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Non-Linear Flow Process (NLFP): a new package implementing the Forchheimer equation in MODFLOW

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Groundwater flow in porous media is usually considered to be laminar and to follow Darcy's law (i.e. a linear relationship between the specific discharge and the hydraulic gradient). However, flow can become non-linear or turbulent if a critical Reynolds number is exceeded. This is known to occur, for example, within the solution conduits of karst aquifers or in the vicinity of pumping wells. As most of the existing distributive groundwater models such as MODFLOW-2005 are based on Darcy's law, there is a lack of tools accounting for the non-linear or turbulent flow conditions encountered in these settings.

For this reason, a new MODFLOW package (Non-Linear Flow Process; NLFP) simulating non-linear flow following the Forchheimer equation was developed and implemented in MODLFOW-2005. This package is essentially based on an iterative modification of the linear conductance used by MODFLOW. The resulting effective Forchheimer conductance decreases with increasing specific discharge and thus mimics the effect of the non-linear term of the Forchheimer equation. The method was implemented such that the different layer types, boundaries conditions, and solvers as well as the wetting capability of MODFLOW are supported. The NLFP package was also successfully integrated in the current version of the conduit flow process CFP (Shoemaker et al., U.S. Geological Survey Techniques and Methods 6-A24, 2008). The correct implementation of the package is demonstrated using three different benchmark scenarios for which analytical solutions are available. Finally, a scenario considering transient flow in a more realistic karst setting and a larger model grid demonstrates that NLFP performs well under more complex conditions, although it converges moderately slower than the standard MODFLOW depending on the non-linearity of flow. Thus, this new tool opens a field of opportunities to non-linear groundwater flow simulation with MODFLOW-2005, especially for core sample simulation or vuggy karstified aquifers as well as for non-linear flow in vicinity of pumping wells.