For Internal Circulation

GROUNDWATER MODELING FRAMEWORK

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Department of Water Resources, RD & GR
Central Ground Water Board

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1.0 INTRODUCTION

Groundwater is a major source of fresh water that is widely used for domestic, industrial and agricultural purposes in most parts of the world. Increasing demand and quest for groundwater due to ever increasing population has thrown light on the unscientific techniques to quench these precious resources. This demand has initiated proper and effective management of available groundwater resources. Groundwater modelling is a powerful management tool which can serve multiple purposes such as providing a framework for organizing hydrologic data, quantifying the properties and behavior of the systems and allowing quantitative prediction of the responses of those systems to externally applied stresses. No other numerical groundwater management tool is as effective as a 3-dimensional groundwater model. A number of groundwater modelling studies have been carried out around the world for effective groundwater management.

A groundwater flow model is intended to calculate the bulk, or average, rate and direction of movement of groundwater through aquifers and confining units in the subsurface. These calculations are referred to as simulations. Numerical groundwater models are based on numerical approximation of both space and time. Basically there are two types of models, they are 1) prediction models, which simulate the behavior of the groundwater system and its response to stress and 2) Resource management models, which integrate hydrologic prediction with explicit management decision procedure. Prediction models are the most used groundwater models till date. These prediction models are divided into two major categories they are flow and contaminant transport models.

1.1 Defining Objective/need of modelling for an area based on issues

Model objectives should be defined which explain the purpose of using a groundwater model (i.e. identify flow direction, flow velocity (Darcy Velocity), impact of pumping well and identification of possible down gradient receptors, estimate contaminant time of travel to identified receptor, delineate capture zone of proposed well, estimation of three-dimensional plume development incorporating dispersion and degradation processes over a future time period). The modeling objectives will profoundly impact the modeling effort required.

Some of the applications of groundwater flow modeling are listed below:

Groundwater flow models can provide important guidelines in solving the explicit problems as given below

1) **Well pumping**: predicting the effects of groundwater withdrawal over piezometric head and stream flow discharge; assessment of safe yield; prediction and movement of saline water interface; prediction of effects of scattered groundwater withdrawals for irrigation.

2) **Groundwater balance estimation**: Assessment of regional groundwater flow both inward and outward patterns of groundwater, surface water within and from neighboring reservoirs/boundaries.
3) **Changes in aquifer recharge** – predicting the impact of urbanization, predicting the changes in resulting from irrigation return of low and canal leakage; analysis of long term climatologically related trends in piezometric levels and separation of man induced changes.
4) **Parameter estimation** – determination of regional distribution of the hydraulic parameters (inverse modeling).
5) **Planning of field investigations**- rationalization of data collection requirements by identifying the measurements most needed.
6) **Prediction of seepage velocities for subsequent use in transport modeling. and Groundwater management** – estimation of optimal yield of aquifer system for the development of groundwater resources using the concepts of conjunctive and consumptive usage.

1.2 What is the purpose of groundwater modeling?

- Is the model to be constructed for prediction, system interpretation, or a generic modeling exercise?
    - Improving hydrogeological understanding (synthesis of data);
- What do you want to learn from the model?
    - Aquifer simulation (evaluation of aquifer behaviour);
    - Designing practical solutions to meet specified goals (engineering design);
    - Optimizing designs for economic efficiency and account for environmental effects (optimization);
    - Evaluating recharge, discharge and aquifer storage processes (water resources assessment);
    - Predicting impacts of alternative hydrological or development scenarios (to assist decision-making);
    - Quantifying the sustainable yield (economically and environmentally sound allocation policies);
    - Resource management (assessment of alternative policies);
    - Sensitivity and uncertainty analysis (to guide data collection and risk-based decision-making);
    - Visualization (to communicate aquifer behaviour).
- What questions do you want the model to answer?
    - Is a modeling exercise the best way to solve the problem(s)?
    - Can an analytical model provide the answer, or must a numerical model be constructed?

1.3 Modelling objectives that will suit to NAQUIM

Numerical three-dimensional groundwater flow model may be developed with the following objectives:

- to simulate regional groundwater flow to identify the distribution of heads,
- Impact on the aquifer system due to various hydrological stresses.
- Impact on the aquifer system due to climate change
- To develop few scenarios for proper understanding & managing the aquifer system.
- For develop efficient and sustainable management plan of the aquifer system.

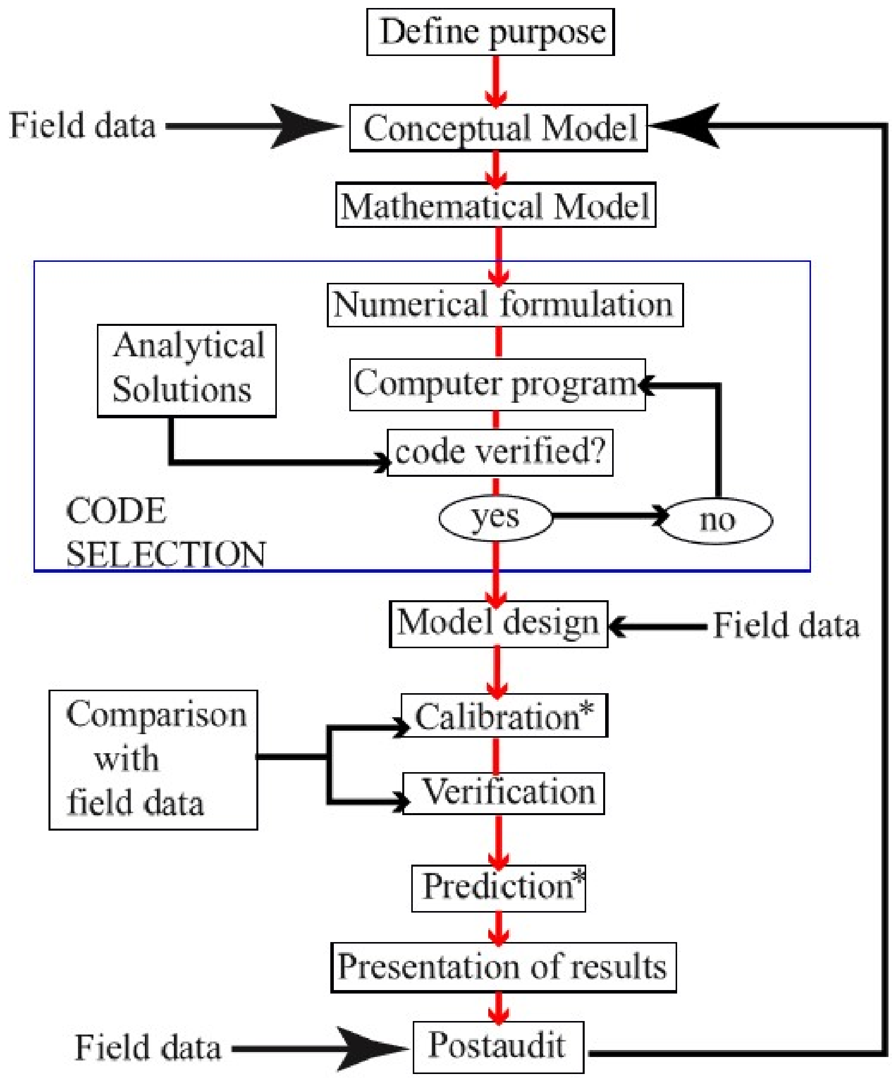
2.0 FLOWCHART AND MODELLING PROTOCOL

The modelling protocol used in this study for the construction of a numerical model involves the following steps&Figure 1 shows a flow chart for modeling.

- The purpose of the modeling will have determined the equations to be solved and what codes will be used.
- A conceptual model identifies hydro-stratigraphic (hydrogeological) units, system boundaries, and boundary conditions. Field data (or hypothetical data in a generic model) are needed to assign heads, to assign values to aquifer parameters, and to identify hydrologic stresses (= pumping, usually).
- This ultimately translates to a mathematical model, then to a computer code. If you write the code, then you have to verify it. If you are using somebody else's code, then you must convince yourself that she/he has verified it.
- Model design puts the conceptual model into a form suitable for modeling. This step could involve design of a grid, selecting time steps, setting initial and boundary conditions, and preliminary selection of aquifer parameters and hydrologic stresses.
- The purpose of calibration is to establish that the model can reproduce field measured heads and flows. During calibration, a set of values for aquifer parameters is found that approximates field measured heads and flows. This can be done by trial and error or by inverse methods or using PEST or parameter estimation.
- Sensitivity analysis involves a perturbation of model parameters to see how much the answers (head, flow) change. This is compared to the uncertainty in the parameters. Clearly, if the model output changes a lot within the uncertainty range of the parameters, you are in way much trouble.
- Model verification is accomplished by holding back some of the data, and seeing if you can predict it after the model is calibrated.
- Prediction (along with a sensitivity analysis) attempts to forecast, with the model, how the hydrogeological system behaves in the future.

- Post-audit: Come back a few years later and see how you did. Adjust model if necessary.

These steps are given in a form of a flowchart (flowchart 1).



Flowchart 1 Groundwater modelling methodology (after Bear 1992)

3.0 DATA REQUIREMENT

The model simulation of groundwater flow requires a thorough understanding of the hydrogeological characteristics of the site. The hydrogeological investigation should include a complete characterization of the following:

- Subsurface extent and thickness of aquifers and confining units translating into number of layers (hydrogeological framework).

- Hydrologic Boundaries (also referred to as boundary conditions) which control the rate and direction of movement of groundwater.
- Hydraulic Properties of the aquifers and confining units translated into layer properties.
- A description of the horizontal and vertical distribution of hydraulic head throughout the modeled area for both beginning conditions (initial conditions) and later conditions that may vary with time (transient conditions).
- Distribution and magnitude of groundwater recharge, pumping or injection of groundwater, leakage to or from surface water bodies, etc. (sources or sinks, also referred to as stresses). These stresses may be constant (unvarying with time) or may change with time (transient).

The model was developed by incorporating geologic data, measured and inferred hydrologic data. Two sets of data are required for the development of a groundwater model as given in Table 1. The two sets of data are the physical framework and hydrological stresses.

Table 1 Data required in developing a numerical model

Physical framework	Hydrological stresses
1. Topography 2. Geology 3. Type of aquifers 4. Aquifer thickness and lateral extent Aquifer boundaries 5. Lithological variations within the aquifer 6. Aquifer characteristics	1. Watertable elevation & Piezometric heads. 2. Type and extent of recharge areas 3. Recharge rates 4. Type and extent of discharge areas 5. Rate of discharge
Groundwater Balance	

4.0 DATA AVAILABILITY & SOURCE OF DATA AVAILABILITY

The above data must be available for developing the groundwater flow model and these can be derived/generated from the following sources:

- Toposheets, satellite data & base maps - (SOI, IRS-NRSC)
- Regional geologic data depicting subsurface geology. (CGWB, GSI, State GW Dept)
- Topographic data - (toposheets, DGPS & RL surveys, SRTM, ASTER, CartoDEM datasets)

- Thematic maps (soil, landuse, geomorphology, drainage, geology etc)
- Presence of surface-water bodies and measured stream-discharge (base flow) data
- River, stream flow data – (CWC or state Dept) River/stream gauge station
- Water bodies/tanks.-Satellite data/toposheet and state dept.
- Borehole litholgs – CGWB (EW/OW/Pz) state GW dept (EW &Pz), local information
- Geologic cross-sections drawn from lithologs and well logs, river section/road cuts.
- Well construction diagrams. (CGWB & State Dept)
- Groundwater head data. (CGWB & State GW Dept)
- Rainfall data (IMD & State Dept)
- Estimates of hydraulic conductivity/ Sy & S derived from APT/ PYT/ slug test data.
- Location and estimated flow rate of groundwater sources and sinks.
- Groundwater draft – Well inventory survey, Electricity Board data, cropping pattern Method.
- Recharge – Rainfall recharge, river/stream recharge, WCS, Irrigation Return flow,tanks/ponds/lakes.

5.0 MODEL CONCEPTUALIZATION (CONCEPTUAL MODEL)

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

Few questions must be answered before developing a conceptual model, but are not limited to:

- Are there adequate hydrogeological data to describe the conditions at the site
- Water table elevations to know the directions in groundwater (3 or 2 directions)?
- Is the aquifer system composed of more than one aquifer, and is vertical flow between aquifers important?
- Does it appear that the aquifer hydrogeological characteristics remain relatively uniform, or do geologic data show considerable variation over the site?
- Can the groundwater flow or contaminant transport be characterized as one-, two- or three-dimensional?
- Is there recharge to the aquifer by precipitation or leakage from a river, drain, lake, or infiltration pond?

- Is groundwater leaving the aquifer by seepage to a river or lake, flow to a drain, or extraction by a well?
- Have the boundary conditions been defined around the perimeter of the model domain, and do they have a hydrogeological or geochemical basis?
- Do groundwater flow or contaminant source conditions remain constant, or do they change with time?
- Are there receptors located generally down-gradient of the contaminant plume?
- Are geochemical reactions taking place in onsite groundwater, and are the processes understood?
- Other questions related to site-specific conditions may also be asked.

6.0 LUMPED MODEL

The modelling exercise begins with a lumped parameter or a black box model which is fundamental for hydrological modeling, where in particular recharge and discharge characteristic or rainfall and runoff characteristics are analyzed. Later parameters and processes are defined. Lumped parameter modelling is an alternative approach that neglects some of the complexities incorporated in physically-based models, but maintains some fundamental physical principles from our conceptual understanding of groundwater systems. These types of models can be assessed against and constrained by physically measured field data, but are simple enough to be run quickly, at little cost and without the need for broad modelling expertise. They also require fewer parameters than physical models, making them easier to constrain through automated calibration procedures. The main advantages of the lumped parameter models are their simplicity and the fact that they do not require the use of large computers.

The water balance of groundwater system can be expressed as

ΔS = Inflow-Outflow

The basic equation for groundwater balance can be expressed as follows

$$\Delta S = (Rr + Rc + Ri + Rirr + Rf) - (Dgw + Det + Df + De \pm \epsilon)$$

where,

ΔS = Change in storage

Rr = Rainfall recharge

Rc = Recharge from canal seepage

Ri = Recharge from influent seepage

Rirr = Return flow from irrigation

Rf = Recharge from flow across boundary

Dgw = Groundwater draft

Det = Loss due to evapotranspiration

Df = Discharge due to flow across boundary

De = Discharge due to effluent seepage

ϵ = Error

7.0 MODEL DESIGN (INPUT PARAMETERS)

Model Design includes all parameters that are used to develop a calibrated model. The input parameters include the following:

- Model grid size and spacing
- Layer elevations
- Boundary conditions
- Aquifer parameters Hydraulic Conductivity/Transmissivity/ Specific yield / Storativity
- Recharge (rainfall recharge/river/lakes/tanks/streams/Irrigation return flow etc.)
- Any additional model input
- Transient or steady state modeling
  - Time/stress period

7.1 Model Calibration

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. The calibration process typically involves a steady-state and transient simulation. With steady-state simulations, there are no observed changes in hydraulic head or contaminant concentration with time for the field conditions being modeled. Transient simulations involve the change in hydraulic head with time (e.g. aquifer Performance test or Slug test or PYT). Models may be calibrated without simulating steady-state flow conditions, but not without some difficulty.

Data describing field conditions may consist of measured hydraulic heads, groundwater or stream flow rates. Model calibration requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model calibrated to a set of conditions that are not representative of actual field conditions.

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

- Hydraulic head data
- Groundwater-flow direction
- Hydraulic-head gradients

- Water balance

Each modeler and model reviewer will need to use their professional judgment in evaluating the calibration results. The normalized Root Mean Square error must be restricted to less than 10 %. However, there are no universally-accepted "goodness-of-fit" criteria that apply in all cases. It is important that the modeler make every attempt to minimize the difference between model- simulated and field conditions.

For initial assessments, it is possible to obtain useful results from models that are not calibrated. Calibrated models only can be used for generating prediction scenarios. The application of non calibrated models can be very useful as a screening tool or in guiding data collection activities.

7.2 Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in value of model parameter) and observing the relative change in model response. Typically, the observed change in hydraulic head, flow rate or contaminant transport are noted. The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data. The sensitivity of one model parameter versus other parameters is also demonstrated. Sensitivity analyses are also beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive would require future characterization, as opposed to data for which the model is relatively insensitive. These data would not require further field characterization.

7.3 Predictive Simulations

A model may be used to predict some future groundwater flow or contaminant transport condition. The model may also be used to evaluate different future scenarios, such as change in hydrologic stresses, climatic changes, changes in landuse pattern and impact of artificial recharge structure. In order to perform these tasks, the model, whether it is a groundwater flow or solute transport model, must be reasonably accurate, i.e., calibration process. However, errors and uncertainties in a groundwater flow analysis and solute transport analysis make any model prediction no better than an approximation. For this reason, all model predictions should be expressed as a range of possible outcomes that reflect the uncertainty in model parameter values.

7.4 Deliverables /Outcome of the modeling study

- Regional groundwater head
- Aquifer management plans
- Predicting the behavior of the aquifer system
  - to changes in landuse pattern
  - to changes in climatic conditions (drought period)
  - to changes in increase in groundwater pumping
- to quantify the impact of construction of artificial recharge structure.

- to quantify the recharge and groundwater abstraction in basin/watershed.
- To determine the outflow components (outflow from system across the boundary)
    - Subsurface seepage across coastal boundaries.
    - Groundwater/surface water interactions.
- Determine the water budget of aquifer system.
- Quantify the impact of river flow on groundwater system.

7.5 Formulation of aquifer management plan

- Demarcate water stress areas from the point of availability & water quality
- In vulnerable areas in reference to availability, formulate plan for water conservation, augmentation measures.
- Study the impact of proposed water conservation, augmentation measures on water budgeting.
- Study the economics of these plans and if found viable, focus on the optimum plan and develop implementation strategies.
- Arrange for workshop involving representatives of all the stake holders and deliberate on the aquifer management plan.
- Based on the outcome of deliberations, consolidate the aquifer management plan.
- Translate the Aquifer Management plan into action plan by involving the representatives of all the stake holders including farmers, clearly indicating the role of all stake holders.

7.6 Data Dissemination to users

Information of aquifer system will be passed on to district administrators, water managers, planners, water user agency, farmers, stake holders, public and villager through:

- Translation of formulated Aquifer Management Plan into Implementation plan in layman terms
- Making the plan available on the website for public access.
- Involve NGOs, PRI, Water Users Association etc in the translation for effective implementation.

7.7 Report layout

Groundwater modeling documentation must detail the process by which the model was selected, developed, calibrated, verified and utilized. The organization of the report should include the following sections:

- Title Page
- Table of Contents
- List of Figures
- List of Tables
- Introduction
- Objectives
- Hydrogeological Characterization
- Model Conceptualization
- Modeling Software Selection
- Model Design (Input, Grid spacing, Boundary conditions, sources/sinks)
- Model Calibration (Steady & Transient state)
- History matching
- Sensitivity Analysis
- Predictive Simulations
- Aquifer Management plan
- Recommendations and Conclusions
- References

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

- Regional location map with topography.
- Site map showing soil boring and well locations, and site topography.
- Geologic cross sections.
- Map showing the measured hydraulic-head distribution (initial head).
- Maps of top and/or bottom elevations of aquifers and confining units.
- Areal distribution of hydraulic conductivity/transmissivity.
- Map of areal recharge (if appropriate).
- Model grid with location of different boundary conditions used in the model.
- Simulated hydraulic-head maps.
- Management plan showing different future scenarios

- Water budget
- Map/graph showing quantum of flow across boundaries.

The following is a **list of tables** that should appear within the body of the model documentation report or in attached appendices:

- Borehole litholog data including:
    - Name of all wells or borings,
    - Top of casing elevation,
    - Well coordinate data,
    - Well screen interval,
    - Hydraulic head data,
- Elevation of bottom of model,
- Hydraulic conductivity or transmissivity, and Specific yield &Storativity.
- Groundwater quality chemical analyses (if appropriate).
- Aquifer performance test, PYT or slug test data.
- Model calibration and verification result showing a comparison of measured and simulated calibration targets and residuals.
- Results of sensitivity analysis showing the range of adjustment of model parameters and resulting change in hydraulic heads or groundwater flow rates.

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