A hillslope-based aquifer model of free-surface flows in crystalline regions

Example of Brittany (France)

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Introduction

Groundwater flow and transport models are primarily based on 3D processes accounting for multiple superposed aquifers. While this approach is adapted to the widest variety of aquifers, it can be simplified in some cases where flows do not extend other multiple layers. This is especially the case for free surface flows in the shallow upper layer of crystalline regions for which the weathered zone does not extend over more than a few tens of meters. We propose a simplified approach based on the decomposition of regions in watersheds and hillslopes, which can be deployed at the regional scale to assess aquifer responses to global climate evolutions and natural resource evaluations.

Because of the depth limited weathering, free surface flows are key component of crystalline aquifers. Flows are controlled by the weathering structures as well as by surface/subsurface interactions. Like depths, shallow aquifer volumes are also limited and can be exceeded by infiltration in the wettest periods of the year. In the absence of extensive and accurate information on weathering, we propose that shallow aquifers be modeled by simple hillslope dominated free-surface flows with storage limitation to account for possible return flow and subsurface excess overland flows [1]. We show that this strategy is especially relevant to temperate climates like in Brittany (France). We discuss possible applications to other climatic contexts.

Methodology

Implementation of the hillslope-based strategy relies on the decomposition of watersheds in hillslope units defined from the hydrographic network (Figure 1). Within each hillslope, groundwaters are led to the closest section of the neighboring stream [2]. Regional flows are not accounted for even though they may locally be dominant because of regional fracture and fault structures.

For each hillslope, free-surface flows are modeled under the Dupuit assumption of vertical integration of flows. The resulting Boussinesq equations are complemented with surface boundary conditions along which the free-surface of the aquifer is limited by the topography. Further integration transversally to the main slope direction is added to improve performances [3]. This approximation is also justified by the absence of detailed local data. Model has been mathematically validated in a previous study [4] and is extended here from the hillslope to the watershed scale. Flows are rooted in the river and are aggregated along the stream network.

In a further methodological step, aquifer parameters (porosity, permeability, aquifer depth) will be calibrated against classically available river flow data, using innovative methods based on hydrological signatures (recession curves) and geochemical data. Calibration is done using river flow rate data due to their availability and representativeness unlike less-covering piezometric data. Eventual objective is to deploy such models at a regional scale with semi-automatic calibration of the local hillslope parameters.

Results

The proposed hillslope-based modelling approached is benchmarked on Britain watersheds of 30 km^2 to 200 km^2 (western part of France). Watershed are decomposed in hillslopes of around 1 km^2. The corresponding rivers are small enough to consider that transit times are dominates by subsurface residence times. Limited to some tens of days, they may be modeled with some generic assumption. This might not be correct for flooding applications but can be justified outside of extreme events. 1D hillslope-based models are compared to morel classical 2D approaches on cases of evolving complexity. The simplest case [4] is tilted constant width hillslope. More complex cases are derived from Britain hillslopes and watersheds.

Sensitivity studies are further performed to identify possible regional tendencies on the relation between geomorphological structures and hydraulic behavior.

Perspectives

This approach is designed to the deployed at the regional Britain scale within the AquiFR project of national aquifer models. AquiFR is meant to provide a global modeling tool of French aquifers based on segmented regional applications. Aquifers in France are split into several families based on their location and geology.

Climate in Brittany is oceanic, with well distributed rains over the year. Its geology consists in large sets of crystalline rocks corresponding to the Hercynian basement, made up of large groups of granite and schist. Over this old mountain root, a weathered layer has developed, shaping a shallow impervious layer with a highly variable thickness. Because of these two elements, water flow coming from rainfall in essentially constrained by the impervious layer, driving flows to the stream network. Watersheds in Brittany are generally small-size (1000 km²), except for the medium-sized Vilaine and the Blavet watersheds. Objective is eventually to provide a calibrated and fully functional modeling tool for all Brittany aquifers.

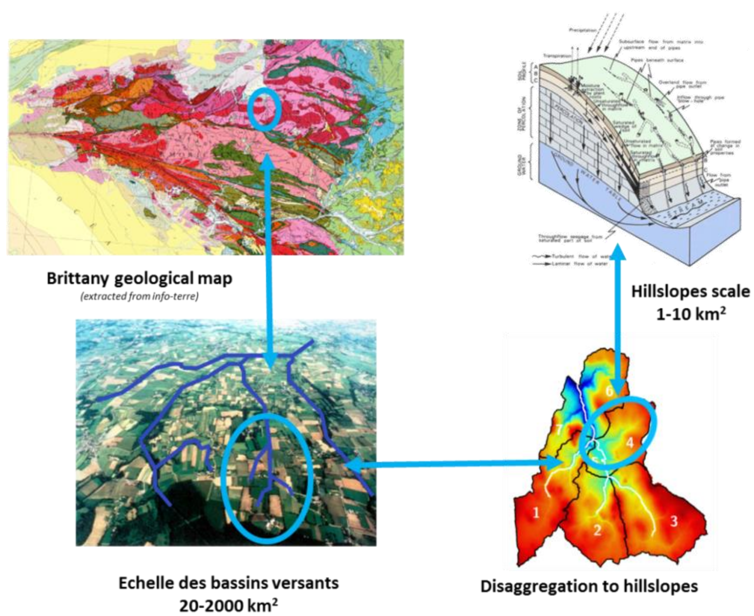

Figure 1 : Hillslope-based strategy of watershed modeling illustrated on a Britain catchment

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