Introduction to Groundwater Flow Modelling

by Samantha Loke Yin Ying

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Groundwater plays a significant role in many water resource systems (Bear & Verruijt, 1987) and it is especially important where surface water is scarce. Groundwater models are simplified representations of groundwater systems and are developed for various purposes such as for prediction of groundwater conditions, natural resources management and estimation of aquifer properties (American Society of Civil Engineers, 1996).

Groundwater models can be classified into various user-defined categories, as illustrated in Figure 1. As shown in Figure 2, three types of models are generally used to study groundwater flow, namely sand tank models, analogue models and mathematical models (Wang & Anderson, 1982). With the advent of computational technology, electric analogue models (Figure 3) have faded-out and are replaced by mathematical models, particularly numerical models (Anderson, 1995). Sank tank models (Figure 4) are now used as a teaching aid to demonstrate basic groundwater concepts instead of solving field problems.

The objective of this review is to compare physically based mathematical models, i.e. analytical and numerical methods in general terms. Two of the most widely used numerical solutions, i.e. finite difference and finite element methods are briefly introduced.

In addition, contribution of remote sensing and geophysical survey to groundwater flow modelling will be briefly presented. Finally, likely future developments in groundwater flow modelling will also be suggested.

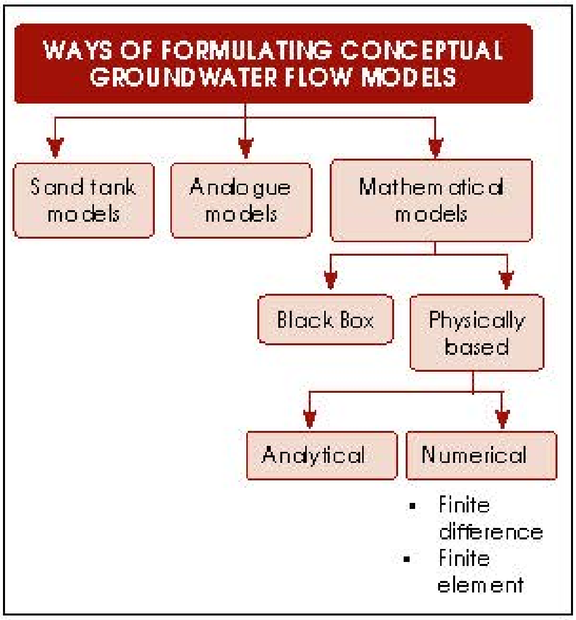


Figure 2: Types of groundwater models according to solution techniques and ways of formulating conceptual models

2.0 GROUNDWATER FLOW MODELLING

In terms of functionality, groundwater models can be divided into two broad categories, i.e. flow and transport models (Mandle, 2002; van der Heijde, El-Kadi, & Williams, 1988). The concern of flow models is

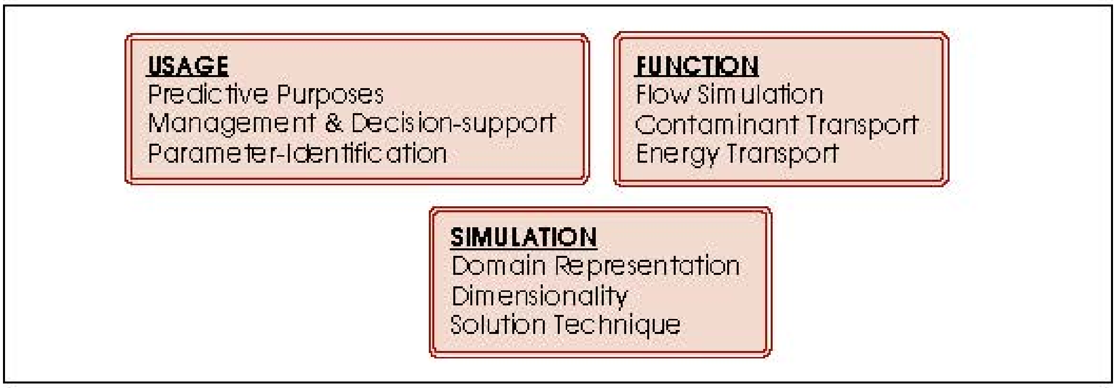


Figure 1: Groups of classification criteria for groundwater models
Groundwater models may be categorised by the criteria of (1) intended use of the model, (2) functional capabilities of the model, (3) simulation framework i.e. formulation and solution of the governing equations
Source: American Society of Civil Engineers (1996, p. 24)

Figure 3: Historical electric analogue groundwater flow models
Source: University of Illinois (2011)

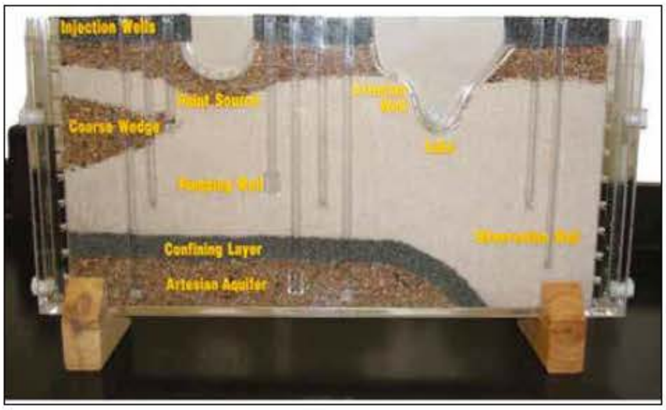


Figure 4: A sand tank model
Source: University of Nebraska-Lincoln (2009)

more on quantity or more specifically, the rate and direction of movement of groundwater (Mandle, 2002). The typical outputs from flow models are groundwater flow rates and hydraulic heads. The data required to develop typical groundwater flow models are as summarised in Table 1:

Table 1: Data required to develop typical groundwater flow models
Adapted from Mandle (2002) and Coffey Geosciences (2006)

DATA	EXAMPLE OF PARAMETER
Subsurface extent and thickness of aquifers and confining units	Ground surface levels
Hydrologic boundaries (also referred to as boundary conditions)	
Hydraulic properties of the aquifers and confining units	Aquifer transmissivity and specific yield
Groundwater levels (hydraulic head) for initial, steady-state and transient state conditions	
Distribution and magnitude of groundwater recharge	Rainfall
Discharge zones - leakage to or from surface-water bodies, etc. (sources or sinks, also referred to as stresses whether it is constant or transient)	

Mathematical models representing groundwater system are made up of a set of partial differential equations (PDE) (American Society of Civil Engineers, 1996). These equations could be solved using analytical and numerical methods using the initial and boundary conditions established.

ANALYTICAL METHODS

Analytical solutions are generally easy to apply and give the modellers a good appreciation of the model. The methods assume the model domain to be continuous in time and space (indicated by blue line in Figure 5) and provide an exact solution to the groundwater flow of low complexity. Analytical methods involve simplifying the flow equations to account only for uniform flow, homogeneous aquifer properties (such as uniform aquifer geometry and hydraulic properties) and steady-state conditions (Mandle, 2002), which are rarely the case in field conditions. Such simplifications do not take into account the spatial and temporal variability of groundwater flow or direction and hence, are unable to address complex interactions (Armstrong & Narayan, 1998). With the drawback of such simplification, analytical solution is recommended to be used for (Mandle, 2002):

- Groundwater system with simple flow processes (justified by field data)
- Checking on the performance of numerical solutions
- Initial assessment of site conditions and setting up of data collection where accuracy is of less concern

Analytical solution is seen as a top-down approach as it starts simple and only adds complexity as required, using big picture hydrogeological principles (considering large time span and hence permit steady-state conditions) and aims to capture generalities.

NUMERICAL METHODS

Numerical methods provide approximate solutions to the groundwater flow equations of more complex conditions. The approximation requires spatial and temporal discretization which is a process of subdividing the modelled area and time into small cells by model grid and time steps respectively, as shown in Figure 5. Unlike analytical methods which are using global values for aquifer properties, numerical methods could

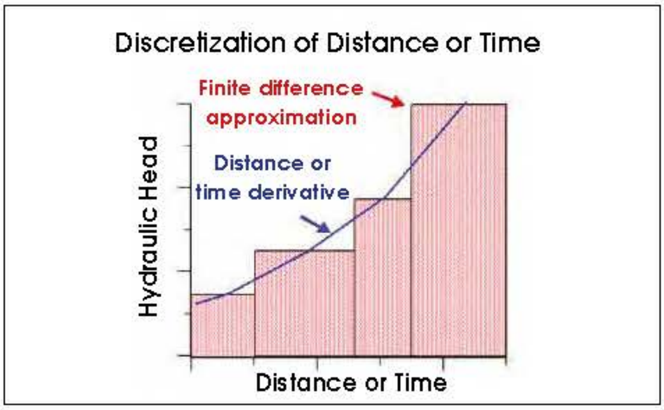


Figure 5: Discretization of distance or time versus continuum in distance or time (blue curve) "The blue curve represents the continuous variation of a parameter across the model space or time domain. The bars represent a discrete step-wise approximation of the curve". Source: Mandle (2002, p. 10)

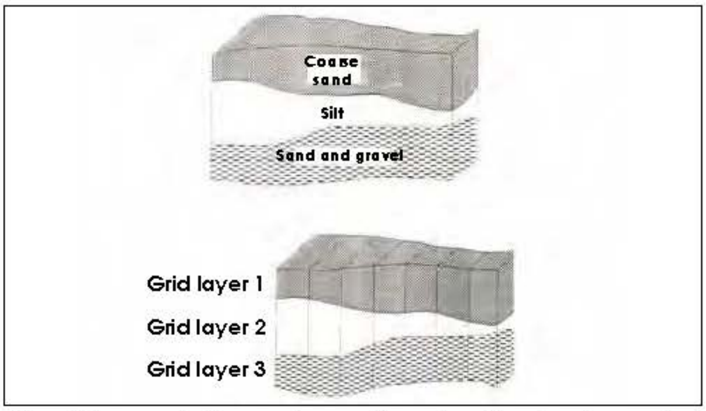


Figure 6: An example of representing a multi-layered aquifer system in a numerical model via discretization. Source: Mandle (2002, p.11)

account for the field conditions that change with time and space such as variation in flow rate or direction, hydraulic and aquifer properties (Figure 6).

Numerical methods are best used for (Mandle, 2002):

- Groundwater system with complex flow processes
- Hydraulic and aquifer properties exhibit significant spatial and temporal variability

In contrast to the analytical method, the numerical method is seen as a pro-bottom-up approach as it conceptualises the temporal and spatial variability and combines into an overall model.

The two most widely used approaches to implement numerical solutions, i.e. finite difference and finite element methods are briefly introduced below.

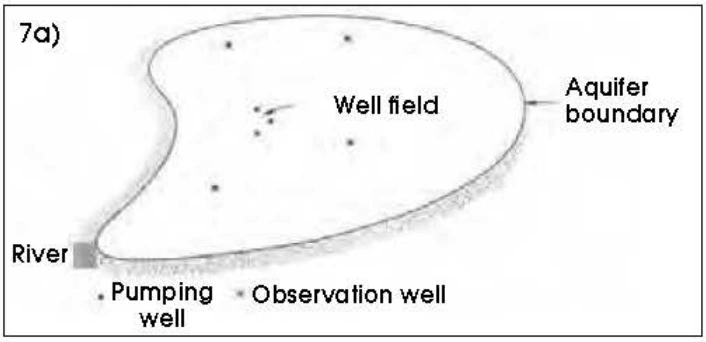
FINITE DIFFERENCE (FD)

Two key features of FD approach are:

- Discretizing the model domain by rectangular shaped and regular-spaced mesh or grid points as shown in Figure 5 (Mandle, 2002)
- Solving the governing flow equations by approximating the derivatives of the PDE (van der Heijde, El-Kadi, & Williams, 1988)

FINITE ELEMENT (FE)

For FE approach, "the PDE is approximated using the method of weighted residuals to obtain a set of algebraic equations which are solved using direct or iterative matrix methods" (Mandle, 2002). Even though FE requires more coding efforts than FD, it provides more flexibility and accuracy in representing irregular aquifer geometries as the cell shape of the discretization could be triangular or almost any polygonal shape (Younger, 2007), as illustrated in Figure 7.



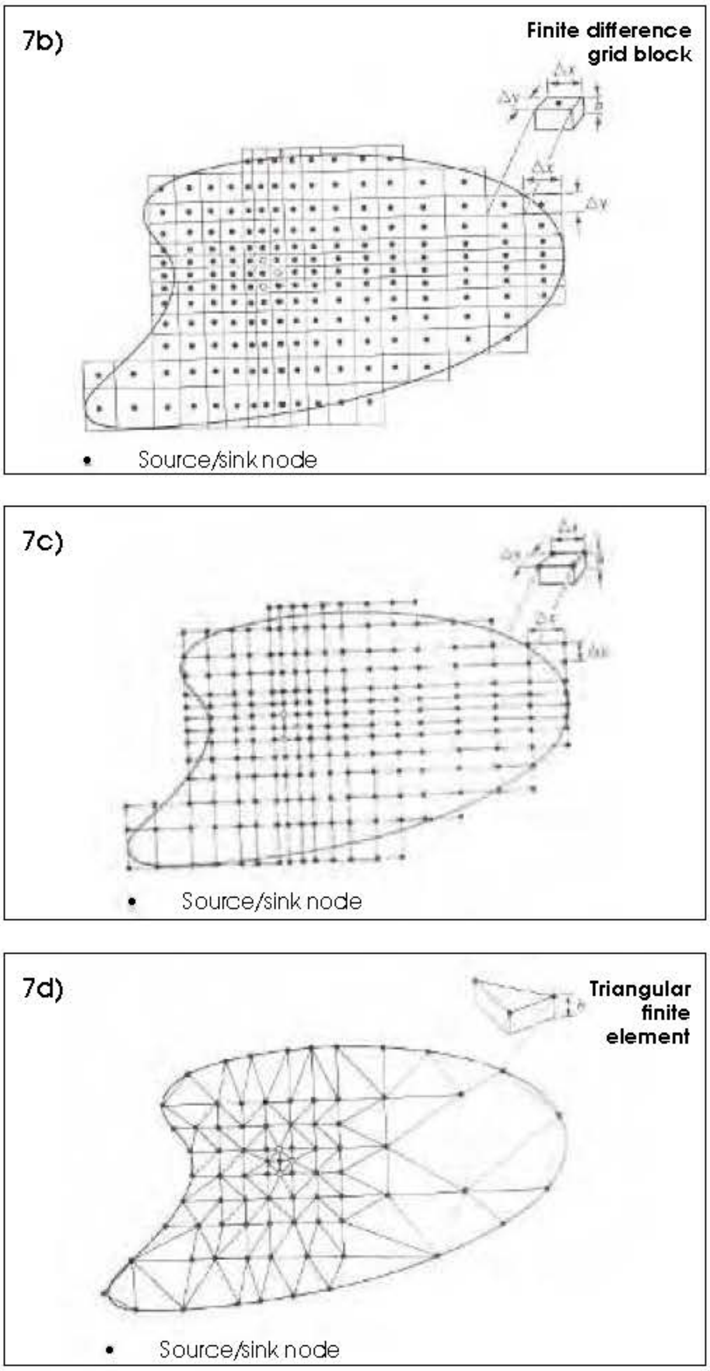


Figure 7: Finite difference and finite element representations of an aquifer region (a) Map view of aquifer (b) Finite difference grid with block-centred nodes where b is the aquifer thickness (c) Finite difference grid with mesh-cantered nodes (d) Finite element mesh.
Source: Wang & Anderson (1982, p. 4-5)

3.0 CONTRIBUTION OF REMOTE SENSING AND GEOPHYSICAL SURVEY IN GROUNDWATER FLOW MODELLING

Even though groundwater flow modelling has come a long way and is now highly evolved and mature, data availability and dealing with spatial variability and data limitations are still big issue. The main benefit brought by remote sensing (RS) and geophysical survey (GS) to groundwater modelling is the ability to provide spatial and temporal distributed input and calibration data (Brunner, Franssen, Kgotlhang, Bauer-Gottwein, & Kinzelbach, 2007). Some may say that RS data often require another modelling step to convert them to useable groundwater modelling data which would involve the correlation with ground observation data and hence be subjected to noise. Even so, RS data is still considered to be more superior than conventional data which are mere mathematical interpolation from point measurements (Brunner *et al.*, 2007).

The airborne RS information which have been identified to be of potential use in groundwater modelling are inclusive but not limited to the following (Brunner *et al.*, 2007):

- Identification of faults and dikes
- Changes in lithology and the depth of magnetic features
- Lineaments on the surface
- Surface elevations (upper boundary of phreatic aquifer)
- Vegetation type, vegetation density or other land surface characteristics (which would affect the infiltration rate)
- River and lake levels

Conventional subsurface measurements which involve drilling, probing and digging can only provide details of specific points. Gravitational, magnetics and electromagnetic GS, which are non-destructive subsurface investigation methods are expected to provide better representation/indication of the following aquifer properties which are required to run typical groundwater flow models:

- Subsurface extent and thickness of aquifers and confining units
- Hydrologic boundaries/boundary conditions
- Hydraulic properties of the aquifers and confining units - temporal changes in the total water storage (surface water, soil water and groundwater), specific yield

4.0 FUTURE DEVELOPMENTS

It is anticipated that future developments of groundwater flow modelling are more to polishing the approaches of parameter optimisation, uncertainty assessment as well as better representation of spatial distribution of input and calibration data.

More contribution is expected from geophysics surveys and remote sensing to supplement distributed spatial data instead of the conventional point measurements (Brunner *et al.*, 2007).

Population growth and climate change have worsened the water scarcity crisis on a global scale. Keeping this in view, it is likely that groundwater flow modelling will emphasise more on multi-disciplinary to address bigger picture i.e. integrated catchment management (ICM), than just conventional surface-groundwater relationship (Middlemis, 2004).

The general lack of communication and consistency among modellers warrant for the need for establishing specific guidelines in the field of groundwater modelling as in the case of Groundwater Modelling Guidelines for Australia (Middlemis, Merrick, Ross, & Rozlapa, 2001). Good and consistent modelling protocols are envisaged to further improve model reliability.

5.0 CONCLUSION

Both analytical and numerical methods have their merits and limitations. Adding complexity to a simulation does not guarantee accuracy. When simplifying assumptions can be justified to be appropriate to the field condition, an analytical solution can out-perform a poorly devised numerical model (Armstrong & Narayan, 1998).

Advancement in computer technologies and modelling software has reduced the calculation and analysis effort of groundwater flow modelling. However, as the modellers only see the final modelling results, potential errors made in the conceptual model and misunderstandings of applications and limitation of numerical methods are difficult to detect. Therefore, it is still essential to have a comprehensive and sound understanding of the underlying concepts and assumptions of groundwater systems in order to develop a reliable groundwater flow model. ■

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IEM DIARY OF EVENTS

Title: Half Day Seminar on Computational Fluid Dynamics in Building Services Applications

25th March 2015
Organised by : Mechanical Engineering Technical Division
Time : 9.00 a.m. – 1.00 p.m.
CPD/PDP : 3.5

Title: Talk on Submarine Landslide Flows Simulation Through Centrifuge Modelling

25th March 2015
Organised by : Geotechnical Engineering Technical Division
Time : 5.30 p.m. – 7.30 p.m.
CPD/PDP : 2

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