C. R. Geoscience 348 (2016) 89–98

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Hydrology, Environment (Hydrology–Hydrogeology)

The reduction of hydrological models for less tedious practical applications

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ARTICLE INFO

Article history:
Received 6 August 2015
Accepted after revision 28 August 2015
Available online 10 December 2015

Handled by Michel Campillo

Keywords:
Integrated hydrological model
Flow dimension
Single and dual continua
Inverse problem
Parameterization

ABSTRACT

This work evidences that inconsistencies may persist between the complexity of hydrological models and available data for model documentation and application. For example, the integrated hydrological models handle the whole water dynamics over a watershed, but are only conditioned on data that incompletely record the dimensions of the flow. It is suggested to reduce this type of model by aggregating the physical background to diminish its Euclidean dimension. Paradoxically, the complexity in the physics of a model may also result in some reduction. For example, handling a flow by relying upon a dual continuum approach conceals the structural heterogeneity of the reservoir in the model equations. The parameterization at the scale of the aquifer becomes much simpler and the model reduction is here associated with diminishing the effort to condition the model onto data.

1. Introduction

It is duly acknowledged today that subsurface hydrological systems are in essence hard to survey despite the promising results brought by near-surface geophysics imaging (e.g., Hinderer et al., 2009; Mari and Porel, 2008; Mari et al., 2009). Subsurface systems remain usually under-sampled when a key question regarding water resources is to foresee with reasonable confidence how water quality and quantity will evolve under various natural and anthropic stresses.

Very early in the modern history of hydrological sciences, numerical models became alternative solutions filling in the blanks due to lack of data to better understand the dynamics of hydrosystems. Therefore, in the early 1980s, a few numerical spatially distributed models appeared with the aim of simulating groundwater flow. Research efforts rapidly translated into operational tools for practical applications in the public domain (e.g., Ledoux et al., 1989; McDonald and Harbaugh, 1980; Thiery, 1990). These tools were first used as frameworks interpreting the few available data. The raise of various requests from stakeholders and decision-makers in the eighties encouraged the development of modeling tasks aimed at large regional aquifers. A few studies at the local scale came out, but they were built as some kind of specific refinements hosted by the models at the large scale (e.g., Stockle et al., 1994). In any case and until the early 2000s, the focus was put on groundwater flow (and to a less extend on mass transfers); hydro-meteorological fluxes, surface flow and the vadose zone behavior being concealed in very simple inlet-outlet terms of the groundwater system (e.g., Kholghi et al., 1996).

Probably triggered by the research activity on climate changes, works on the continental water cycle rediscovered that surface and subsurface compartments of the cycle were tightly linked together (e.g., Fleckenstein et al., 2010; Winter et al., 1998). The physics of the simple water mass

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http://dx.doi.org/10.1016/j.crte.2015.08.002
1631-0713/

exchanges between surface and subsurface compartments revealed a poor explanation to observation data. In the meantime, the evolutions of stresses on hydrosystems, such as irrigation of the intensive agriculture, have generated new difficulties for the water resources management. One observes that deeper aquifers are rapidly depleted and, in return, severe droughts occur in valleys of large rivers. The accelerated cycling of water also increases groundwater contamination and excess of water mineralization (e.g., Skaggs et al., 1994; Yadav et al., 2002). All the above features were conducive to the development of revisited hydrological models.

The second generation of hydrological models appeared recently. They are also called "integrated" models because they handle three compartments of the water cycle, namely, the surface, the vadose zone, and the subsurface of a watershed (e.g., Frei et al., 2010; Furman, 2008; Goderniaux et al., 2009; VanderKwaak and Loague, 2001; Weill et al., 2013). The hydro-meteorological part in these models is still rough, probably because the identification of meteorological parameters and fluxes at the local scale are yet a fertile research domain with many unanswered questions (local radiative budget, separation between evaporation and vegetation transpiration, etc.; Mirus et al., 2011; Sophocleous, 2002).

While the first generation of groundwater flow models has mostly dealt with large-scale studies and partly homogenized systems (or assumed as such), the integrated models often handle problems at a smaller scale over heterogeneous domains. It must be acknowledged that the dynamics of water fluxes is very contrasted between the surface, the soil, and the aquifer; the characteristic travel time of water being roughly on the order of a few days, a few weeks to a few months, a few months to several years, in the respective compartments. In addition, numerous applications of integrated models target high resolution over small to mid-scale systems (1–1000 km^2). The strong structural heterogeneity of the reservoirs (e.g., fractured porous aquifers, soil with multiple porosities...) cannot be overlooked.

The main features evoked above make that the integrated models have become more and more complex and consequently less and less conditioned onto available data. Even if more data are available today, this is mostly because local variables are monitored in time to obtain long histories, regarding for example the flow rates in rivers, the hydraulic head in aquifers, the major dissolved chemical elements. Except for the very specific cases of research experimental sites, some oil fields or underground repositories (e.g., Mari et al., 2009), the "routine" investigations about for instance underground heterogeneity or exchange rates between rivers and aquifers did not evolve very much. Finally, one has at reach, on the one hand, precise three-dimensional and multi-physics models, and on the other hand, very few high-resolution data to document any practical application. In general, complex models are not ensured to escape from the so-called intrinsic equifinality making that the same model outputs may stem from different processes. The consequence is that model predictions become flawed because they rely upon irrelevant settings. The point is not to undermine the technical and scientific advances brought by the integrated models, but their application must pass through a preliminary stage of "reduction" that adjusts the model complexity to conditioning data and expected objectives.

A couple of examples illustrating the notion of model reduction are proposed in the following. Within the framework of calculating surface and subsurface flow and their coupling in small- to mid-size catchment areas, the first example rests on the argument that usual flow data do not distinguish all the flow geometries. For example, flow rate measurements or water levels in rivers provide us with averaged values that do not really see the three-dimensionality of free-surface flow in a draining network. In the same vein, the hydraulic heads in aquifers are often measured as water levels in open boreholes where the hydraulic potential equilibrates at a mean value quite uniform over the wetted thickness of the aquifer. The head sees neither the heterogeneity of the aquifer along the vertical direction nor the vertical component of flow (Delay et al., 2011, 2012). We propose to reduce the surface draining system (ditches, river...) to a connected network of one-dimensional bonds with simplified cross-sections. The subsurface flow is handled over a continuum vadose zone saturated zone via the integration along the vertical direction of both the soil-aquifer hydrodynamic parameters and heads (or capillary pressures). Therefore, the vadose zone and the aquifer are modeled as a single deformed two-dimensional layer (with some thickness), the deformation accounting for the variations in elevation of both the soil surface and the aquifer bottom.

The second example focuses on the aquifer compartment, especially that of fractured porous and/or karstified systems. We mentioned already that the vertical heterogeneity and the vertical fluxes were hardly identifiable on the basis of classical hydraulic head measurements. In the presence of strong heterogeneity, as observed in fractured porous media, a classical approach depicting the geometry of both the fracture network and the porous matrix will be hampered by the lack of information on the fractures. In opposite, a single-continuum approach (a unique porous medium) should be carefully and accurately discretized to show high contrasts of hydrodynamic properties over short distances that allow the occurrences of channeled flows. By keeping a two-dimensional approach to the aquifer but introducing a more complex physics of flow, it becomes possible to reduce the groundwater model. The local heterogeneity of the flow is merged into a dual continuum that depicts explicitly the fluxes in an open network of fractures and the fluxes in the porous matrix. An example at the scale of an experimental site is discussed by solving the inverse problem on the basis of hydraulic interference data between open wells. A single-continuum approach needs highly variable local hydrodynamic properties and a huge model parameterization. Conversely, the more complex physics of flow in a dual continuum depicts the local heterogeneity and only needs a rough spatial resolution on the model's parameters. Incidentally, the model reduction here associated with lighter parameterizations is prone to the so-called "Monte Carlo" uncertainty evaluations of various forecasts by diminishing the calculation efforts for