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A general methodology to simulate groundwater flow of unconfined aquifers with a reduced computational cost

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Summary The computational cost of groundwater flow simulation can be crucial when analyzing complex conjunctive use water resources systems that need to simulate simultaneously surface and groundwater components. A general methodology for accurate simulation of unconfined groundwater flow with low computational cost is presented. It requires linearizing the unconfined groundwater flow problem governed by the Boussinesq equation. The technique is based on a change of variable and depends on the reference level adopted. Some recommendations have been provided to set the reference level to estimate the spatially variant parameters required to define the linearized problem. Using this linearization, more accurate results can be obtained than those derived with the classical assumption of invariant transmissivity. Solving the problem with eigenvalue techniques, the solution can be defined with a semi-explicit state equation with low computational cost. Some case studies have been analyzed in order to demonstrate that the methodology can be applied to any aquifer geometry (including non-horizontal bottoms), hydrodynamic properties and boundary conditions (even different prescribed head values). The results have been compared with those obtained with other linearization methods and MODFLOW [McDonald, M.G., Harbaugh, A.W., 1988. A modular three dimensional finite difference ground water flow model. Open – File Report 83-875, US Geological Survey, Washington DC] for unconfined aquifers. A case study defined from a

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previously calibrated finite-difference model of the ''Delta Adra'' aquifer, located in southern Spain, has been also analyzed.

Introduction

Due to the growing scarcity and conflict between uses, the water resources planning and management decision are often studied at a river basin scale, considering the conjunctive use of surface and groundwater. The necessity of multi-objective, multi-purpose and multi-facility analysis to solve water allocation problems, forces to use increasingly complex water management models that link hydrologic, economic and institutional relationships with water uses and allocation decision processes (McKinney et al., 1999; Simonovic, 2000). In this framework, mathematical models for simultaneously simulating surface and groundwater components and their interaction are required to evaluate management alternatives or to optimize water allocation through river basin management models with conjunctive use systems.

At the usual monthly time scale in which river basin management models work, surface water flow can be represented by simple mass-balance in a flow network. However, the simulation of groundwater flow and surface—groundwater interactions within a conjunctive use model usually requires more complex modeling approaches (Gorelick, 1983). The simulation of many management alternatives over long time horizon or the optimization of complex large-scale systems (with many competing demands, several reservoirs and aquifers, and a high interconnection among these elements) force the use of computationally efficient groundwater flow models. Furthermore, the requirement of low computational cost become crucial even for system that are not so complex if we wish to account for the stochasticity of surface inflows using a Monte Carlo approach in our management model.

Simulation of groundwater flow considering space variability of stresses and aquifer properties is only possible through distributed-parameter models. The most extended distributed methodologies to solve the groundwater flow differential equation (PDE) are the Finite Difference (FD) and Finite Element (FE) Methods. These methods discretize the time and flow domains, and require calculating the hydraulic head in each cell by dividing the stress periods into smaller time steps. The number of model constraints defined using these classic numerical methods can be excessively high, especially in hardly discretized aquifers. It can entail numerical problems and an excessive computational cost (Gorelick, 1983; Peralta et al., 1991, 1995; Theodossiou, 2004; Matsukawa et al., 1992), issues that are exacerbated for transient analysis of large aquifers in complex systems containing several aquifers, reservoirs, etc. These methods allow modeling unconfined aquifers by recalculating the transmissivity values, and solving with an iterative procedure an implicit system of equations at each time step.

When the aquifer transmissivity can be considered invariant, different explicit numerical techniques have been developed for simulating the groundwater flow with a lower computational cost. The influence function method (e.g., Maddock, 1972; Morel-Seytoux and Daly, 1975; Schwarz, 1976; Andreu et al., 1982; Belaineh et al., 1999) is one of these techniques. It requires estimating and storing the responses (response matrix) to some unit stresses. The simulation of the groundwater flow in a stress period will be computed with the response matrix applying the superposition principle. The Eigenvalue Method (Sahuquillo, 1983) is another explicit numerical solution defined using eigenvalue techniques. Several authors have applied eigenvalue techniques as an approach to solving the groundwater flow in linear aquifer systems (e.g., Kuiper, 1973; Rai et al., 1998; Sloan, 2000). The cited Eigenvalue Method was formulated to solving the groundwater flow problem discretizing the spatial domain but not the time. This approach does not require storing either the previous stresses or their influences, because the solution in each stress period is defined through an explicit state equation which depends on the initial conditions and the stresses applied during the stress period. The solution presents important computational advantages (Andreu and Sahuquillo, 1987) and has been employed to model the management of complex conjunctive use systems with monthly stress period using the Decision Support System AQUATOOL (Andreu et al., 1996).

But many aquifers hydraulically connected with the surface systems are unconfined and present important hydraulic head changes. They cannot be simulated in an accurate way considering time-invariant transmissivity. Pulido-Velazquez et al. (2006) presented an efficient solution of the unconfined groundwater flow problem for aquifers with a nearly horizontal bottom and connected to surface water bodies that produce a prescribed head condition whose value is constant in space and time. The solution, obtained by discretizing the space but not the time, is defined with a two-step explicit state equation. A generalization of this methodology is presented in this paper. Different case studies of aquifers with a non-horizontal bottom have been solved and compared with other solutions of these problems. In nearly horizontal aquifer bottoms, the results obtained with the new approach have also been compared with those calculated with the methodology presented by Pulido-Velazquez et al. (2006) in order to show the improvement of the generalization proposed. A case study defined with prescribed head boundary conditions whose values change in space has been also analyzed under different hypotheses. Finally, the proposed methodology has been applied to simulate a real unconfined aquifer (Delta Adra aquifer) with a finite difference calibrated model. The solution, defined using eigenvalue technique, provides accurate simulation of unconfined groundwater flow maintaining the computational advantages of the Eigenvalue Method for linear problems (Andreu and Sahuquillo, 1987).