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Standard Guide for
Application of a <u>Numerical</u> Groundwater Flow Model to a Site-Specific Problem[1]

This standard is issued under the fixed designation D5447; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. ~~Scope~~ Scope*

1.1 This guide covers the application and subsequent documentation of a groundwater flow model to a particular site or problem. In this context, "groundwater flow model" refers to the application of a mathematical model to the solution of a site-specific groundwater flow problem.

1.2 This guide illustrates the major steps to take in developing a groundwater flow model that reproduces or simulates an aquifer system that has been studied in the field. This guide does not identify particular computer codes, software, or algorithms used in the modeling investigation.

1.3 This guide is specifically written for saturated, isothermal, groundwater flow models. The concepts are applicable to a wide range of models designed to simulate subsurface processes, such as variably saturated flow, flow in fractured media, density-dependent flow, solute transport, and multiphase transport phenomena; however, the details of these other processes are not described in this guide.

1.4 This guide is not intended to be all inclusive. Each groundwater model is unique and may require additional procedures in its development and application. All such additional analyses should be documented, however, in the model report.

1.5 This guide is one of a series of standards on groundwater model applications. Other standards ~~have~~include D5981~~been,~~ D5490~~prepared,~~ D5609~~on,~~ D5610~~environmental,~~ D5611~~modeling, such as Practice~~ , and ~~E978~~D6033.

1.6 *This standard does not purport to address all of the safety ~~problems,~~concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to ~~its~~use.*

1.7 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D5490 Guide for Comparing Groundwater Flow Model Simulations to Site-Specific Information
D5609 Guide for Defining Boundary Conditions in Groundwater Flow Modeling
D5610 Guide for Defining Initial Conditions in Groundwater Flow Modeling
D5611 Guide for Conducting a Sensitivity Analysis for a Groundwater Flow Model Application

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[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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*A Summary of Changes section appears at the end of this standard

E978D5981 Practice for Evaluating Mathematical Models for the Environmental Fate of ChemicalsGuide for Calibrating a
Groundwater Flow Model Application (Withdrawn 2002)2017)[3]

D6033 Guide for Describing the Functionality of a Groundwater Modeling Code

3. Terminology

3.1 *Definitions:*

3.1.1 For common definitions of technical terms used in this standard, refer to Terminology D653.

3.2 *Definitions:Definitions of Terms Specific to This Standard:*

3.1.1 *application verification*—using the set of parameter values and boundary conditions from a calibrated model to
approximate acceptably a second set of field data measured under similar hydrologic conditions.

3.1.1.1 *Discussion*—

Application verification is to be distinguished from code verification, that refers to software testing, comparison with analytical
solutions, and comparison with other similar codes to demonstrate that the code represents its mathematical foundation.

3.2.1 *boundary condition—condition, n—in hydrogeologic properties,* a mathematical expression of a state of the physical
system that constrains the equations of the mathematical model to account for the addition or removal of fluid or solutes to or from
the mathematical model.

3.2.2 *calibration (model application)—application), n—in hydrogeologic properties,* 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 simulation and observations of the groundwater flow system.

3.1.4 *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.

3.1.5 *conceptual model*—an interpretation or working description of the characteristics and dynamics of the physical system.

3.2.3 *groundwater flow model—model, n—in hydrogeologic properties,* application of a mathematical model to represent a
site-specific groundwater flow system.

3.1.7 *mathematical model*—mathematical equations expressing the physical system and including simplifying assumptions. The
representation of a physical system by mathematical expressions from which the behavior of the system can be deduced with
known accuracy.

3.2.4 *model—model, n—in hydrogeologic properties,* an assembly of concepts in the form of mathematical equations that
portray understanding of a natural phenomenon.

3.2.5 *sensitivity (model application)—application), n—in hydrogeologic properties,* the degree to which the model result is
affected by changes in a selected model input representing hydrogeologic framework, hydraulic properties, and boundary
conditions.

3.3 For definitions of other terms used in this guide, see The following terms are contained in Terminology D653., but are
included here for the convenience of the user:

3.3.1 *conceptual model, n—in hydrogeologic properties*, an interpretation or working description of the characteristics and
dynamics of the physical system.

4. Summary of Guide

4.1 The application of a groundwater flow model ideally would follow several basic steps to achieve an acceptable
representation of the physical hydrogeologic system and to document the results of the model study to the end-user,
decision-maker, or regulator. These primary steps include the following:

4.1.1 Define study objectives,

4.1.2 Develop a conceptual model,

4.1.3 Select a computer code,

4.1.4 Construct a groundwater flow model,

4.1.5 Calibrate model and perform sensitivity analysis,

4.1.6 Make predictive simulations,

4.1.7 Document modeling study, and

4.1.8 Perform postaudit.

4.2 These steps are designed to ascertain and document an understanding of a system, the transition from conceptual model to
mathematical model, and the degree of uncertainty in the model predictions. The steps presented in this guide should generally be

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[3] The last approved version of this historical standard is referenced on www.astm.org.

followed in the order they appear in the guide; however, there is often significant iteration between steps. All of the steps outlined in this guide are required for a model that simulates measured field conditions. In cases where the model is only used to understand a problem conceptually, ~~not all~~ some steps are ~~necessary.~~unnecessary. For example, if no site-specific data are available, the calibration step would be omitted.

5. Significance and Use

5.1 ~~According to the National Research Council~~ Model applications (**1**),[4] ~~model applications~~ are useful tools to:

5.1.1 Assist in problem evaluation,

5.1.2 Design remedial measures,

5.1.3 Conceptualize and study groundwater flow processes,

5.1.4 Provide additional information for decision making, and

5.1.5 Recognize limitations in data and guide collection of new data.

5.2 Groundwater models are routinely employed in making environmental resource management decisions. The model supporting these decisions ~~must~~should be scientifically defensible and decision-makers ~~must be~~ informed of the degree of uncertainty in the model predictions. This has prompted some state agencies to develop standards for groundwater modeling (**2**). This guide provides a consistent framework within which to develop, apply, and document a groundwater flow model.

5.3 This guide presents steps ideally followed whenever a groundwater flow model is applied. The groundwater flow model will be based upon a mathematical model that may use numerical, analytical, or ~~any~~ other appropriate technique.

5.4 This guide should be used by practicing groundwater modelers and by those wishing to provide consistency in modeling efforts performed under their direction.

5.5 Use of this guide to develop and document a groundwater flow model does not guarantee that the model is valid. This guide simply outlines the necessary steps to follow in the modeling process. For example, development of an equivalent porous media model in karst terrain may not be valid if significant groundwater flow takes place in fractures and solution channels. In this case, the modeler could follow ~~all~~the steps in this guide and not end up with a defensible model.

6. Procedure

6.1 The procedure for applying a groundwater model includes the following steps: define study objectives, develop a conceptual model, select a computer code or algorithm, construct a groundwater flow model, calibrate the model and perform sensitivity analysis, make predictive simulations, document the modeling process, and perform a ~~postaudit.~~post-audit. These steps are generally followed in order, however, there is substantial overlap between steps, and previous steps are often revisited as new concepts are explored or as new data are obtained. The iterative modeling approach may also require the reconceptualization of the problem. An example of these feedback loops is shown in Fig. 1. These basic modeling steps are discussed below.

6.2 Definition of the study objectives is an important step in applying a groundwater flow model. The objectives aid in determining the level of detail and accuracy ~~required~~needed in the model simulation. Complete and detailed objectives would ideally be specified prior to ~~any~~ modeling activities.

6.3 A conceptual model of a groundwater flow and hydrologic system is an interpretation or working description of the characteristics and dynamics of the physical hydrogeologic system. The purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into a set of assumptions and concepts that can be evaluated quantitatively. Development of the conceptual model requires the collection and analysis of hydrogeologic and hydrologic data pertinent to the aquifer system under investigation. Standard guides and practices exist that describe methods for obtaining hydrogeologic and hydrologic data.

6.3.1 The conceptual model identifies and describes important aspects of the physical hydrogeologic system, including: geologic and hydrologic framework, media type (for example, fractured or porous), physical and chemical processes, hydraulic properties, and sources and sinks (water budget). These components of the conceptual model may be described either in a separate document or as a chapter within the model report. Include illustrations, where appropriate, to support the narrative, for example, contour maps, cross sections, or block diagrams, or combination thereof. Each aspect of the conceptual model is described as follows:

6.3.1.1 Geologic framework is the distribution and ~~configuraton~~configuration of aquifer and confining units. Of primary interest are the thickness, continuity, lithology, and geologic structure of those units that are relevant to the purpose of the study. The aquifer system domain, that may be composed of interconnected aquifers and confining units, often extends beyond the domain of interest. In this case, describe the aquifer system in detail within the domain of interest and at least in general elsewhere. Analysis of the geologic framework results in listings, tabulations, or maps, or combination thereof, of the thickness, extent, and properties of each relevant aquifer and confining unit.

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[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

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                    Data
                  Collection
                      |
                      v
                  Conceptual
                    Model
                      |
                      v
                  Sufficient        No
                    Data? -------------->
                      | Yes
                      v
                    Code
                  Selection
                      |
                      v
              Groundwater Flow
              Model Construction
                      |
                      v
                  Calibration
                  & Sensitivity
                      |
                      v
                  Adequate?         No
                      |    -------------->
                      | Yes
                      v
                  Predictive
                  Simulations
```
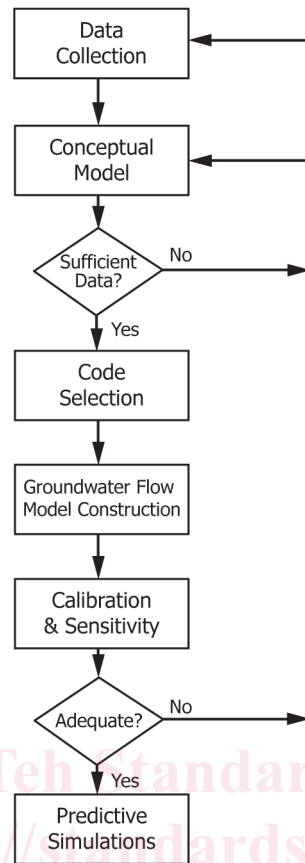
FIG. 1 Flow Chart of the Modeling Process

6.3.1.2 Hydrologic framework in the conceptual model includes the physical extents of the aquifer system, hydrologic features that impact or control the groundwater flow system, analysis of groundwater flow directions, and media type. The conceptual model ~~must~~should address the degree to which the aquifer system behaves as a porous media. If the aquifer system is significantly fractured or solutioned, the conceptual model ~~must~~should address these issues. Hydrologic framework also includes flow system boundaries that may not be physical and can change with time, such as groundwater divides. Fluid potential (head) measurements allow assessment of the rate and direction of groundwater flow. In addition, the mathematical model is typically calibrated against these values (see 6.5). Water level measurements within the groundwater system are tabulated, both spatially and temporally. This analysis of the flow system includes the assessment of vertical and horizontal gradients, delineation of groundwater divides, and mapping of flow lines.

6.3.1.3 Hydraulic properties include the transmissive and storage characteristics of the aquifer system. Specific examples of hydraulic properties include transmissivity, hydraulic conductivity, storativity, and specific yield. Hydraulic properties may be homogeneous or heterogeneous throughout the model domain. Certain properties, such as hydraulic conductivity, may also have directionality, that is, the property may be anisotropic. It is important to document field and laboratory measurements of these properties in the conceptual model to set bounds or acceptable ranges for guiding the model calibration.

6.3.1.4 Sources and sinks of water to the aquifer system impact the pattern of groundwater flow. The most common examples of sources and sinks include pumping or injection wells, infiltration, evapotranspiration, drains, leakage across confining layers and flow to or from surface water bodies. Identify and describe sources and sinks within the aquifer system in the conceptual model. The description includes the rates and the temporal variability of the sources and sinks. A water budget should be developed as part of the conceptual model.

6.3.2 Provide an analysis of data deficiencies and potential sources of error with the conceptual model. The conceptual model usually contains areas of uncertainty due to the lack of field data. Identify these areas and their significance to the conceptual model evaluated with respect to project objectives. In cases where the system may be conceptualized in more than one way, these alternative conceptual models should be described and evaluated.

6.4 Computer code selection is the process of choosing the appropriate software algorithm, or other analysis technique, capable of simulating the characteristics of the physical hydrogeologic system, as identified in the conceptual model. The computer code ~~must~~should also be tested for the intended use and be well documented (~~3-2~~54).