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**SENSITIVITY AND ERROR ANALYSES
IN GROUND WATER FLOW MODELLING**

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**UNCOVERING THE HIDDEN RESOURCE:
GROUNDWATER LAW, HYDROLOGY AND POLICY LAW
IN THE 1990s**

**Rocky Mountain Ground-Water Conference
Colorado Ground-Water Association
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SENSITIVITY AND ERROR ANALYSES IN GROUND WATER FLOW MODELLING

**by Dr. Devraj Sharma
Principia Mathematica Inc.**

Central Premises

- A. *The essential paradox in ground water flow modelling is that the necessary data can never be completely available.*
- B. *It is therefore virtually impossible to prove, beyond reasonable doubt, that the solution to the problem as posed for modelling is unique.*
- C. *The next best thing possible is to demonstrate the existence of an envelope of equally-probable results, such as explanations for observed events.*
- D. *The crucial task for the modeler is to try and reduce, through realistic means, this envelope to the smallest possible size.*
- E. *In spite of constraints, this task can be achieved only through the relentless pursuit of truth, i.e. systematic analysis of model strengths and weaknesses.*
- F. *In undertaking the task, it must be expected that the tools employed for diagnosis, in data preparations, model analyses, predictions, interpretations and even in presentation of results will require progressive refinement.*
- G. *Progressive refinements cause models to become more complex and to incorporate more detail. This requires the number of grid cells, and time steps, used to increase dramatically. Consequently, data processing tasks become necessarily computational. The number of tasks related to modelling in which errors can occur, thus increases greatly.*

A Rational Approach to Error Analysis

I. Errors in Ground Water Flow Modelling.

- A. *The context.*
- B. *Types of errors.*
- C. *Evaluating consequences of errors.*
- D. *Rectifying errors.*

II. Types of Common Errors (with specific examples wherever appropriate).

- A. *Random Modelling Errors:*

- (1) basic data used for modelling;
 - (a) assembling available data
 - (b) analyzing data to be used in modelling
 - (c) performing data interpretations
 - (d) compartmentalizing data for modelling uses
- (2) processing information used to generate model input data;
 - (a) decisions on data processing
 - (b) techniques used for processing
- (3) coding of model, its pre-processors and post-processors;
 - (a) use of proprietary versus public-domain models
 - (b) pre-processing methods
 - (c) post-processing methods
- (4) coding of application-specific changes to models;
 - (a) decisions to make changes
 - (b) implementing changes and testing them
- (5) numerical results from model runs;
 - (a) machine-dependent truncation errors
 - (b) round-off errors
 - (c) convergence of solutions
- (6) computing-system hardware and software features;
 - (a) single and double precision arithmetic operations
 - (b) operating system and compiler idiosyncracies
- (7) processing results predicted by models; and,
 - (a) extracting information from regular output
 - (b) extracting additional output
 - (c) performing operations on model predicted results
- (8) presenting modelling information as exhibits.
 - (a) datum of variables in computer-generated plots
 - (b) scale of spatial and temporal plots
 - (c) precision to which variables are plotted
 - (d) internal consistency of plotted variables

B. *Systematic Model-Development Errors:*

- (1) representation of ground water flow mechanisms;
 - (a) mechanisms included

- (b) mechanisms excluded
 - (c) algebraic methods used
 - (d) available data used to justify methods
- (2) model framework selected;
- (a) aquifer-type representation
 - o unconfined/confined
 - o other
 - (b) model domain, shape, size and orientation
 - o predominant flow direction/s
 - o coordinate system used
 - (c) numerical grid cell sizes, shapes and number
 - o numerical accuracy versus economy
 - o ability to represent mechanisms
 - (d) model layers, thickness and number
 - o vertical flow information
 - o layer separation information
- (3) mode selected for model operations;
- (a) linear/non-linear system
 - (b) head mode versus change mode
- (4) boundary-condition representations;
- (a) recharge and discharge estimates
 - (b) constant-head boundaries
 - (c) general-head boundaries
- (5) initial-condition representations;
- (a) consistency of water-balance
 - (b) history leading up to initial condition
- (6) representation of aquifer features;
- (a) material-type variations
 - (b) fault-zones and their quantitative influences
 - (c) distribution of ground-surface elevations
- (7) representation of aquifer-stream interactions;
- (a) locations of streams
 - (b) identifications of intermittency or regularity of stream flows
 - (c) stream conductance values

- (d) vertical connection distance
 - (e) stream-bed elevation and changes with time
 - (f) stream connections with local aquifer conditions
 - (g) stream gain/loss balances
- (8) representation of vegetative consumptive use;
- (a) locations of vegetation, by type
 - (b) changes to vegetation with time
 - (c) density of vegetative growth, by type and location
 - (d) maximum consumptive-use rates, by type
 - (e) depth functions of consumptive use, by type
 - (f) seasonal functions of consumptive use, by type
 - (g) calculating depths-to-water
- (9) representation of irrigation practices;
- (a) location of applied irrigation water to vegetation
 - (b) changes to irrigated acreage, by type
 - (c) type/s of irrigation employed
 - (d) soil-moisture accounting procedures
 - (e) making estimates of deep-percolation rates
 - (f) use of surface and sub-surface drains
 - (g) representing sub-irrigation features
- (10) representations of well pumping; and,
- (a) number and locations of irrigation wells
 - (b) time of introduction of wells during modelling period
 - (c) wells accumulated into model grid cells
 - (d) decreed acreage associated with wells
 - (e) well-pumping estimates, seasonal and annual totals
 - (f) well-pumping capacities

C. *Model Calibration Errors:*

- (1) the calibration process;
- (a) steady-state and transient steps
 - (b) what parameter value/s to vary
 - (c) decisions on what adjustments not to make
 - (d) the concept of progressive refinements
- (2) selecting the calibration time span;
- (a) available input data
 - (b) available data for comparing with model calculations
 - (c) available estimates of major "stresses"

- (3) the parameter-estimation procedure;
 - (a) the essential technique
 - (b) automatic versus manual schemes
 - (c) checking calibrated values against measured values
- (4) evaluating calibration satisfactoriness; and,
 - (a) hydrograph comparisons
 - (b) water-level and potentiometric-head maps
 - (c) integrated flows such as return flows between stream gauges
- (5) demonstrating that the model is calibrated.
 - (a) depicting comparisons between predictions and measurements
 - (b) identifying poor comparisons and the inferred reasons for it

D. *Interpretative Errors:*

- (1) mode of model operations;
 - (a) consequences of change-mode operations
 - (b) consequences of linear-aquifer assumptions
- (2) model verifications;
- (3) comparisons of model results with well hydrographs;
 - (a) grid-cell water levels
 - (b) observation-well location water levels
 - (c) changes to depth-to-water as a result of topographic relief
 - (d) measurement uncertainties
- (4) comparisons of integrated model results with measurements;
 - (a) filtering ground water contributions to stream gains
 - (b) ground water capture by drains
- (5) predictions of long-term events; and,
 - (a) postulation of long-term boundary conditions
 - (b) postulation of long-term aquifer recharge estimates
 - (c) consistent model parameter values that are held constant
- (6) evaluating alternative plans for water development.

III. Consequences of Errors.

- A. *Identifying Errors:*
- B. *Quantifying Consequences of Errors to Model Predictions:*

C. *Making Adjustments to Rectify Errors.*

A Rational Approach to Model Sensitivity Analysis

I. The Central Purpose:

- A. *Establish the sensitivity of predicted results, which will be relied upon, to systematic variations in input parameter values*
- B. *Distinguish dominant variables from those possessing less significance*
- C. *Establish ranges of uncertainty*

II. Modelling Stage at Which Sensitivity Analyses are Conducted:

- A. *Model selection and adaptation stage*
- B. *Upon completion of model calibration and verification*

III. Forensic Uses:

- A. *Explain observed phenomena or model calculated values*
- B. *Simulate "what-if" water-use scenarios*

IV. Systematic Sensitivity Analyses:

- A. *Model domain.*
- B. *Numerical grid-cell sizes.*
- C. *Aquifer property values.*
- D. *Relative magnitude of mechanisms and their interactions.*
- E. *Influence of assigned model-parameter values.*
- F. *Uniqueness of model calibrations.*

V. Uncertainty in Available Information:

- A. *Aquifer characteristics.*
- B. *Observation-well measurements.*
- C. *Stream-aquifer connections:*
 - (1) *gauged stream flows;*
 - (2) *un-gauged tributary inflows;*
 - (3) *effects of diversions on local stream flows; and,*
 - (4) *stream discharge-stage relationship.*
- D. *Geologic features and their quantitative influences:*
 - (1) *fault-zone property values.*

- E. *Historical well-pumping information:*
 - (1) number and locations of wells;
 - (2) ditch identification of wells;
 - (3) year and month of first introduction;
 - (4) power-consumption records of wells;
 - (5) conversions of power consumed to pumped water;
 - (6) ranges of uncertainty in pumping rates; and,
 - (7) effects of well pumping rates on grid-cell "dry-out".

- F. *Historical vegetative consumptive-use rates:*
 - (1) areas occupied by vegetation and changes with time;
 - (2) changes to density of vegetative growth; and,
 - (3) changes of depth-to-water with time.

- G. *Effects of irrigation efficiency changes on soil moisture balances.*

VI. Envelope of Equally-Probable Explanations for Events:

- A. *The nature and size of the envelope.*
- B. *Efforts that can be made to reduce its size.*
- C. *The irreducible uncertainty in predicted results.*
- D. *Expected precision in predicted results.*

VII. Quantify Influences of Unintentional Errors, Detected in Time.

Summary Comments

There are no short cuts to reducing the potential for errors that can occur in ground water flow modelling. Identifying errors that do occur in a timely manner requires close attention to detail, laborious effort and a variety of diagnostic computational tools which are suited for the purpose. Relevant comments on the successes and failures of modelling methods will be made during the presentation, and some examples will be provided.

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