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Representation of turbulent groundwater flow in continuum models

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Flow in karst aquifers can be described as composed of two components, namely slow, laminar flow in the fissured and / or porous matrix and rapid, often turbulent flow in solution conduits. One approach to the numerical implementation of this conceptual model is to couple a continuum model, which simulates flow in the matrix, with a discrete pipe network simulating conduit flow. Compared to standard groundwater flow models (i.e. single continuum models) this hybrid model approach, however, is computationally more demanding and requires higher investigation efforts, because the geometric and hydraulic properties of the conduit system need to be characterized. Thus, in practical applications standard groundwater models such as MODFLOW are more frequently applied. One major drawback of these models is that they usually do not account for turbulent flow. To overcome this drawback the recently published Conduit Flow Process Mode 2 (CFPM2) for MODFLOW 2005 considers turbulent flow in highly porous layers by adjusting the hydraulic conductivity of a laminar continuum model (Shoemaker et al., 2008). CFPM2 was intended for aquifers with large ('vuggy') pores where the onset of turbulence is at low Reynolds numbers (approximately between 1 and 100). Therefore, the relationship between hydraulic gradient and discharge obtained with this approach is found to be different from that obtained with standard turbulent flow equations (e.g., Darcy-Weisbach, Manning). While the latter predict a square-root relationship between gradient and discharge CFPM2 computes a power law with an exponent of 0.75. In addition, the existing code requires multiple time steps for convergence due to iterative adjustment of the hydraulic conductivity. Thus, the existing CFPM2 was modified by implementing a general power law with a user-defined exponent and by removing the iterative solution for adjustment of the hydraulic conductivity (Reimann et al., in review). The modified CFPM2 is verified by evaluating the relationship between hydraulic gradient and discharge resulting from simulations with single conduits. In addition, a coupled conduit-matrix system is considered to investigate effects of turbulent flow on the response of karst springs to rainfall events using the modified CFPM2 approach, existing hybrid models, and MODFLOW 2005. Spring responses computed by the modified CFPM2 are in good agreement with those obtained with the more complex hybrid models. Further, the results demonstrate the importance of considering turbulent flow processes in numerical models of karst aquifers: Laminar models overestimate maximum spring discharge and underestimate hydraulic gradients within the conduit. The modified CFPM2 thus represents a new method that makes it possible to account for these effects with reduced practical and numerical efforts as compared to hybrid models.

References:

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