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Standard Guide for
Calibrating a Ground-Water Flow Model Application[1]

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1. Scope

1.1 This guide covers techniques that can be used to calibrate a ground-water flow model. The calibration of a model is the process of matching historical data, and is usually a prerequisite for making predictions with the model.

1.2 Calibration is one of the stages of applying a ground-water modeling code to a site-specific problem (see Guide D 5447). Calibration is 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 ground-water flow system.

1.3 Flow models are usually calibrated using either the manual (trial-and-error) method or an automated (inverse) method. This guide presents some techniques for calibrating a flow model using either method.

1.4 This guide is written for calibrating saturated porous medium (continuum) ground-water flow models. However, these techniques, suitably modified, could be applied to other types of related ground-water models, such as multi-phase models, non-continuum (karst or fracture flow) models, or mass transport models.

1.5 Guide D 5447 presents the steps to be taken in applying a ground-water modeling code to a site-specific problem. Calibration is one of those steps. Other standards have been prepared on environmental modeling, such as Guides D 5490, D 5609, D 5610, D 5611, D 5718, and Practice E 978.

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

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 5447 Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem[2]

D 5490 Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information[2]

D 5609 Guide for Defining Boundary Conditions in Ground-Water Flow Modeling[2]

D 5610 Guide for Defining Initial Conditions in Ground-Water Flow Modeling[2]

D 5611 Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application[2]

D 5718 Guide for Documenting a Ground-Water Flow Model Application[2]

E 978 Practice for Evaluating Mathematical Models for the Environmental Fate of Chemicals[3]

3. Terminology

3.1 *Definitions:*

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, which refers to software testing, comparison with analytical solutions, and comparison with other similar codes to demonstrate that the code represents its mathematical foundations.

3.1.2 *calibrated model*—a model that has achieved a desired degree of correspondence between the model simulations and observations of the physical hydrogeologic system.

3.1.3 *calibration (model application)*—the process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 11.05.

desired degree of correspondence between the model simulations and observations of the ground-water flow system.

3.1.4 *calibration targets*—measured, observed, calculated, or estimated hydraulic heads or ground-water flow rates that a model must reproduce, at least approximately, to be considered calibrated.

3.1.4.1 *Discussion*—The calibration target includes both the value of the head or flow rate and its associated error of measurement, so that undue effort is not expended attempting to get a model application to closely reproduce a value which is known only to within an order of magnitude.

3.1.5 *fidelity*—the degree to which a model application is designed to resemble the physical hydrogeologic system.

3.1.6 *ground-water flow model*—an application of a mathematical model to represent a site-specific ground-water flow system.

3.1.7 *hydraulic properties*—properties of soil and rock that govern the transmission (for example, hydraulic conductivity, transmissivity, and leakance) and storage (for example, specific storage, storativity, and specific yield) of water.

3.1.8 *inverse method*—solving for independent parameter values using knowledge of values of dependent variables.

3.1.9 *residual*—the difference between the computed and observed values of a variable at a specific time and location.

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

3.1.11 *simulation*—in ground-water flow modeling, one complete execution of a ground-water modeling computer program, including input and output.

3.2 For other definitions used in this guide, see Terminology D 653.

4. Summary of Guide

4.1 The steps to be taken to calibrate a flow model are: establishing calibration targets and associated acceptable residuals or residual statistics (as described in Section 6), identifying calibration parameters (as described in Section 7), and history matching (as described in Section 8). History matching is accomplished by using the trial-and-error method to achieve a rough correspondence between the simulation and the physical hydrogeologic system, and then using either the trial-and-error method or an automated method to achieve a closer correspondence.

5. Significance and Use

5.1 Most site-specific ground-water flow models must be calibrated prior to use in predictions. In these cases, calibration is a necessary, but not sufficient, condition which must be obtained to have confidence in the model's predictions.

5.2 Often, during calibration, it becomes apparent that there are no realistic values of the hydraulic properties of the soil or rock which will allow the model to reproduce the calibration targets. In these cases the conceptual model of the site may need to be revisited or the construction of the model may need to be revised. In addition, the source and quality of the data used to establish the calibration targets may need to be reexamined. For example, the modeling process can sometimes identify a previously undetected surveying error, which would results in inaccurate hydraulic head targets.

5.3 This guide is not meant to be an inflexible description of techniques for calibrating a ground-water flow model; other techniques may be applied as appropriate and, after due consideration, some of the techniques herein may be omitted, altered, or enhanced.

6. Establishing Calibration Targets

6.1 A calibration target consists of the best estimate of a value of ground-water head or flow rate. Establishment of calibration targets and acceptable residuals or residual statistics depends on the degree of fidelity proposed for a particular model application. This, in turn, depends strongly upon the objectives of the modeling project. All else being equal, in comparing a low-fidelity to a high-fidelity model application, the low-fidelity application would require fewer calibration targets and allow larger acceptable residuals.

NOTE 1—Some low-fidelity models are not necessarily intended to make specific predictions, but rather provide answers to speculative or hypothetical questions which are posed so as to make their predictions conditional on assumptions. An example might be a model that answers the question: "If the hydraulic conductivity of the soil is 50 feet per day, will the drawdown be more than 10 ft?" This model will not answer the question of whether or not the drawdown will, in reality, be more than 10 ft because the value of hydraulic conductivity was assumed. Since the answer is conditional on the assumption, this "what-if" type of model does not necessarily require calibration, and, therefore, there would be no calibration targets.

6.2 For a medium- to high-fidelity model application, establish calibration targets by first identifying all relevant available data regarding ground-water heads (including measured water levels, bottom elevations of dry wells, and top of casing elevations of flowing wells) and flow rates (including records of pumping well or wellfield discharges, estimates of baseflow to gaining streams or rivers or recharge from losing streams, discharges from flowing wells, springflow measurements, and/or contaminant plume velocities). For each such datum, include the error bars associated with the measurement or estimate.

6.3 Establish calibration targets before beginning any simulations.

6.4 For any particular calibration target, the magnitude of the acceptable residual depends partly upon the magnitude of the error of the measurement or estimate of the calibration target and partly upon the degree of accuracy and precision required of the model's predictions. All else equal, the higher the intended fidelity of the model, the smaller the acceptable absolute values of the residuals.

6.4.1 Head measurements are usually accurate to within a few tenths of a foot. Due to the many approximations employed in modeling and errors associated therewith (see Guide D 5447), it is usually impossible to make a model reproduce all heads measurements within the errors of measurement. Therefore, the modeler must increase the range of acceptable computed heads beyond the range of the error in measurement. Judgment must be employed in setting these new acceptable residuals. In general, however, the acceptable residual should be a small fraction of the difference between the highest and lowest heads across the site.

NOTE 2—Acceptable residuals may differ for different hydraulic head calibration targets within a particular model. This may be due to different errors in measurement, for example, when heads at some wells are based on a survey, but other heads are estimated based on elevations estimated from a topographic map. In other circumstances, there may be physical reasons why heads are more variable in some places than in others. For example, in comparing a well near a specified head boundary with a well near a ground-water divide, the modeled head in the former will depend less strongly upon the input hydraulic properties than the head in the latter. Therefore, acceptable residuals near specified head boundaries can be set lower than those near divides.

NOTE 3—One way to establish acceptable hydraulic head residuals is to use kriging on the hydraulic head distribution. Although kriging is not usually recommended for construction of hydraulic head contours, it does result in unbiased estimates of the variance (and thus standard deviation) of the hydraulic head distribution as a function of location within the modeled domain. The acceptable residual at each node can be set as the standard deviation in the hydraulic head at that location. Some researchers question the validity of this technique **(1)**.[4] An alternative is to perform trend analysis of regions of similar heterogeneity. Since a model will usually only be able to represent trends over length scales larger than the scale of local heterogeneity that is causing variations, the magnitude of the residuals from the trend analysis should approximate the magnitude of residuals in the model in that region.

6.4.2 Errors in the estimates of ground-water flow rates will usually be larger than those in heads **(2)**. For example, baseflow estimates are generally accurate only to within an order of magnitude. In such cases, the upper and lower bounds on the acceptable modeled value of baseflow can be equal to the upper and lower bounds on the estimate.

6.5 *Multiple Hydrologic Conditions*—When more than one set of field measurements have been collected, identify the different hydrologic conditions that are represented by the available data sets. Include only one data set from each hydrologic condition in the set of calibration targets. Use the remaining data sets for verification.

6.5.1 *Uniqueness (Distinct Hydrologic Conditions)*—The number of different distinct hydrologic conditions that a given set of input aquifer hydraulic properties is capable of representing is an important qualitative measure of the performance of a model. It is usually better to calibrate to multiple hydrologic conditions, if the conditions are truly distinct. Matching different hydrologic conditions is one way to address nonuniqueness, because one set of heads can be matched with the proper ratio of ground-water flow rates to hydraulic conductivities; whereas, when the flow rates are changed, representing a different condition, then the range of hydraulic conductivities that produce acceptable residuals becomes much more limited.

6.5.1.1 Other ways to address the uniqueness problem are to include ground-water flows with heads as calibration targets, and to use measured values of hydraulic properties as model inputs.

6.5.2 *Verification (Similar Hydrologic Conditions)*—When data are available for two times of similar hydrologic conditions, only one of those data sets should be used as calibration targets because they are not distinct. However, the other data set can be used for application verification. In the verification process, the modeled data are compared, not to the calibration data set, but to the verification data set. The resulting degree of correspondence can be taken as an indicator or heuristic measure of the uncertainty inherent in the model's predictions.

NOTE 4—When only one data set is available, it is inadvisable to artificially split it into separate "calibration" and "verification" data sets. It is usually more important to calibrate to data spanning as much of the modeled domain as possible.

NOTE 5—Some researchers maintain that the word "verification" implies a higher degree of confidence than the verification process imparts **(3)**. Used here, the verification process only provides a method for heuristically estimating the range of uncertainty associated with model predictions.

NOTE 6—Performing application verification protects against over-calibration. Over-calibration is the fine-tuning of input parameters to a higher degree of precision than is warranted by the knowledge or measurability of the physical hydrogeologic system and results in artificially low residuals. Without performing application verification, the artificially low residuals might otherwise be used to overstate the precision of the model's predictions.

6.6 In transient modeling, it is often easier to match changes in heads (that is, drawdowns) rather than the heads themselves. If project objectives and requirements allow, consider recasting the calibration targets as drawdowns rather than heads.

6.7 In some cases, the circumstances under which data were collected do not correspond exactly to those for which the model may be computing values. For example, the steady-state water level in a pumping well may be affected by turbulent well losses whereas the model will usually be computing the formation head at that location. To make a fair comparison and to avoid skewing calibrated hydraulic parameters to compensate for the discrepancy, either the calibration target or the computed value in the simulation should be adjusted to account for the difference. To maintain the proper perspective regarding the relative importance between measured data and modeling results, it is recommended that the computed value be adjusted prior to making the comparison, and that the calibration targets remain unaltered.

7. Identifying Calibration Parameters

7.1 Calibration parameters are groups of hydraulic properties or boundary conditions whose values are adjusted as a group during the calibration process. Examples of calibration parameters for some hypothetical model applications could be:

7.1.1 The horizontal hydraulic conductivity of a kame terrace deposit;

7.1.2 The ratio of recharge at each node in the springtime to the average annual recharge at a particular node;

7.1.3 The ground-water flux into a site in a particular corner of the model;

7.1.4 The assumed elevation of surface water in a lagoon when waste liquids were disposed of from 1969 through 1975;

7.1.5 The leakance of glacial till in an area near the toe of an earth dam; and

7.1.6 The thickness of streambed silt deposits as used to calculate the leakance of river nodes.

7.2 The calibration parameters are often specified as the values of certain hydraulic properties (as in the examples in

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[4] The boldface numbers given in parentheses refer to a list of references at the end of the text.

7.1.1 and 7.1.5) or boundary conditions (as in the examples in 7.1.3 and 7.1.4) that are approximately homogeneous in space or time. In these cases, the calibration parameters are actual inputs to the flow modeling computer code. Just as often, however, calibration parameters are quantities used in the preprocessing phase of a simulation (as in the examples in 7.1.2 and 7.1.6), where other computer codes are used to create the input files for the flow modeling computer code. In these cases, use of a homogeneous calibration parameter may result in inhomogeneous inputs to the flow modeling computer code. For example, a uniform streambed thickness may result in different leakances at different river nodes due to variation in node areas.

7.3 Establish calibration parameters by identifying zones of similar aquifer hydraulic properties based on lithology, stratigraphy, and aquifer testing. Identify zones of similar recharge based on variations in surface soil type, vegetative cover, slope, and elevation. Identify other groups of inputs that can be parameterized pursuant to and consistent with project objectives.

7.4 The number of calibration parameters equals the number of degrees of freedom in a model. Ideally, this number should not exceed the number of available calibration targets. Prior information in the form of measured hydraulic properties or knowledge of the required mathematical form of the solution can relax this constraint.

7.5 For each calibration parameter, identify the range of possible realistic values that parameter may have in the physical hydrogeologic system. Establish these ranges before beginning any simulations.

8. History Matching

8.1 History matching is the part of calibration that involves varying inputs until the model simulation reproduces measured site-specific information to the desired degree of accuracy. The site-specific information can pertain to data collected during either steady-state or transient conditions. History matching is accomplished either manually, using the trial-and-error method, or automatically, using a computer program with an inverse algorithm.

8.2 Early in the calibration process it is often advisable to conduct a "calibration sensitivity analysis" by varying different inputs systematically to determine which inputs have the greatest effect on computed ground-water heads and flow rates. In early stages of calibration, this analysis allows the modeler to avoid spending time varying inputs which will have little effect on the results. In later stages of calibration, the calibration sensitivity analysis can also be used to fine-tune the input so as to minimize residuals.

NOTE 7—A "calibration sensitivity analysis" differs from a "sensitivity analysis" because the latter includes the effects of varying inputs on model predictions as well as on the calibration and therefore provides a method of distinguishing between significant and insignificant degrees of sensitivity. In contrast, the former is merely a systematic way to find the value of an input that results in the lowest residual at a point.

8.3 When comparing the results of a simulation to site-specific information, use quantitative and qualitative techniques, as described in Guide D 5490. Quantitative techniques include calculating potentiometric head residuals, assessing correlation among head residuals, and calculating flow residuals. Qualitative techniques include assessing the correspondence between the overall patterns of measured and modeled head contours, evaluating the number of distinct hydrologic conditions that a model is capable of reproducing, and assessing whether the model input parameters fall within the ranges of reasonable values previously established.

8.4 In many cases, it is possible to achieve the same degree of correspondence between simulated and measured calibration targets using different input data. This is called nonuniqueness. Since the accuracy of a prediction depends strongly on using (at least approximately) correct hydraulic conductivity values, it is necessary to resolve the nonuniqueness of the calibrated data set **(4)**. This is done by using measured hydraulic conductivities or transmissivities (see 9.3), calibrating to measured ground-water flow rates as well as heads, or calibrating to data collected from multiple distinct hydrologic conditions, or both.

8.4.1 When modeling transient responses to a change in hydrologic conditions, the response in head at any point will depend primarily upon the hydraulic diffusivity of the aquifer (the ratio of the transmissivity to storativity or of hydraulic conductivity to specific storage) rather than to either hydraulic property alone. Unless one or the other property is fixed independently, a nonuniqueness in the calibrated inputs may result.

8.4.2 In a linear ground-water flow model, if all of the recharges and discharges in a model are increased by some factor and all hydraulic conductivities are increased by the same factor, the resulting computed hydraulic heads will usually remain unchanged. Unless one or the other is fixed independently, a nonuniqueness in the calibrated inputs may result.

9. Manual Calibration

9.1 The manual method of calibration is the process of changing a model input, running the modeling program with the new input, and then comparing the results of the simulation with the calibration targets. If the computed values of ground-water head and flow rate compare favorably with the measured values, then the model has been calibrated. If not, the process is repeated. This is also called the trial-and-error method.

9.2 The trial-and-error method of calibration should be used in the initial stages of calibration for all models, regardless of the method used for final calibration, although initial runs of an inverse code can give a modeler insight into fruitful directions for first calibration efforts.

9.3 When estimates of hydraulic parameters are available for the regions of the modeled physical hydrogeologic system, the corresponding values of those parameters in the model should be similar, but do not have to be identical. There are two reasons for this. First, the estimates themselves have associated errors, often of an order of magnitude. Second, when these estimates are based on hydraulic tests, the volume of soil or rock stressed by the test is often smaller than the volume in the model for which the parameter applies. In that case, the input hydraulic conductivity or transmissivity required to calibrate the model is often larger than the measured value due to the scale effect **(5)**.

9.4 Some specific suggestions for achieving a successful trial-and-error calibration follow. These techniques are strictly heuristic, and the modeler should have independent justification for such variations in input data. However, it is true that, as long as the values are reasonable for the soil or rock being modeled and the uniqueness problem is eventually addressed, the ability to match historical ground-water levels and flow rates is some justification for use of specific aquifer hydraulic properties in a model.

9.4.1 In steady state, if a particular flow line at a site begins at a specified flux boundary (for example, the no-flow boundary at an aquifer boundary or regional divide) and ends at a specified head boundary (for example, a gaining stream or river), the head at any point along the flow line depends primarily on the resistances to flow at all points between it and the specified head boundary. (This is identical to the backwater effect used by surface water hydrologists to model streamflow.) Therefore, if recharge values are not changed during the course of calibration, it is usually best to begin matching heads near the specified head boundary and then work towards the specified flux boundary.

9.4.2 When modeling transient ground-water flow, it is often advisable to begin with a steady-state scenario to calibrate the hydraulic conductivity (or transmissivity). Then, use the transient scenario to calibrate the specific storage (or storativity). This technique depends on the availability of a data set that represents approximately steady conditions in the field. (This technique is similar to, but should not be confused with, a prescription in Guide D 5447 to use the output from a calibrated steady-state model run as the initial heads for a transient simulation.)

9.4.3 To raise the hydraulic head at a point in a model, decrease the hydraulic conductivity or transmissivity, increase the recharge, decrease the conductance of the boundary nodes to which ground water at that point discharges, or increase the flow of ground water through that node, or combination thereof.

9.4.4 Speed up the response of water levels at a point to a change in boundary conditions by increasing the transmissivity or hydraulic conductivity between that area and the changed boundary, or decreasing the storativity, or specific storage in that area, or combination thereof.

9.4.5 Near a surface water body, vary the transmissivity or hydraulic conductivity to raise or lower the slope of the water table or piezometric surface and vary the conductance (or leakance) term for the boundary for the reference head to raise or lower all water levels nearby by the same amount. If the conductance term is made too large, however, the boundary will function equivalently to a constant head boundary.

9.4.6 In the vicinity of two adjacent specified head boundaries with different levels (that is, near a dam, bridge, or culvert in surface water), expect a circular component to the ground-water flow paths.

9.4.7 Increasing the leakance of a confining layer causes ground-water levels on opposite sides of a confining layer to be more equal. Decreasing the leakance can cause the levels to differ more.

9.4.8 It is usually best to begin with a simple pattern of the distribution of hydraulic properties (for example, large areas with homogeneous values) and then split some of the zones as necessary. If possible, though, avoid creating too many such zones.

9.4.9 If there are undesirable spatial correlations among residuals, try re-parameterizing the model inputs, redefining zones of equal parameter values, and smoothing transitions between zones.

9.4.10 If a model proves to be difficult to calibrate, there may be too many constant head boundaries, which would tend to overconstrain the solution. Reinvestigate the conceptual model to see whether some constant head boundaries should really be constant flux or mixed-type boundaries.

10. Automated Calibration

10.1 Automated calibration is analogous to manual calibration except that a computer code rather than the modeler adjusts model inputs or input parameters. After each simulation, the computer code compares model output against calibration targets and systematically adjusts input parameters until an objective function, based on residuals, is minimized.

10.2 There are two fundamental automated calibration techniques: direct solution and indirect solution **(6)**.

10.2.1 Direct solution uses a reformulated version of the partial differential equation of flow in which the hydraulic properties are the state variables and the hydraulic heads are the parameters and solves that equation once using numerical techniques. Direct solution requires specification of a calibration target at every node, and is generally considered to be more prone to instability than indirect solution.

10.2.2 Indirect solution iteratively improves the estimate of the inputs or input parameters until the residuals or residual statistics are acceptably small. Changes to inputs or input parameters are based on optimization or operations research techniques, most notably nonlinear least-squares optimization. Most automated calibration computer codes utilize indirect solution.

10.3 Before using automated calibration, it is often advisable to use manual calibration until the residuals or residual statistics are within an order of magnitude of the acceptable residuals or residual statistics. Using automated calibration before the model is semi-calibrated manually often results in unstable or unrealistic solutions.

10.4 For models involving a large number of input parameters, unstable or unrealistic solutions can often be avoided by estimating values for only a few of the calibration parameters at a time. It is best to begin with the parameters to which the residuals are most sensitive. For example, in a model with five hydraulic conductivity zones and three recharge zones, suppose that the residuals are more sensitive to the conductivities than to the recharge values. Then, the three recharge values would be held constant while hydraulic conductivity values are being estimated. Once the hydraulic conductivity values have been estimated, the updated hydraulic conductivity estimates are held constant and the values for the three recharge zones are estimated. After hydraulic conductivity and recharge parameters have been estimated separately, the updated values for all parameters are used as model inputs, and automated calibration is performed to determine optimal values for all parameters together. In some cases, it may be necessary to use the above technique but estimate values for one parameter at a time.

10.5 Sometimes model residuals or results, or both, are insensitive to some inputs or input parameters. These inputs or input parameters cannot be estimated using any calibration technique. Insensitive input parameters are those parameters for which a large range of values produces little change in residuals. An example would be the value of hydraulic conductivity in a small zone within a large model domain. Changing the input value for this zone may have little effect on residuals at locations that are not within or near the zone and no effect away from the zone. To assess whether the insensitivity is important in the context of the modeling objective, perform a sensitivity analysis using Guide D 5611. If the sensitivity is unimportant, remove that parameter from the list of parameters that the code is assigned to estimate.

10.6 If the automated calibration computer code allows, assign different weights to individual residuals to improve parameter estimates. For example, calibration targets associated with more precise measurements or more important locales can be given higher weights in the objective function, thereby increasing the significance of those residuals with respect to the remaining residuals. Use of weights is essential when utilizing both head and flow calibration targets in the same objective function because they have different units.

10.7 If automated calibration yields unreasonable parameter estimates, try re-parameterizing the model inputs or revisiting the conceptual model that the computer model is based upon. Some codes allow the user to assign ranges of reasonable values of each parameter, such as established in Section 7. Often, the resulting estimate for a parameter will be at one or the other limit of its allowable range. In that case, consider removing that parameter from the list of parameters that the code is assigned to estimate.

11. Report

11.1 Prepare a report (or a section of a larger report) discussing the methods used to calibrate the model. Use techniques presented in Guide D 5718.

11.2 Identify each of the calibration targets and its corresponding acceptable residual. Discuss the methods used to set the acceptable residuals.

11.3 Identify the rationale behind the choices of which model inputs were varied and which were not varied during the course of calibration.

11.4 Present quantitative and qualitative comparisons between modeled and measured information using methods presented in Guide D 5490.

12. Keywords

12.1 calibration; ground water; inverse methods; modeling; residual; trial-and-error; uniqueness; verification

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