

Application of groundwater models in karstic aquifers

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Abstract The simulation of groundwater flow and transport, using various numerical methods, and taking into account as far as possible the spatial variability of the hydrodynamic and hydrodispersive properties of the karstic aquifers is certainly not an easy exercise. Four groups of models are used: models based on the REV approach, models based on the discrete approach, geostatistical models and black-box mathematical models. The choice of an adequate tool for analysing karst aquifer behaviour will depend strongly on the kind of problem to be solved: a steady-state flow problem will be considerably more simple to simulate than a transient transport problem within transient groundwater flow conditions. Unfortunately, in practice this last problem is more realistic than the former one. Another overwhelming factor is the scale of the study: local modelling simulations need more detailed data and probably a more discrete approach in the way of describing the spatial variability than regional models.

Application des modélisations dans les aquifères karstiques

Résumé La simulation des écoulements souterrains et du transport de contaminant, en utilisant différentes techniques numériques, et tenant compte au maximum de toutes les variations spatiales des propriétés hydrodynamiques et hydrodispersives des aquifères karstiques, n'est certainement pas un exercice aisé. Quatre groupes de modèles sont utilisés: les modèles basés sur le concept d'EVR, les modèles basés sur une description discrète des hétérogénéités, les modèles basés sur les géostatistiques, et les modèles mathématiques de type boîte noire. Le choix de l'outil idéal pour chaque cas d'étude dépend fortement du type de problème à résoudre: un problème d'écoulement considéré en régime permanent n'est évidemment pas aussi complexe que la simulation du transport en régime transitoire dans des conditions d'écoulement également transitoires. Malheureusement, dans la pratique la réalité est plus proche de laquelle le modèle est réalisé: des simulations à caractère local demanderont des données plus détaillées et représentées de manière plus discrète dans le modèle que ce n'est le cas pour des modèles régionaux.

GENERAL CONTEXT

Karst specialists generally agree about the high degree of heterogeneity and complexity of karst aquifers, although the conceptual models representing the structure and the hydraulic behaviour of a karst may differ considerably. The classical modelling techniques where the aquifer is assumed to present hydraulic conductivity and storativity values changing progressively in space can be difficult to accept when dealing with the hydrodynamic and hydrodispersive behaviour of a

karstic aquifer. Classically, the properties are measured locally from tests in boreholes or wells, and then regionally generalized in models of the whole aquifer or substantial parts of it. Additionally, geostatistical techniques tend to give most probable estimates of the aquifer characteristics where they are not measured. The application of such techniques to karst aquifers may lead to unacceptable results and even if simulated results are well fitted to available observations, it is often done by assigning questionable or non realistic values to the hydrodynamic parameters (Bakalowicz, 1995). Two basic questions arise: what modelling techniques are most suitable for karstic aquifers and how may the best technique to solve a particular problem be chosen?

For a long time, scientists have distinguished between conduit flow and diffuse flow in karst aquifers (Ashton, 1966; Pitty, 1966) and Bakalowicz *et al.* (1995) defined the structure of a karstic system by the organization of flow paths inside the aquifer, resulting from karst processes. The hydraulic behaviour of the system is the response of the structure to any input. In some cases, the structure can be deduced from the study of this hydraulic behaviour, as well as from field investigations. As shown on Fig. 1, the epikarst zone may provide important storage and can play a fundamental role in enhancing exchanges with the biosphere and highly non uniform recharge to the saturated zone. In the saturated zone, the main voids consist of conduits which determine the conductive function, together with other important karstic voids which provide essentially the storage or capacitive function of the aquifer. We can distinguish (Fig. 1):

- (a) the connected and saturated conduits with high conductive and low capacitive functions;
- (b) the connected and non saturated conduits with a potential high conductive function if the piezometric levels become higher;

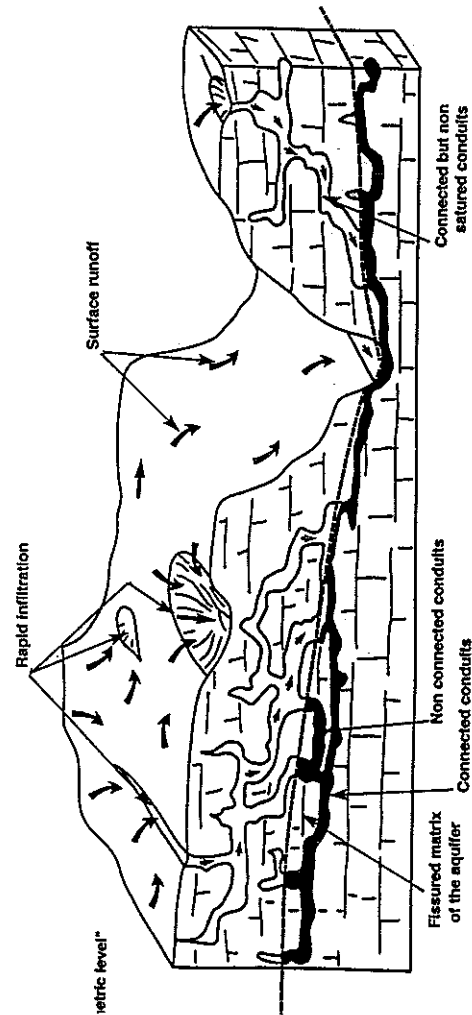


Fig. 1 Complex network of connected or non connected conduits, the limited meaning of "piezometric" water levels and the highly non-uniform recharge in karst aquifers (modified after Chauve *et al.*, 1986).

- (c) the non connected conduits or voids with no conductive function but a high capacitive function;

- (d) the fissured matrix of the aquifer with a low conductive function (compared to the connected saturated conduits) and a low to high capacitive function.

In such a complex system, the actual hydrodynamic and hydrodispersive behaviour is certainly not easy to describe with regionalized values of the parameters. Additionally, if important changes in piezometric levels are created by overexploitation, intensive irrigation or by any main changes in extraction or recharge, the active connected conduits will change so that the systems behaviour could also be drastically changed. This last point must be stressed particularly in the framework of global change studies or for any impact studies involving local or regional changes in groundwater levels.

Bear (1993) suggests that modelling should aim to achieve the following objectives:

- (a) to predict the future behaviour of the studied aquifer in response to new developments,
- (b) to provide information required in order to comply with local regulations,
- (c) to obtain a better understanding of the aquifer system from the geological, hydrogeological and chemical points of views and
- (d) to provide information for the design of future observation networks and field experiments.

The geological medium is not an engineering system, and to characterize it in detail and deterministically, so many boreholes would be necessary that it would no longer be the same medium as at the beginning (Tsang *et al.*, 1994). The modelling approach is a part of the whole programme of investigations coupling site characterization and predictive assessment to provide a more reliable understanding of the groundwater flow and solute transport processes occurring in the studied medium.

In this paper the terms "model" and "modelling approach" are used to refer to groundwater flow and transport numerical models dedicated to the representation and the simulation of the flow and solute transport processes occurring in fissured and karstic aquifers. All the so-called "balance models" which are based on, and limited to, a global balance approach to water quantity (and eventually pollutant quantity) for the studied aquifer considered as a whole are excluded.

Models describing the movement of contaminants through the discontinuous and highly heterogeneous karst media can be classified in four groups: models based on the REV approach, models based on the discrete approach, geostatistical models and black-box mathematical models (Dassargues & Brouyère, 1997). The choice of tool for analysing the behaviour of a karst aquifer will depend strongly on the kind of problem to be solved:

- (a) steady-state flow problem;
- (b) transient flow problem;
- (c) steady-state flow and steady-state transport problem;
- (d) transient transport problem with steady-state flow;
- (e) transient flow and transient transport problem.

For example, in the approach considered by the author (Dassargues & Brouyère, 1997; Dassargues *et al.*, 1996), transient transport is simulated in steady-state

are defined and calculated only in the conduit areas effectively described (discretized) in the model.

A more complete and accurate solution consists of combining a discrete model, representing explicitly the main karst conduits and the more important fissures, with a classical model assuming continuity with equivalent flow and transport parameters in order to represent the fissured matrix of the aquifer as a porous medium. One of the difficulties is the quite different time scales. For flood events in karst conduits the scale is in the order of hours whereas in porous media they are in the order of days, weeks and months.

Clemens *et al.* (1996) presented a combined continuum and discrete network reactive transport model including the simulation of the karst development itself. In their approach, the flow module calculates laminar and turbulent groundwater flow in a conduit network coupled by a linear exchange term to a porous continuum representing the fissured system. They have added to these simulated processes the fact that the rate of enlargement of the conduits is also dependent on the diameters and the rate of groundwater recharge, both of which vary in time. This last approach has been applied only in academic simple examples but the authors do hope that the model should be able to simulate consistently groundwater flow and transport conditions due to the fact that the simulated karst network is deduced from simulation of the calcite dissolution model. Up to now, application to actual cases has not been tried.

More generally, one of the difficulties when coupling the discrete network of karstic conduits to a continuous porous medium is to find a physically consistent description of the fraction of groundwater flow which transits within the karstic network (rapid flow) and that which transits the low permeability sections of the equivalent porous medium (slow flow). This kind of problem is pointed out by Jeannin & Grasso (1997) in an actual case study. They showed:

- (a) the limitations of the use of piezometric maps (of water levels) in karstic environments;
- (b) the important role of the epikarst in the distribution of the infiltration waters between the conduit network and the equivalent porous medium;
- (c) the importance of knowing the hydraulic conductivity of the geological formations traversed by the boreholes before interpreting the water level measurements.

Modelling academic cases, Rossier & Kiraly (1992) have varied the density, the topology and the dispersivity of the karst network which is draining the fissured and slightly karstified volumes, to simulate flow and tracing tests for different theoretical aquifers with different degrees of karstification.

MODELS BASED ON GEOSTATISTICS

In the "geostatistical approach" a stochastic method is used to generate karstic media statistically equivalent to the studied aquifer. On the basis of all available data, conditional simulations tend to reconstitute different karstic media which have in common a similar behaviour with respect to the measurements and data. Normally, this approach satisfies the constraints required by hydrogeological applications (Jaquet & Jeannin, 1993). The generated media are equiprobable and the uncertainty

and the confidence interval of each parameter of the model can theoretically be known, if the assumption (often admitted) that the errors in the model parameters can be considered as normally distributed (Gaussian law). Consequently, the uncertainty of the solution can also be computed.

BLACK-BOX MODELS

In highly karstified aquifers, it is sometimes very difficult to adopt a "physically consistent" model using any of the techniques described above. The reason is always insufficient knowledge of the real functioning karst system and the general lack of accurate topological and geometrical data concerning the main karst conduits. In this case, simulations of the whole karstic system are usually realized by calibrating black-box models. These models are used to assess the transient behaviour of the karstic system in terms of water quantity. When solute transport is considered, the transport is thought of as being highly dominated by convection.

Kernel functions were used by Doerflinger (1993) to predict the transient flow/transport behaviour of a karstic system and interpretation of tracer tests using convolution treatments has been realized by Dzikowski & Crampon (1994). Precipitation-runoff models have been used at a regional scale and multi-reservoir black-box models can be coupled to snow-melting processes (Mania *et al.*, 1991). Stochastic black-box models are used to forecast the time varying discharge in zones where spatially distributed information is not available. For example, Dimitrov *et al.* (1997) used a model based on an autoregression on the dependent variable as well as on the residuals and multiple regression on the independent variables (precipitation and other inputs).

CONCLUSIONS

On the basis of the concepts discussed above, Table 1 has been built describing the different kind of models which are used according to the different situations to be modelled. After a complete collection of available data concerning geology, morpho-structural geology, geophysical prospecting, piezometer drilling, etc. the local heterogeneity of a studied aquifer can be characterized or at least assessed. If the set of data is exceptionally detailed and accurate a discrete approach can be considered, but most often the heterogeneity of the aquifer is still to be described more or less globally and in the framework of the REV approach, "equivalent" values for the parameters are used. However, this last approach often provides unacceptable results

Table 1 The different types of groundwater models for karstic aquifers in function of the use to be made.

	Fissured or slightly karstified aquifers		Karstified aquifers	
	REV—discrete	REV—geostatistical	REV—discrete	REV—geostatistical
Local scale				
Flow			Black-box—discrete	
Regional scale				
Local scale	REV—discrete	REV—geostatistical		REV—geostatistical
Transport			Black-box—discrete	
Regional scale	REV—geostatistical			REV—geostatistical

in terms of transport behaviour or even for transient flow problems. If such a model is fitted on measured data, the values of the calibrated parameters no longer have the physical significance which they normally do in the REV approach. As a result, these REV based models become, to some extent, black-box models where the physical consistency of the models constitutive laws is not being sought.

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