Chapter 3
Planning a Groundwater Investigation and Modeling Study

3-1. General

a. This chapter will present basic guidelines for performing a site characterization study, integrating hydrogeologic information into a conceptual model, performing simple analytical procedures, and formulating a computer model of groundwater flow. Specific attention is given to site reconnaissance, initial data interpretation, data acquisition, the formulation of conceptual and numerical/computer models, and guidelines for project management and personnel requirements. Additional information on performing an investigation study can be found in EC 1110-2-287 (1995), and U.S. Geological Survey (1977). Chapter 4 presents an overview of field investigation methods. Chapter 5 presents an overview on the technical aspects of computer modeling of groundwater flow.

b. In order to properly plan a hydrogeologic site investigation, the purpose of the investigation, the general geologic and hydrologic characteristics of the site, and the management constraints under which the investigation is to take place (financial and time restraints, availability of necessary equipment, availability of expertise) should be well understood by all involved in the project. Subsurface investigations are a dynamic and inexact science. The ability of the data acquired to provide an increasingly accurate representation of the hydrogeologic system increases with time, money, and the expertise of the specialists involved. Thus, the success of a groundwater investigation relies not only on the technical expertise of the specialists involved, but also on the effectiveness and efficiency of project management.

c. Examples of groundwater investigations related to Corps projects include the following:

(1) Contaminant remediation.

(2) Well production.

(3) Infiltration of runoff to the subsurface.

(4) Baseflow between aquifers and fixed bodies including streams and reservoirs.

(5) Effects of aquifer pumping on adjacent lakes and streams.

(6) Well installation involved with seawater infiltration barriers.

(7) Estimating grouting requirements.

(8) Dewatering of an excavation for construction purposes.

(9) Groundwater and surface water interrelated projects.

d. Groundwater investigations are based on the creation of an accurate conceptual model. A conceptual model is a simplified description of the groundwater system to be studied. The conceptual model can serve as a basis for formulating a numerical model. Due to recent advances in computer technology, the use of numerical models has been increasingly commonplace for predicting site reactions to defined stresses. A simplified flowchart that summarizes the general steps involved in a hydrogeologic site characterization and potential modeling study is presented as Figure 3-1.

3-2. Steps Involved in a Hydrogeologic Site Investigation and Potential Modeling Study

Hydrogeologic investigations generally are complex and require expertise from a number of different fields. Developing a plan that coordinates all the aspects of an investigation is vital to the success of the project. Study results can be derived from simplified analytical methods (as presented in Chapters 2 and 6) or a more complex numerical model which requires the use of computers (as presented in Chapter 5). Accuracy of the final product relies on efficient use of time, money, and personnel. The plan generally consists of a detailed outline of the objectives, scope, level of detail, procedures, available equipment, existing and potential problems, necessary data, well-thought-out schedule of tasks, and the resources available. Specific deliverables and milestones are defined. All personnel should

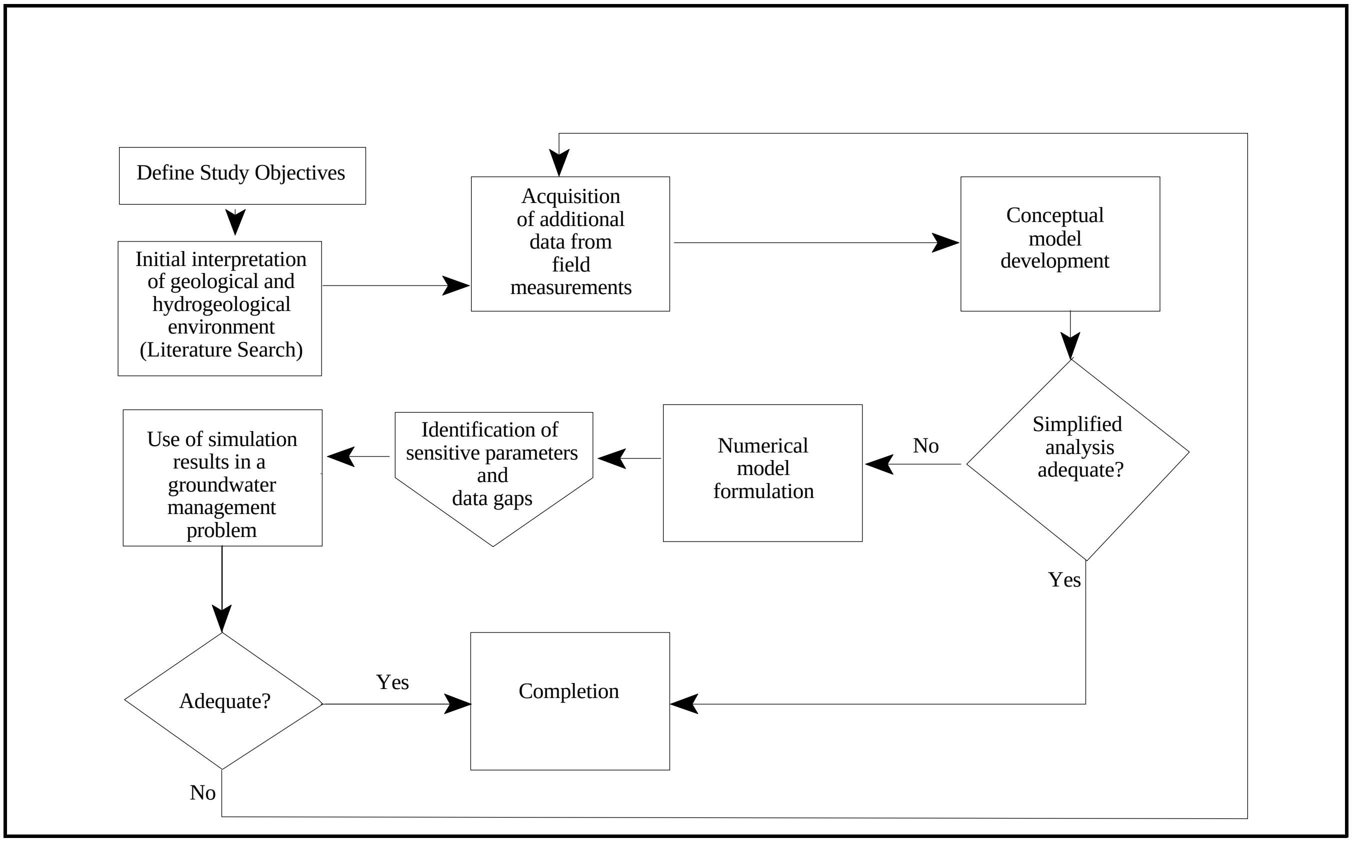

Figure 3-1. General flow diagram for characterizing a groundwater flow system for a management decision-making process

be well-informed of the importance of each job in relation to others.

a. Determining study objectives.

(1) Objectives defined. Objectives for a groundwater site investigation and analysis consist of a series of statements defining, as specifically as possible, the intended use and nature of the results being sought. The objectives define what answers are being sought. Defining sound and clear objectives early in the study is not as easy as it sounds. In some cases, simple analytical hand calculations will sufficiently address study objectives. In other cases, a more in-depth numerical analysis using computers will be required. When customers do not understand the capabilities and limitations of analytical procedures and groundwater models, and the study managers do not fully understand the needs of the customer, the work may begin with only a general idea of their objectives. This may lead to unmet expectations and waste of work time. It benefits the project manager, the technical assistance team, and the customer to take the time at the beginning of the study to define study objectives and also to define performance criteria.

(2) Desired specificity. Part of the study objectives statement should contain specific and descriptive constraints on what is expected (see below).

(a) The overall purpose of this study is to determine if reservoir inflows will significantly decrease as a result of upstream pumping at proposed irrigation and water supply wells. Groundwater modeling is desired to determine the maximum changes in water levels resulting from proposed pumping of up to 1,000 m^3/min from three wells located 200 m north of the stream. The wells are located 2,000 m, 5,000 m, and 7,000 m upstream of the reservoir inflow. The analysis should be performed for both the average seasonal high and seasonal low conditions. Perform the analysis using both a best-estimate approach and a worst-case approach that considers the uncertainty in the range of expected values of aquifer hydraulic conductivity and storage coefficient, streambed conductance, and recharge from precipitation. If significant reduction in streamflow is predicted, repeat the analysis for well locations of 300 m and 700 m north of the river.

(b) The overall purpose of this study is to determine groundwater flow travel times and directions beneath Swan Lake Landfill. Pollution from the landfill may contaminate nearby supply wells. Estimate the groundwater pore velocities and flow directions in the unconfined aquifer beneath the Swan Lake Landfill at the northeast property corner, the southeast property corner, and at the midpoint between. Estimate pore velocities directly down-gradient from these three points every 50 m until intersecting the western property boundary of the landfill. Estimate overall groundwater travel times from these three points to the western property boundary in the form of "best estimate, and expected ± 30 percent confidence interval values reflecting uncertainties in hydraulic conductivities and boundary conditions.

(3) Objectives and code selections. Modeling objectives should be set before conceptual model development and numerical code selection. Differing objectives lead to different modeling approaches. For example, data for a particular site may indicate that the water table elevations vary seasonally and interact with the levels of a nearby reservoir. If modeling objectives included determining the effects of reservoir level changes on the water table throughout the year, a conceptual model may describe the changing water table in a step-wise manner (e.g., monthly averages). This approach would lead to the construction of a model with time-varying boundary conditions and would require a software code with this capability. However, if the modeling objective is to determine effects only during that period of low reservoir levels, a simpler conceptual model describing only the typical low reservoir conditions may suffice. This latter case would allow construction of a much simpler steady-state numerical model. Additional information on proper code selection is presented in Chapter 5.

(4) Performance criteria. Performance criteria are set early in the modeling study and specify standards to measure the appropriateness of data acquisition, modeling approach, model construction, calibration, use, and presentation. Examples of criteria include: the basis for zones of homogeneous aquifer properties, limits on the magnitude of allowable calibration residuals, number and location of calibration targets, and type and degree of sensitivity analysis testing. These serve as a basis for evaluating model performance. Criteria are developed and agreed upon between the modeling team and the customer. In certain cases, a high degree of unknowns prior to the modeling effort requires the specification of criteria as model development progresses.

b. Initial interpretation of geologic/hydrologic environment.

(1) Field reconnaissance. A site investigation should be scheduled for all relevant personnel involved in the project. Field reconnaissance will provide a more complete understanding of site hydrogeology and project objectives. Additionally, it will aid in the determination of the feasibility of proposed methods and use of equipment. Objectives which should be documented by photographs and a trip log include the following:

(a) General character of local geology.

(b) Prominent topographic features.

(c) Location and flow rates of wells and adequacy of local wellhead protection.

(d) Nature, volume, flow, and location of surface waters.

(e) Nature, volume, and location of any potential surface and sub-surface contamination.

(f) Nature and location of any significant impermeable areas.

(g) Nature and location of areas of significant vegetative ground cover.

(2) Literature search, accessing existing data. Existing data should be assessed completely as a first step to any hydrogeologic site investigation. Much of the data necessary for developing a conceptual model may already have been collected during previous investigations of the site. Geologic, hydrologic, geographic, and other data can be obtained from electronic databases and from reports by the Corps, the U.S. Geological Survey, other federal agencies, and state, local, and private organizations. The level of detail desired will also affect the data needs. All data should be critically reviewed to validate their accuracy and applicability to investigation purposes. Data that should be reviewed include the following:

(a) Regional hydrogeologic reports.

(b) Previous investigations of aquifer and/or surface waters.

(c) Available information on groundwater use, including purpose, quantities, and future projections.

(d) Boring log data.

(e) Cone penetrometer log data.

(f) Monitoring well data.

(g) Production well data.

(h) Well construction characteristics.

(i) Geophysical data.

(j) Geologic, hydrologic, and topographic maps and cross sections of study area.

(k) Aerial photographs.

(l) Land use maps.

(m) Soil maps.

(n) Long-term climatic data.

c. Acquisition of additional data. Data requirements should be assessed by the investigator as a function of cost and the level of acceptable uncertainty associated with the particular groundwater investigation. Such recommendations will be consistent with the level of detail required. The investigator should choose the investigative methods which provide the most valuable data within time and cost constraints. The following is a list of some available sources.

(1) Geologic information.

(a) Surficial structures and deposits.

(b) Drilling samples.

(2) Hydrologic data.

(a) Distribution of groundwater levels (horizontally and vertically).

(b) Flow to/from wells.

(c) Slug tests.

(d) Laboratory tests of drilling samples.

(e) Response of groundwater levels to fluctuations in surface water.

(f) Response of groundwater levels to loading events.

(g) Water chemistry (geochemistry and isotope hydrology).

(h) Artificial tracers.

(3) Geophysical data.

(a) Borehole.

(b) Surface methods.

(c) Ground penetrating radar.

(d) Cone penetrometers.

d. Conceptual model development.

(1) Definition. A conceptual model is a simplified description of the groundwater system to be

studied. Development of a conceptual model is the most important step in developing a computer model. Natural area boundaries, hydrostratigraphy, water budget, aquifer properties, potentiometric surfaces and other features are described in a level of detail commensurate with the ability of the data to represent the system. In other words, a highly heterogeneous system requires more (and/or higher quality) data to provide for the same level of detail in representing a more homogeneous system. Features often described in conceptual models include the following:

(a) Relationship and extent of hydrogeologic units (hydrostratigraphy, hydrofacies).

(b) Aquifer material properties (porosity, hydraulic conductivity, storativity, isotropy).

(c) Potentiometric surfaces.

(d) Water budget (inflows and outflows such as: surface infiltration, lateral boundary flux, leakage through confining units, withdrawals and injections).

(e) Boundary locations (depth to bedrock, impermeable layer boundaries, etc.).

(f) Boundary conditions (fluxes, heads, natural water bodies).

(g) System stresses (withdrawal wells, infiltration trenches, etc.).

(h) Dynamic relationships varying through time.

(i) Water chemistry (varies with purpose; drinking, irrigation, pumping, etc.).

(2) Data requirements.

(a) What is the physical extent of the system to be studied (horizontally and vertically)?

(b) What are the distinct measurable components of the system?

(c) What data are currently available?

(d) Does some of the available data add little value toward meeting study objectives?

(e) What aspects of the conceptual model lack adequate definition?

(f) If data are not available for a particular feature, is a computer model expected to be sensitive to that feature?

(3) Integrated interpretation. During conceptual model formulation, technical specialists perform an integrated interpretation of all the data available to produce the most accurate assessment of site conditions (Figure 3-2). The integrated approach to a site characterization assesses data from multiple sources, and combines the data to produce a more accurate interpretation of the site characteristics. The accuracy of the model will depend on the accuracy of the available data, the time frame in which the results were collected, and the expertise of the specialists in combining and interpreting the data.

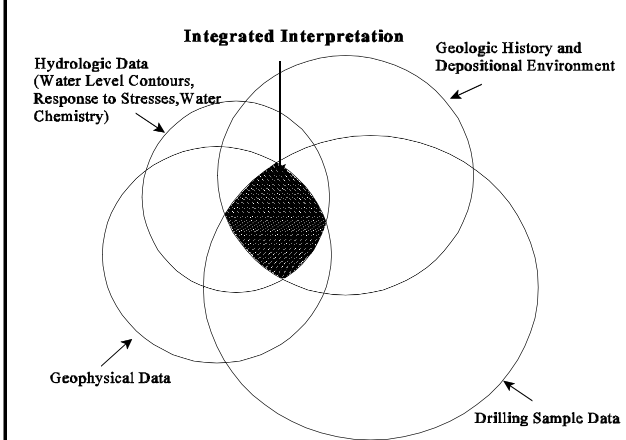

Figure 3-2. Example of an integrated approach to a site characterization study

(4) Presentation of conceptual model. Graphic descriptions of the conceptual model can include simplified hydrogeologic cross sections,

potentiometric surface maps, structure maps of hydrogeologic units, three-dimensional graphics, and schematic water balance diagrams. Graphics should complement a written description.

(a) Topographic maps. Topographic maps aid in delineating drainage areas, locating desired cross sections, and locating boundaries for other maps (including geologic, depth to water, flow gradients, recharge and discharge areas, and other related features). Many different scales are available ranging from 1:126,700 to 1:4,800.

(b) Aerial photographs. Aerial photos are often used as substitutes for topographic maps. Multiple photographs may be used with a stereoscope to obtain a three-dimensional view of the area. The Department of Agriculture and the U.S. Geological Survey are good sources for these photographs.

(c) Geologic maps and sections. These maps are helpful when complex geologic structures and variances occur. When accompanied by analysis reports, they aid in locating aquifers, water level conditions, structural and stratigraphic control of water movement, and other related factors. The U.S. Geological Survey is the primary source of such materials, although mining companies, universities, and other geology-related organizations may also be helpful in locating a map and/or study of a specific area.

(d) Water table contour maps. These maps are similar to topographic maps, the difference being that they show water table elevations as opposed to ground elevations.

(e) Piezometric surface maps. Piezometric surface maps are similar to water table contour maps, except they are based on the piezometric potential developed in piezometers which penetrate a single confined aquifer.

(f) Depth-to-water maps. These maps show the depth from the ground surface to the water table. Care should be taken when using these maps due to their condition-specific accuracy. They are usually developed using a limited number of reference points during a specific condition. Thus, fluctuations may occur through time, and misleading data could arise.

(g) Cross-sectional maps. These maps are developed using borehole data. The vertical stratigraphy of the subsurface is mapped out using multiple boreholes spaced in a horizontally planar manner. Water table, aquifer, and other variances in the subsurface can be identified and mapped out.

(h) Fence diagrams. These maps are similar to cross-sectional maps, except they illustrate the surface and subsurface in three dimensions.

(i) Hydrographs. Hydrographs show water level changes for individual wells over time.

(j) Water budget. A description of the inflows and outflows (water budget) through the model area boundaries is key to the conceptual model. Recharge through the upper surface, leakage through the lower surface, and flux through the sides of the model area should be estimated using methods from hydraulic and seepage theory. These estimates are required to ensure that predicted and calculated flux through model boundaries match to an acceptable degree. Examples of inflows into the study area include: subsurface flow from upgradient of the study area, recharge from precipitation, leakage from surface water, and injection wells. Examples of outflows from the study area include: subsurface flow downgradient of the study area, evapotranspiration, leakage to surface water, and extraction wells.

e. Conceptual model use. The conceptual model, together with the computer modeling objectives, helps guide code selection, grid design, boundary condition and time variation designation, and setting of initial conditions in the numerical model. For example, if the conceptual model describes a simple horizontal flow system in an unconfined aquifer above a relatively flat impermeable layer, construction of a simple two-dimensional mathematical model would likely suffice. If, however, the conceptual model reveals a much more complex system, then a quasi three-dimensional or fully three-dimensional model should be considered. The conceptual model also helps to identify data needs.

f. Uncertainty in conceptual models. Formulation of the conceptual model requires dealing with uncertainty. Most of the conceptual model components can be represented either as single values, ranges of values, or as statistical distributions. Where possible, the values should be carried through the analysis as ranges or distributions. This is particularly the case for hydraulic conductivity estimates, the variation of which has a relatively large impact on modeling results. The computer modeler's approach in dealing with uncertainty depends on the quality and completeness of available data, the level of confidence required by the modeling objectives, and the quality and quantity of resources available to do the modeling job. Eliminating uncertainty altogether is an unlikely and impractical objective for groundwater modeling. Managing uncertainty and communicating its effects are essential to good modeling. During conceptual model development, the following should be considered when managing uncertainty:

(1) Document the quality, quantity, and completeness of the data upon which the model is based.

(2) Document data sources.

(3) Assess additional data needs.

(4) Document the boundary condition assumptions.

(5) If a component is set at a single value, or if a hydrofacie surface is set as unique, document the assumptions and implications of doing so.

(6) If components are to be carried forward to the numerical model as a range or a distribution, document how these were derived and why doing so meets the modeling objectives.

g. Simplified analysis. In cases where data are limited or a detailed analysis is not required, study objectives can often be met without the use of computer models. In these cases, simplified analytical calculations (see Chapters 2 and 6), such as estimating the capture zone of a pumping well or using Darcy's Law to estimate groundwater flow volumes, may adequately address study objectives. In cases when a computer model is required, initial analytical analyses should be performed for comparison with simulated results.

h. Numerical model development. Once a complete conceptual model has been developed, a numerical model can be generated. Parameters determined during conceptual model development are integrated into a computer model. The computer model is then calibrated to reproduce measured field conditions. If model calibration is judged acceptable, the computer model can be used to predict other hydrogeologic changes due to new stresses; for instance, the introduction of a pumping well for groundwater cleanup, within the site. If the numerical model does not produce acceptable results during calibration, then it may be necessary to completely reanalyze the geologic and hydrogeologic parameters. A complete discussion of numerical model development is presented in Chapter 5.

3-3. Project Management

a. General. A successful modeling analysis involves much more than manipulating modeling software. The analysis should develop and present information that answers the questions posed by the project. This requires proper planning and control.

b. Planning and control. Project management involves project planning and project control. Because groundwater models often play a decisive role in water supply and remediation studies, the modeler should be part of the project management team and take part in setting the objectives and schedules in the project management plan.

(1) Project planning. Project planning includes identification of existing data and data needs, definition of work requirements, work time frame, and resources needed. Definition of work requirements, primarily in the form of establishing modeling objectives, is the single most important key to project planning for groundwater modeling studies. Before constructing the conceptual model and before choosing the modeling software, groundwater modelers and their customers need to understand what exactly the objectives of performing a modeling study are. An understanding of

modeling objectives and some experience with modeling is also necessary when estimating expected schedule and resource requirements. There is no “one size fits all” schedule and technical resource requirements in groundwater modeling. Simple models can be performed in a matter of weeks while complex models often require months or even years.

(2) Project control. Project control includes monitoring progress, measuring performance, and making adjustments as necessary. Key intermediate milestones that can be used to monitor progress are:

(a) Establishment of modeling objectives.

(b) Completion of a conceptual model.

(c) Successful calibration of the model application.

(d) Obtaining preliminary results.

(e) Model testing.

(f) Obtaining final results and reporting.

Measuring the quality of model development and making appropriate adjustments to the work scope are not easy tasks. Typically, a modeler requires outside review to aid in assessing the adequacy of model development as it progresses. At a minimum, peer review should be performed at the completion of the conceptual model and then again when interpreting preliminary results even if the modeler feels that things are going well.

c. Maintaining/developing corps technical expertise. Performing groundwater modeling studies “in-house” provides the advantage of development of expertise within the Corps. Such expertise greatly increases the Corps’ capacity to write scopes of work that give specific and complete direction for both in-house and contracted work. Expertise within the Corps also adds flexibility for performing small projects as well as controlling changes in large projects. Where many changes are likely to occur, contracting out without adequate control can lead to excessive costs. When it is necessary to contract out groundwater modeling projects, scope of work specifications should be detailed and closely reviewed by Corps personnel having a high degree of expertise. In Corps offices where expertise in groundwater modeling is limited, personnel could be sent to several groundwater modeling courses which are available. Corps centers of expertise and research and development centers can assist in providing direction and review.

3-4. Personnel

a. Project team. A groundwater modeling project truly requires a multidisciplinary approach. Although the modeler performs a key role, also required are the project manager, geologists and/or hydrogeologists, geotechnical engineers, field data collection personnel, hardware and software specialists, and graphics support personnel. In addition, interfaces with hydrologists and hydraulic engineers, meteorologists, chemists, soil engineers/physicists, Geographical Information Systems specialists, environmental engineers and data management specialists are often required. The basic modeling team should consist of the following positions:

(1) Project manager.

(2) Groundwater modeler.

(3) Geologist, hydrogeologist.

(4) Software/graphics support.

(5) Peer review.

A single individual can perform more than one of the above roles. It is important that the modeler maintain close relationships with geologists and other field personnel who characterize the site. Arranging for offsite peer review increases the soundness of the modeling approach and adds credibility to the final product.

b. Roles.

(1) Project manager. The project manager is responsible for overall planning and control. The setting of objectives, schedules, and allocation of

resources require early planning by the project manager. Oversight of funds and interaction with various larger project elements, customers, and regulatory agencies are main activities. The project manager also monitors progress and actively participates in making corrective actions to the scope and schedule. The project manager is also responsible for the assembly of the modeling team and delegating specific project assignments and responsibilities.

(2) Groundwater modeler. The groundwater modeler is responsible for developing the conceptual model, designing the model grid, determining parameter inputs, model calibration, model execution, and interpretation of results. Because of the highly subjective nature of the modeling process, it is important that the modeler have a strong background in hydrogeology, along with an intimate understanding of site geology.

(3) Geologist/hydrogeologist. The responsibilities of the geologist can include direct gathering of field data, interpretation of site characterization information, and development of the conceptual model with the modeler.

(4) Software and graphics support. These personnel provide assistance in code installation and testing, linking programs, and developing formulation of output. Graphics support is important in model documentation and presentation of model results.

(5) Peer review. A highly qualified expert in the field of groundwater modeling should be retained to provide periodic technical oversight along with critical review of the final model. Review of the conceptual model is essential. To provide a different perspective in the modeling effort, it is helpful that this person be somewhat removed from the daily modeling project effort.

3-5. Example of Site Characterization and Modeling Process

This example outlines simplified steps in performing a groundwater investigation and modeling study. An overview of the technical aspects of groundwater modeling is presented in Chapter 5.

a. Define objectives. A feasibility study was performed for construction of a wastewater treatment plant that will discharge up to 5 million gallons per day to an aquifer recharge lagoon. Groundwater modeling was used to: (1) make predictions of the highest water table elevations expected in a typical 10-year time period resulting from maximum natural and wastewater recharges, and (2) make predictions of the groundwater flow paths for the same conditions. Specific detailed statements defining modeling objectives were agreed upon by the parties involved.

b. Form study team. To perform this task, a study team was assembled consisting of a project manager, a geologist, a groundwater modeler/ hydrogeologist, a hydrologist, and a graphics support technician; several of these tasks can be performed by the same person. A knowledgeable modeler from another District agreed to provide peer review. The team defined the modeling objectives, schedule, and milestones for tracking progress.

c. Develop conceptual model. A conceptual understanding of site hydrogeology was initially compiled from several existing well logs, water table measurements, climate records, a topographic map, and field observations. These sources indicated several data gaps that led to the installation of three additional wells and performance of a pumping test. Using the additional data gathered, a conceptual model was developed that described the hydrogeologic units, hydrogeologic boundaries, water budget, existing water table surface, and aquifer transmissivities.

d. Simplified analysis. Darcy's Law (see Chapter 2) was applied to provide an initial estimate of seepage rates from the recharge lagoon to the groundwater table.

e. Select computer model. Having defined the study objectives and groundwater flow system, modeling software with the capability of computing water table elevations and flow paths was then selected. The software had the capability to perform a two-dimensional, steady-state approach that was determined to be consistent with the modeling objectives.

f. Develop the initial model input files. At this point the features of the conceptual model were transferred to the modeling software input file where, with help from the software, they were represented on a two-dimensional grid. This grid was superimposed on a site map which aided the assignment of transmissivities and recharge locations. The grid structure and zonation of aquifer properties was kept as simple as possible; i.e., the complexity of the model should be commensurate with the ability of the data to represent the system. The boundaries of the grid required special attention to ensure that flows and heads within the model area realistically matched those of the surrounding areas.

g. Model calibration. After a software input file containing the "best estimate" representation of the natural system was created, the modeling software was run repeatedly to resolve any obvious anomalies. This process of iteratively running the modeling software, comparing the output to observed site conditions, then adjusting inputs within specified ranges is called calibration and was continued until the computed heads and boundary flows matched field conditions.

h. Sensitivity analysis. Sensitivity analysis is the measure of uncertainty in the calibrated model caused by uncertainty in aquifer parameters and boundary conditions. Sensitivity analysis was performed by systematically changing the calibrated values of hydraulic parameters by defined factors (such as 0.5 and 2.0), while holding all other model parameters constant. Sensitivity analysis identifies parameters most important in conceptual model development, and can be used as a guide for additional data acquisition.

i. History matching. Model simulations were run and results were compared with field data which were not used in the calibration process. For example, if the model was calibrated to simulate seasonal water level fluctuations for 1994, a comparison between measured and simulated water levels from 1993 can be performed if data are available. A favorable comparison lends greater validity to model predictive capability. An unfavorable comparison indicates that further calibration (and perhaps data acquisition) is necessary.

j. Model application. The calibrated model was then used to simulate the "worst case" condition (highest water table elevations expected) that included maximum wastewater discharge plus natural recharge from the 10-year storm. The highest typical seasonal water table condition and the lowest estimates of transmissivities for the hydrogeologic units were also used.

k. Produce modeling results. The modeling software produced output in the form of water table maps and flow-line graphics. When compared with observed conditions, the simulated output presented expected changes in groundwater flow directions as a result of wastewater plant discharge. The simulations demonstrated that several low-lying areas at the site may be inundated by raised groundwater levels for the conditions tested.

l. Final report. The modeling study report documented the purpose, approach, and results of the analysis. The report fully addressed the following topics:

(1) Definition of model objectives.

(2) Data acquisition.

(3) Summary of geologic and hydrologic conditions.

(4) Development of conceptual model.

(5) Computer code selection.

(6) Definition of model grid and model layer.

(7) Boundary and initial conditions.

(8) Determination of hydrogeologic properties (calibration).

(9) Sensitivity analysis.

(10) Model application.

(11) Interpretation of results.

(12) Recommendations for future monitoring and data gathering.

A complete explanation of the physical basis or other justification for all parameters used in model development was included. Additionally, a discussion of how uncertainty was dealt with was included in the modeling report. (Approaches for dealing with uncertainty are discussed in Chapter 5). Tabular comparisons of computed and observed values used for calibration and for results of the sensitivity analysis were included. Graphical representation, including color graphics, were included for conveying the complexities of spatially distributed information. Time-varying graphics in the form of video presentations were provided.

m. Post audit. Following development of the initial numerical model, the predictive capability of the model was periodically monitored as new field data became available. Model recalibration should be performed if it is judged that the additional data allow for a significantly more accurate conceptualization of site conditions.

3-6. Conclusion

The purpose of this chapter was to present a general overview of performing a groundwater site investigation and modeling study from a project management perspective. The following chapters provide technical information on investigative methods, and numerical modeling of groundwater flow. Additionally, a detailed summary of a specific groundwater site investigation and modeling study is presented as Appendix C.