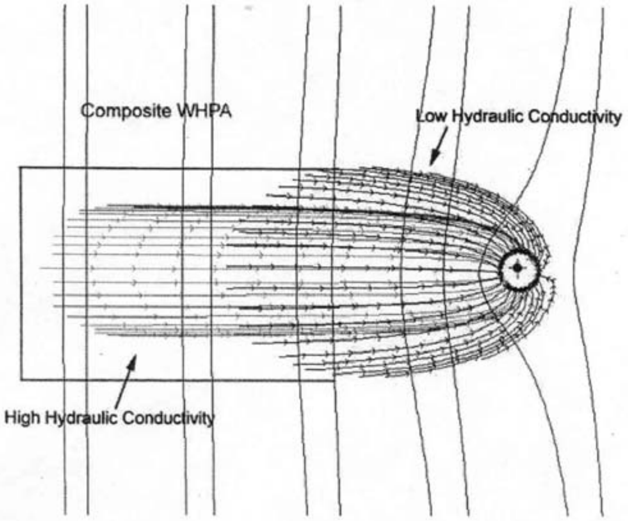


Figure 12. Simulated wellhead protection areas using range of hydraulic conductivities.

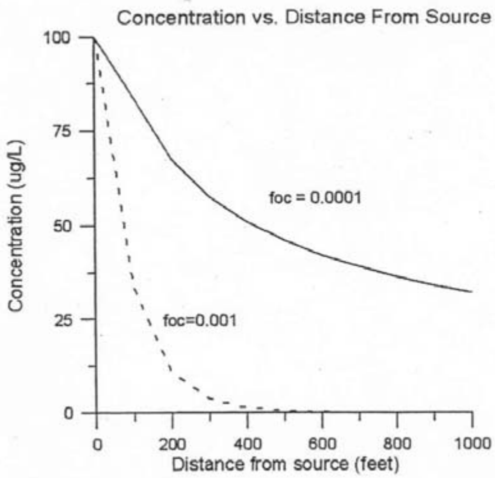


Figure 13. Simulated contaminant concentrations.

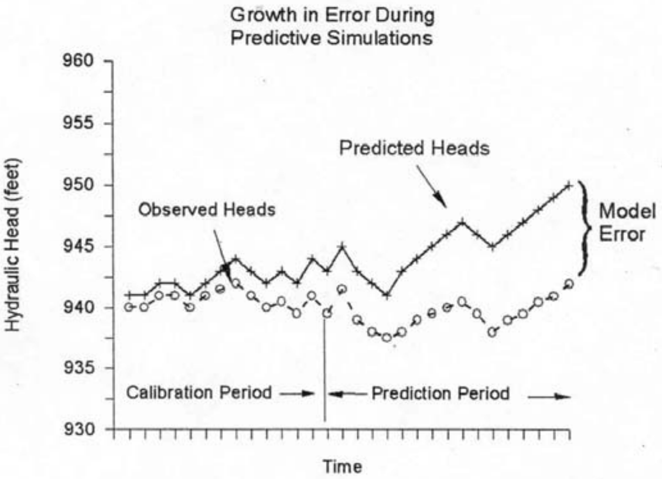


Figure 14. Example of growth of model error in predictive simulation.

Appendix 1. Glossary of Groundwater Hydrology and Modeling Terms

Absorption - dissolving or mixing of a substance in gaseous, liquid or solid form with groundwater.

Adsorption - adherence of molecules in solution to the surface of solids.

Adsorption Isotherm - the graphical representation of the relationship between the solute concentration and the mass of the solute species adsorbed on the aquifer sediment or rock

Advection - the process by which solutes are transported by moving groundwater. This is also called convective transport.

Analytical Model - a mathematical model generally assuming homogeneous aquifer properties, uniform flow direction and hydraulic gradient, uniform aquifer thickness, with simple upper and lower boundaries, and lateral boundaries are placed at an infinite distance.

Anisotropy - the condition of having different values of hydraulic conductivity (in particular) in different directions in geologic materials. This is especially apparent in fractured bedrock or layered sediment.

Aquifer - a geologic formation, group of formations, or part of a formation that is saturated and is capable of providing a significant quantity of water.

Aquifer, Confined - an aquifer bounded above and below by confining beds in which the hydraulic head is above the top of the aquifer.

Aquifer, Unconfined - an aquifer that has a hydraulic head surface (water table) which in equilibrium with the atmosphere.

Area of influence of a well - the area surrounding a well over which the potentiometric surface has changed as the result of pumping groundwater from or recharging groundwater to an aquifer. Same as Zone of Influence. This is not to be confused with the Capture area of a well.

Base Flow - the part of stream flow that is attributable to long-term discharge of groundwater to the stream. This part of stream flow is not attributable to short-term surface run off, precipitation or snow melt events.

Biodegradation, Aerobic - decomposition of organic matter by microorganisms in the presence of free oxygen. The decomposition end-products are carbon dioxide and water.

Biodegradation, **Anaerobic** - decomposition of organic matter by microorgansms in the absence or near absence of free oxygen. Other electron acceptors, other than oxygen, are used by bacteria in this decomposition process. The decomposition end-products are enriched in carbon.

Boundary Condition - a mathematical statement specifying the dependent variable (e.g.) hydraulic head of concentration) at the boundaries of the modeled domain which contain the equations of the mathematical model. Examples are Specified Head, Specified Concentration, Specified Flux (flow or mass flux), or Mixed Boundaries.

Calibrated Model - a model for which all residuals between calibration targets and corresponding model outputs, or statistics computed from residuals, are less than pre-set acceptable values.

Calibration - the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulations and observations of the groundwater flow system, which includes both measured hydraulic head and flux.

Calibration Target - measured, observed, calculated, or estimated hydraulic heads or groundwater flow rates that a model must reproduce, at lease approximately, to be considered calibrated.

Capillary Fringe - the best region of the vadose zone comprising sediments that are saturated, or nearly saturated, near the water table, gradually decreasing in water content with increasing elevation above the water table.

Cell - also called element, a distinct one-two-or three dimensional model unit representing a discrete portion of a physical system with uniform properties assigned to it.

Code Selection - the process of choosing the appropriate computer code, algorithm, or other analysis technique capable of simulating those characteristics of the physical system required to fulfill the modeling project's objective(s).

Computer Code (computer program) - the assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of input data and instructions to delivery of output. Examples: MODFLOW, BIOSCREEN, MT3d, etc.

Concentration Gradient - the rate of change in solute concentration per unit distance at a given point and in a given direction.

Conceptualization Error - a modeling error where model formulation is based on incorrect or insufficient understanding of the modeled system.

Conceptual Model - an interpretation of the characteristics and dynamics of an aquifer system which is based on an examination of all available hydrogeological data for a modeled area. This includes the external configuration of the system, location and rates of recharge and discharge, location and hydraulic characteristics of natural boundaries, and the directions of groundwater flow throughout the aquifer system.

Cone of Depression - a depression of the potentiometric surface that develops around a well which is being pumped.

Confining Bed (Confining Unit) - a hydrogeologic unit of less permeable material bounding one or more aquifers. Synonymous with aquitard, aquiclude, and aquifuge.

Constant-Head Boundary - see **Specified Head Boundary**.

Constant-Head Node - a location in the discretized groundwater flow model domain (node) where the hydraulic head remains the same over the time period considered; see also specified head.

Contaminant Fate - chemical changes and reactions that change the chemical nature of the contaminant, effectively removing the contaminant from the subsurface hydrologic system.

Contaminant Transport Model - a model describing the movement of contaminants in the environment.

Contaminant Transport Velocity - is the rate in which contamination moves through an aquifer.

Degradation Constant - term used to address the decay of contaminant concentration due to factors other than dispersion.

Desorption - all processes by which chemicals move from the solid phase and concentrate them in the liquid phase (groundwater).

Diffusion - process by which ions or molecules move in a random manner, because of their thermal kinetic energy, from areas of high solute concentrations to areas of low concentration in the direction of the solute concentration gradient. Also referred to as molecular diffusion.

Diffusion Coefficient - a constant of proportionality which relates the mass flux of a solute to the solute concentration gradient.

Discretization - is the process of subdividing the continuous model and/or time domain into discrete segments or cells. Algebraic equations which approximate the governing flow and/or transport equations are written for each segment or cell.

Dispersivity - a scale dependent property of an aquifer that determines the degree to which a dissolved constituent will spread in flowing groundwater. Dispersivity is comprised of three directional components - longitudinal, transverse and vertical.

Dispersion - process by which some of the water molecules and solute modecules travel more rapidly than the average linear velocity and some travel more slowly; spreading of the solute in the direction of the groundwater flow (longitudinal dispersion) or direction perpendicular to groundwater flow (transverse dispersion).

Dispersion Coefficient - (1) a measure of the spreading of a flowing substance due to the nature of the porous medium, with its interconnected channels distributed at random in all directions; (2) the sum of the coefficients of mechanical dispersion and molecular diffusion in a porous medium.

Distribution Coefficient - the quantity of the solute, chemical or radionuclide sorbed by the solid per unit weight of solid divided by the quantity dissolved in the water per unit volume of water.

Drawdown - (1) the vertical distance the potentiometric surface is lowered due to the removal of water from a hydrogeologic unit.

Eh - also known as redox potential. Eh is a numerical measure of the intensity of oxidation or reducing conditions. A positive potential indicates oxidizing conditions and a negative potential indicates reducing conditions.

Elevation Head - that part of hydraulic head which is attributable to the elevation of a measuring point (e.g. mid-point of a well screen) above a given datum (e.g. mean sea level).

Equipotential Line - a line connecting points of equal hydraulic head (potential). A set of such lines provides a contour map of a potentiometric surface.

Field Characterization - a review of historical, on-and off-site, as well as surface and sub-surface data and the collection of new data to meet project objectives; field characterization is a necessary prerequisite to the development of a conceptual model.

Finite Difference Method (FDM) - a discretization technique for solving a partial differential equation (PDE) by (1) replacing the continuous domain of interest by a finite number of regular-spaced mesh-or grid-points (i.e., nodes) representing volume-averaged sub-domain properties; and (2) by approximating the derivatives of the PDE for each of these points using finite differences; the resulting set of linear or nonlinear algebraic equations is solved using direct or interactive matrix solving techniques.

Finite Element Method (FEM) - similar to finite difference method with the exception that (1) the mesh may consist of regular or irregular-spaced grid points which may have irregular shapes; and (2) the PDE is approximated using the method of weighted residuals to obtain a set of algebraic equations. These algebraic equations are solved using direct or iterative matrix solving techniques.

Finite Difference Model - a type of numerical model that uses a mathematical technique called the finite-difference method to obtain an approximate solution to the governing partial differential equation (in space and time).

Finite Element Model - a numerical model that uses a mathematical technique called the finite-element method to obtain an approximate solution to the governing partial differential equation (in space and time).

Flow Path - the subsurface course a water molecule or solute would follow in a given groundwater velocity field.

Flux - the volume of fluid crossing a unit cross-sectional surface are per unit time.

Groundwater - that part of the subsurface water that is in the saturated zone.

Groundwater Basin - a groundwater system that has defined boundaries and may include more than one aquifer of permeable materials, which are capable of furnishing a significant water supply. Note - a basin is normally considered to include the f\surface area and the permeable materials beneath it. The surface water divide need not coincide with a groundwater divide.

Groundwater Discharge - the water released from the zone of saturation; also the volume of water released.

Groundwater Flow - the movement of water in the zone of saturation.

Groundwater Flow Model - an application of mathematical model to represent a regional or site-specific groundwater flow system.

Ground Flow System - a water saturated aggregate of aquifers and confining units in which water enters and moves and which is bounded by a basal confining unit that does not allow any vertical water movement and by zones of interaction with the earth's surface and with surface water systems. A groundwater flow system has two basic hydraulic functions: it is a reservoir for water storage, and it serves as a conduit transmitting water from recharge to discharge areas. A groundwater flow system may transport dissolved chemical constituents and heat.

Groundwater Modeling Code - the computer code used in groundwater modeling to represent a non unique, simplified mathematical description of the physical framework, geometry, active processes, and boundary conditions present in a reference subsurface hydrologic system.

Head (Total; Hydraulic head) - the height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. In a well it is the elevation of the height of water in a well above the mid-point of a well screen (Pressure Head) plus the elevation of the mid point of the well screen (Elevation Head).

Head Dependent Boundary - see Mixed Boundary.

Heterogeneity - a characteristic of a medium in which material properties vary from point to point everywhere.

History Matching - Also referred to as Model Verification.

Homogeneity - a characteristic of a medium in which material properties are identical everywhere.

Hydraulic Conductivity - a constant of proportionality which relates the rate of groundwater flow to the hydraulic head gradient. It is a property of the porous media (Intrinsic Permeability) and the density and viscosity of the water moving through the porous media. It is defined as the volume of water at the existing kinematic viscosity that will move in unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of low. Estimated by, in order of preference, aquifer tests, slug tests, grain size analysis.

Hydraulic Gradient - the change in total hydraulic head per unit distance of flow at a given point and in the direction of groundwater flow.

Hydraulic Head - the height above a datum plane (such as sea level) of the column of water than can be supported by the hydraulic pressure at a given point in a groundwater system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

Hydraulic Properties - properties of solid and rock that govern the entrance of water and the capacity to hold, transmit and deliver water, e.g. porosity, effective porosity, specific retention, permeability and direction of maximum and minimum permeability. Synonymous with Hydrologic Properties.

Hydrologic Boundaries - physical boundaries of a hydrologic system.

Hydrologic Unit - geologic strata that can be distinguished on the basis of capacity to yield and transmit fluids. Aquifers and confining units are types of hydrologic units. Boundaries of a hydrologic unit may not necessarily correspond either laterally or vertically to lithostratigrapic formations.

Impermeable Boundary - the conceptual representation of a natural feature such as a fault or depositional contact that places a boundary of significantly less-permeable material laterally adjacent to a aquifer.

Initial Conditions - the specified values for the dependent variable (hydraulic head or solute concentration) at the beginning of the model simulation.

Intrinsic Permeability - a term describing the relative ease with which a porous medium can transmit a liquid under a hydraulic gradient or potential gradient. It is distinguished from hydraulic conductivity in that it is a property of the porous medium alone and is independent of the nature of the liquid or the potential field.

Inverse Method - a method of calibrating a groundwater flow model using a computer code to systematically vary inputs or input parameters to minimize residuals or residual statistics.

Kriging - a geostatistical interpolation procedure for estimating spatial distributions of model inputs from scattered observations.

Leakage - (1) the flow of water fro one hydrogeologic unit to another. The leakage may be natural, as through semi-impervious confining layer, or human made, as through an uncased well; (2) the natural loss of water from artificial structures as a result of hydrostatic pressure.

Leaky Aquifer - aquifers, whether artesian or water table, that lose or gain water through adjacent less permeable layers.

Mathematical Model - a set of mathematical equations expressing the physical system and including simplifying assumptions; (b) the representation of a physical system by mathematical expressions from which the behavior of the system can be deduced with known accuracy.

Mixed Boundary - is a linear combination of head and flux at a boundary. An example of a mixed boundary is leakage between a river and an underlying aquifer.

Model - an assembly of concepts in the form of mathematical equations that portray an understanding of a natural phenomenon.

Model Construction - the process of transforming the conceptual model into a parameterized mathematical form; as parameterization requires assumptions regarding spatial and temporal discretization, model construction requires a-priori selection of computer code.

Model Grid - system of connected nodal points superimposed over the problem domain to spatially discretize the problem domain into cells (finite difference method) or elements (finite element method) for the purpose of numerical modeling.

Modeling - the process of formulating a model of a system of process.

Model Input - the constitutive coefficients, system parameters, forcing terms, auxiliary conditions and program control parameters required to apply a computer code to a particular problem.

Modeling Objectives - the purpose(s) of a model application.

Model Verification - in model application: a) the procedure of determining if a (site-specific) model's accuracy and predictive capability lie within acceptable limits of error by tests independent of the calibration data; b) in model application: using the set of parameter values and boundary conditions from a calibrated model to acceptably approximate a second set of field data measured under similar hydrologic conditions. Also referred to as History Matching.

Node (Nodal Point) - in a numerical model, a location in the discretized model domain where a dependent variable (hydraulic head) is computed.

No-Flow Boundary - model boundary which is a Specified Flux Boundary where the assigned flux is equal to zero. Also see Boundary condition.

Numerical Methods - in subsurface fluid flow modeling, a set of procedures used to solve the groundwater flow equations in which the applicable partial differential equations are replaced by a set of algebraic equations written in terms of discrete values of state variables (e.g. hydraulic head) at discrete points in space and time. The most commonly used numerical methods in groundwater models re the finite-difference method, the finite-element method, the boundary element method and the analytic element method.

Numerical Model - in subsurface fluid flow modeling, a mathematical model that uses numerical methods to solve the governing equations of the applicable problem.

Numerical Solution - an approximate solution of a governing (partial) differential equation derived by replacing the continuous governing equation with a set of equations in discrete points of the model's time and space domains.

Over calibration - achieving artificially low residuals by inappropriately adjusting model input parameters without field data to support the adjusted model parameter value.

Output - in subsurface fluid flow modeling, all information that is produced by the computer code.

Parameter - any of a set of physical properties which determine the characteristics or behavior of a system.

Parameter Identification Model (inverse model) - a computer code for determination of selected unknown parameters and stresses in a groundwater system, given that the response of the system to all stresses is known and that information is available regarding certain parameters and stresses.

Partitioning Function - a mathematical relation describing the distribution of a reactive solute between solution and other phases.

Pecelt Number - a relationship between the advective and diffusive components of solute transport expressed as the ratio of the product of the average interstitial velocity, times the characteristic length, divided by the coefficient of molecular diffusion; small values indicate diffusion is the dominant transport process, large values indicate advection dominance.

Perched Ground Water - unconfined groundwater separated from an underlying body of ground water by an unsaturated zone.

Percolation - the movement of water through the vadose zone, in contrast to infiltration at the land surface and recharge across the water table.

Piezometric Surface - see Potentiometric Surface

Porosity, Total - the ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity, Effective - (1) the ratio, usually expressed as a percentage, of the total volume of voids to the total volume of the porous medium; (2) the ratio of the volume of the voids of a soil or rock mass that can be drained by gravity to the total volume of the mass; (3) the amount of interconnected pore space and fracture openings available for the transmission of fluids, expressed as the ratio of the volume of interconnected pores and openings to the volume of rock.

Postprocessing - using computer programs to assist in preparing data sets for use with generic simulation codes; may include grid generation, parameter allocation, control parameter selection, and data file formatting.

Pressure head - the head of water at a point in a porous system; negative for unsaturated systems, positive for saturated systems. Quantitatively, it is the water pressure divided by the specific weight of water.

Reaction Path Modeling - a simulation approach to studying the chemical evolution of a (natural) system.

Recharge, Groundwater - the process of water addition to the saturated zone usually from precipitation.

Residual - the difference between the model-computed and field-measured values of a variable, such as hydraulic head or groundwater flow rate, at a specific time and location.

Retardation Factor - is used to simulate the resistance of the contamination to move through the groundwater aquifer. A factor of one (1) represents the least resistance while increasing values show increasing resistance.

Saturated Zone - (1) those parts of the subsurface in which all voids are filled with water under pressure greater than atmospheric; (2) that part of the subsurface beneath the regional water table in which all voids, large and small, are filled with water under pressure greater than atmospheric; (3) means that part of the subsurface beneath the regional water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

Seepage Face - a physical boundary segment of a groundwater system along which groundwater discharges and which is present when a water table surface ends at the downstream external boundary of a flow domain; along this boundary segment, of which the location of the upper end is a priori unknown, water pressure equals atmospheric pressure and hydraulic head equals elevation head. Commonly referred to as "seeps" or "springs".

Semi-Analytical Model - a mathematical model in which complex analytical solutions are evaluated using approximate techniques, resulting in a solution discrete in either the space or time domain.

Sensitivity - the variation in the value of one or more output variables (such as hydraulic heads) or quantities calculated from the output variables (such as groundwater flow rates) due to changes in the value of one or more inputs to a groundwater flow model (such as hydraulic properties or boundary conditions).

Sensitivity Analysis - a procedure based on systematic variation of model input values (1) to identify those model input elements that cause the most significant variations in model output; and (2) to quantitatively evaluate the impact of uncertainty in model input on the degree of calibration and on the model's predictive capability.

Simulation - in groundwater modeling, one complete execution of a groundwater modeling computer program, including input and output. Simulation is sometimes also used broadly to refer to the process of modeling in general.

Sink - in subsurface fluid flow modeling, a process whereby, or a feature from which, water is extracted from the groundwater flow system.

Site Characterization - (1) a general term applied to the investigation activities at a specific location that examines natural phenomena and human-induced conditions important to the resolution of environmental, safety and water resources issues; (2) means the program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions are the ranges of those parameters of a particular site relevant to the program. Site characterization includes geophysical testing, borings, surface excavations, excavation of exploratory shafts, limited subsurface lateral excavations and borings and in situ testing a depth needed to determine the suitability of the site.

Soil Bulk Density - the mass of dry soil per unit bulk soil.

Solubility - the total amount of solute species that will remain indefinitely in a solution maintained at constant temperature and pressure in contact with the solid crystals from which the solutes were derived.

Solute Concentration - the concentration of a chemical species dissolved in groundwater.

Solute Transport Model - application of a model to represent the movement of chemical species dissolved in groundwater.

Sorption - (1) a general term used to encompass the process of absorption and adsorption; (2) all processes which remove solutes from the fluid phase and concentrate them on the solid phase of the medium.

Source - a process, or a feature from which, water, vapor NAPL, solute or heat is added to the groundwater or vadose zone flow system.

Source of Contaminants - the physical location (and spatial extent) of the source contaminating the aquifer; in order to model fate and transport of a contaminant, the characteristics of the contaminant source must be known or assumed.

Source Loading - the rate at which a contaminant is entering the groundwater system at a specific source.

Specific Capacity - the rate of discharge from a well divided by the drawdown of the water level within the well at a specific time since pumping started.

Specific Discharge - the rate of discharge of groundwater per unit area of a porous medium measured at right angle to the direction of groundwater flow. Synonymous with flow velocity, darcian velocity and specified flux.

Specific Storage - the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

Specific Yield - the ratio of the volume of water that the saturated rock or soil will yield by gravity to the volume of the rock or soil. In the field, specific yield is generally determined by tests or unconfined aquifers and represents the change that occurs in the volume of water in storage per unit area of unconfined aquifer as the result of a unit change in head. Such a change in storage is produced by draining or filling of pore space and is therefore, mainly dependent on particle size, rate of change of the water table, and time of drainage.

Specified Flux Boundary - a model boundary condition in which the groundwater flux or mass flux is specified; also called fixed or prescribed flux, or Neumann boundary condition.

Specified Concentration Boundary (Constant Concentration) - a boundary at which the solute concentration is specified; also called fix or prescribed concentration, or Dirichlet boundary condition.

Steady State Condition - a condition in which system inputs and outputs are in equilibrium so that there is no net change in the system with time.

Steady State Flow - a characteristic of a groundwater or vadose zone flow system where the magnitude and direction of specific discharge at any point in space are constant in time.

Storage Coefficient - the volume of water an aquifer releases from or takes into storage per unit surface are of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to specific yield.

Storativity - see Storage coefficient.

Superposition Principle - the addition or subtraction of two or more different solutions of a governing linear partial differential equation (PDE) to obtain a composite solution of the PDE. As an example, the superposition of drawdown caused by a pumping well on a regional, nonpumping potentionmetric surface.

Transient Conditions - a condition in which system inputs and outputs are not in equilibrium so that there is a net change in the system with time.

Transient Flow - a condition that occurs when an any location in a groundwater or vadose zone flow system the magnitude and/or direction of the specific discharge changes with time.

Transmissivity - the volume of water at the existing kinetic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer. It is the product of the hydraulic conductivity multiplied by the aquifer thickness.

Unsaturated Zone - the zone between the land surface and the water table which may include the capillary fringe. Water in this zone is generally under less than atmospheric pressure and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the water pressure locally may be greater than atmospheric.

Vadose zone - see Unsaturated zone.

Vadose zone Flow System - an aggregate of rock, in which both water and air enters and moves and which is bounded by rock that does not allow any water movement, and by zones of interaction with the earth's surface, atmosphere and surface water systems. A vadose zone flow system has two basic hydraulic functions: it is a reservoir for water storage and it serves as a conduit by facilitating the transmission of water from intake to discharge areas, integrating various inputs and dampening and delaying the propagation of responses to those inputs. A vadose zone flow system may transport dissolved chemical constituents and heat.

Velocity, Darcian - See Specific Discharge.

Velocity, Average Interstitial - the average rate of groundwater flow to interstices expressed as the product of hydraulic conductivity and hydraulic gradient divided by the effective porosity. Synonymous with average linear groundwater velocity or effective velocity.

Water Mass Balance - an inventory of the difference source and sinks of water in a hydrogeologic system. In a well-posed model, the sources and sinks should balance.

Water table - the surface of a groundwater body at which the water pressure equals atmospheric pressure. Earth material below the groundwater table is saturated with water.

Zone of Saturation - A hydrologic zone in which all the interstices between particles of geologic material or all of the joints, fractures, or solution channels in a consolidated rock unit are filled with water under pressure greater than that of the atmosphere.

Appendix 2. Groundwater Modeling References

The following references are grouped into general categories related to modeling. This list is intended to provide background information to help you develop a better understanding of difference aspects of groundwater and fate and transport modeling. This reference list is not meant to be all-inclusive.

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