# Hydrological simulation of flow in aquifers of high incertitude

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Publication year: 2010

## Abstract

The modern computational systems have enabled the simulation of hydrological processes with physically based models that offer satisfactory speed and friendly user interface. In the case of groundwater applications these models solve numerically, based on a dense discretization of the flow domain, the differential equation that describes the groundwater flow. However cases can be found where these models are not the best option. Examples of such cases are the following:

- If the aquifer boundaries are unspecified then the domain of the unknown function (hydraulic head) is not defined and consequently it is not possible to solve the differential equation either numerically or analytically.
- If no water level measurements are available then the reliability of the simulated water level fluctuation cannot be verified. In this case, even though the simulated water level has limited use, it consumes computational resources for its simulation.
- If the aquifer is comprised of two distinct and interactive porous media and the primary porosity has unknown spatial deployment then only conceptual approaches can be used for modelling this aquifer. The accuracy of these approaches does not increase with the discretization density.
- If the groundwater flow takes places primarily inside discontinuities of the aquifer (e.g. karstic aquifers) then this flow, switching between free surface and pressurized flow, cannot be described by the Darcy equation. A mixed flow equation suitable for both phases and the transition between them may be more suitable for simulating these processes.

Aquifers exhibiting at least one of the previous characteristics are referred in this thesis with the term aquifers of high incertitude. The objective of this thesis is to suggest methods and to develop specialized models for these aquifers.

During this thesis, innovative techniques were devised and applied on one synthetic aquifer and six real aquifers (Almyros Agiou Nikolaou, Lilaia springs, Boeotikos Kephisos, Western Thessaly and Bregava springs in Boznia Erzegovina). The hydraulic properties of the synthetic aquifer were obtained using a stochastic 2D model. The produced heterogeneous conductivities field has realistic statistical structure that exhibits large almost-homogeneous areas. The six aquifers are representative, as far as concerns the available information, of the cases with data availability, limited data availability and lack of data. All aquifers are karstic except from the Western Thessaly aquifer. Both conventional and alternative modelling methods were employed and conclusions were deduced from comparisons between them. The discretization in the alternative methods was based, depending on the available information, on single-cell, few-cell and multi-cell meshes.

The following techniques, which are original contributions of this thesis, were used to study the previous issues:

- Flexible discretization. A model was developed which can be used with single cell or multi-cell discretization mesh.

- Hydraulic analogous. The development of this model was based on the concept of a hydraulic analogous. According to this, the flow in an aquifer is represented by the flow in a network of tanks and pipes. The tanks simulate the processes related to water storage and the pipes simulate the processes related to water movement. Each cell of the multi-cell model is related with a tank. The fluctuation of the water level inside a tank corresponds to the fluctuation of the water level inside the aquifer area defined by the corresponding discretization cell.
- Multi-cell models' error. The multi-cell models have been used extensively in steady state environmental and hydrological applications (e.g. use of flow networks to study the water leakage under dams). In this thesis the application of multi-cell models in transient flow conditions is attempted. The error of multi-cell models was investigated in transient flow conditions for different types of discretization. The investigation was based on theoretical and numerical analysis of the error (comparisons with finite difference models).
- Mixed flow equation. A mixed flow equation was devised which is applicable in both flow conditions within a karstic conduit, i.e. free surface and pressurized flow. The idea is derived from the hydraulic behaviour of tunnels that drain water from a reservoir. When the reservoir level is above the roof of the tunnel inlet then the tunnel behaves as pressurized conduit. When the level drops below the roof, the flow has free surface. These two conditions correspond to the flow conditions inside the aquifer during the wet and dry seasons of the hydrological year and the tunnel corresponds to the karstic conduits.
- Holistic approach. The coarse discretization, the parsimonious parameterization and the hydraulic analogous concept minimize the number of inputs and outputs of the model, which facilitates its integration with other hydrologic models. This enables the holistic modelling of all processes of a hydrological unit.

The application of the proposed mixed flow equation in the karstic aquifers of Lilaia and Bregava achieved a significant improvement of the modelling efficiency. However, according to the conclusions of the case study in Almyros spring, whenever no water level measurements are available or there is no interest in simulating the fluctuation of the water level then the linear equation, i.e. the Darcy equation, is advantageous in terms of reliability (fewer assumptions) and in operational terms (faster simulation).

The disadvantages and advantages of the multi-cell models compared with the finite difference method (the reference method used in this thesis for estimating the multi-cell models accuracy) were highlighted at the case study in Western Thessaly. The main advantage of the multi-cell models is the good accuracy even with limited number of discretization cells, which results in fast calculations. The disadvantages of the multi-cell models are the requirement of prior hydraulic information (equipotential lines) for the design of the cells, the rough description of the spatial variation of the aquifer properties and the inability to provide an a priori estimation of the model error.

An important advantage of the model developed during this thesis is its successful integration with other hydrological models (e.g. models simulating surface flow and human intervention). In all case studies the holistic modelling of the water basin with conceptual but fully integrated hydrological models was more consistent than the modelling of the hydrological processes using sequential physically based models with dense discretization. This is because in the latter case the inputs that dynamically depend on the interaction between the hydrological subsystems are estimated whereas in the former case they are simulated.

In the engineering applications there is always uncertainty due to the insufficient knowledge of the nature's properties and conditions. In transient flows, the multi-cell models' error is smaller than the error due to this uncertainty and consequently these models are eligible since they provide significant advantages like speed, plausibility and simplicity.