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Linking groundwater simulation and reservoir system analysis models: The case for California's Central Valley

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ABSTRACT

Groundwater is an important resource. In many developed basins it meets part or all of the water demands. In addition, the management of groundwater resources directly impacts stream flows through stream-aquifer interactions. Yet many reservoir system analysis models that are used for the management of surface water resources either include a simplified representation of the groundwater flow dynamics or rely on surrogate models (linear response functions, artificial neural networks, etc.) which are trained using more complex groundwater models. These approaches may introduce restrictive, sometimes inaccurate, representation of the groundwater flow dynamics and additional modeling steps. In this study a reservoir system analysis model that utilizes an LP solver is linked directly to a non-linear, three-dimensional, finite element groundwater model. The linked model is a general-purpose model and can be applied to any basin. Some of the features of the linked model are showcased by an application to California's Central Valley.

1. Introduction

Usable surface and subsurface water resources are shrinking as the population increases and more river basins are developed through farming and urbanization. Farmers, urban users and environmental groups are all competing for these dwindling resources. The threat of climate change is increasing the uncertainty on the future availability and sustainability of stream flows and groundwater. The questions and concerns regarding the conjunctive management of surface and subsurface water resources are becoming increasingly complex. Water managers and scientists are turning to computer models to answer these complex water resources management questions.

Reservoir system analysis models are one set of tools water managers and scientists use to identify the optimal operation of reservoirs to meet a complex set of downstream requirements. Reservoir operation constraints can include satisfying agricultural and urban diversions, honoring water rights, providing minimum in-stream flow requirements for environmental and recreational purposes, flood control and hydropower generation. Reservoir system analysis models employ optimization methods to identify the best reservoir operation policies to meet these complex, sometimes competing, requirements.

Groundwater plays an integral part in the water resources management of many developed basins. For instance, in the intensely-farmed Central Valley of California, USA, groundwater meets approximately 40% of California's water demand in an average year, and as much as 60% in a dry year (CADWR, 2005; Megdal et al., 2009). Groundwater affects the stream flows through stream-aquifer interaction, usually contributing to stream flows during dry periods and receiving flow from streams during wet periods. Groundwater overdraft can adversely affect stream flows (Fleckenstein et al., 2004; Glennon, 2002). Aquifers can also be used to regulate surface flows, or as "water banks" to store excess water during wet periods to be used in dry periods where stream flows are not enough to meet all the demand (Gracheva et al., 2009; Scherberg et al., 2014). Overall, in a basin, the management of reservoir releases and stream flows are closely related to the management of the aquifer for the health of the basin and the sustainability of the water resources as a whole.

Some reservoir system analysis models include a simplified representation of the groundwater flow dynamics and the stream-aquifer flow exchange. Groundwater flow dynamics are often simplified because i) in real-world conditions where the aquifer is multi-layered and heterogeneous, the groundwater flow equation

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can only be solved using complex numerical techniques such as finite-element or finite-difference methods, and ii) linking reservoir system analysis models with groundwater simulation models poses computational challenges. Emch and Yeh (1998) linked a finite-element groundwater simulation model with an optimization model that employed nonlinear programming techniques to manage the conjunctive use of coastal surface and subsurface water resources. They followed an iterative approach in which the nonlinear optimization model tested new policies of decision variables for feasibility and optimality. Their model objective function and constraints were functions of groundwater heads, which were obtained from the groundwater simulation model. Although their approach was successful, they reported extensive computer run times and problematic local minima in converging to the global minimum. The issue of problematic local minima encountered in nonlinear programming methods is also reported by Labadie (2004) and Rani and Moreira (2010). Vedula et al. (2005) used an explicit-in-time finite-element model to simulate the groundwater flow in a homogenous, single-layer, unconfined aquifer. They used the linear algebraic equations resulting from the application of the finite-element method to the groundwater equation as constraints in a linked reservoir-aquifer-irrigated area optimization model. Their test case included 111 finite-element nodes to represent and simulate the groundwater flow dynamics. Valerio et al. (2010) linked RiverWare (Zagona et al., 2001) to the finite-difference groundwater simulation model MODFLOW (Harbaugh et al., 2000) to calculate the reservoir releases required to achieve instream flow targets in the Middle Rio Grande Basin in New Mexico, USA. In each time step, they used the known groundwater heads from the previous time step in computing stream-aquifer interactions. However, they did not utilize the optimization algorithm of the model; instead, they utilized a manual trial-and-error approach to meet the flow targets.

Labadie (2004), Rani and Moreira (2010) and Ahmad et al. (2014) provide extensive reviews of the optimization techniques used in reservoir system analysis models. Linear programming (LP), or its variants, tend to be the method of choice to tackle the optimization problem because they are easy to set up and understand, provide efficient solutions to large-scale problems, converge to the global optimal solution, have low computational requirements, and low-cost LP solvers are readily available (Labadie, 2004). WRIMS (CADWR, 2014c), MODSIM (Fredericks et al., 1998; Labadie and Larson, 2007) and RiverWare (Zagona et al., 2001) are all examples of reservoir system analysis models that utilize LP. LP models require that both the objective function and the constraints be linear or piecewise linear. This requirement necessitates any nonlinearity either in the objective function or in the constraints to be completely or piecewise linearized.

To simulate the stream-aquifer interaction in LP-based reservoir system analysis models, the groundwater flow dynamics can be simplified either by using a lumped-parameter approach, by assuming linearity in the groundwater flow dynamics, by conceptually simplifying the aquifer system (e.g. assuming a single-layer aquifer regardless of the existence of vertical hydraulic gradients), or by employing a combination of these approaches. For instance, in the California Value Integrated Network (CALVIN) model (Draper et al., 2003; Zikalala, 2013), a hydro-economic optimization model of California's water distribution system, stream-aquifer interactions are fixed time-series obtained from the historical run of California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), an integrated hydrologic simulation model for California's Central Valley (Brush and Dogrul, 2013; Brush et al., 2013). Jain et al. (2005) used basin-level utilizable groundwater storage less current drawdown values to supplement surface water resources in a study to analyze the effect of inter-basin surface water transfers on optimal operation of reservoirs in India. Water Evaluation and Planning System (WEAP) uses a lumped-parameter, linear-bucket style representation of the groundwater flow system in their simulation and optimization algorithms (SEI, 2014; Yates et al., 2005). Similarly, Cai et al. (2003) used a linear-bucket type approach to represent the groundwater flow system in a case study of water management in Syr Darya River basin in Central Asia. In MODSIM (Fredericks et al., 1998; Labadie and Larson, 2007), stream-aquifer interaction is simulated using a stream depletion factor (SDF) based on the semi-analytical solution of the linearized groundwater flow equation for a single-layer, homogenous aquifer (Glover, 1968; Jenkins, 1968).

A common approach to represent the groundwater and stream-aquifer interaction in reservoir system analysis models is to develop linear response functions from a calibrated (non-linear) finite-difference or finite-element groundwater simulation model by assuming that groundwater response to stresses is linear (Belaineh et al., 1999; Cosgrove and Johnson, 2004; Illangasekare and Morel-Seytoux, 1986; Labadie and Larson, 2007; Morel-Seytoux and Daly, 1975; Pulido-Velazquez et al., 2008). In this method, groundwater response to a unit stress at a given location and time is calculated independently from other stresses, and multiple stresses are later superimposed (by the assumption of linearity) to simulate their net effect on groundwater heads and stream-aquifer interaction. These linear response functions can then be used as constraints in the LP-based reservoir system analysis models.

Although simplification of the groundwater flow dynamics and stream-aquifer flow exchanges for reservoir system analysis projects can be justified for some cases, this approach may not be universally applicable. Aquifers are generally composed of multiple hydro-geologic layers, and wells are generally screened in multiple layers according to the water-yielding capacities of these layers. Pumping from a multi-layer aquifer generally creates vertical head gradients and non-linear flow patterns that cannot be represented by simplified lumped-parameter linear bucket style representations or linear response functions. In addition, although the linearity assumption for the groundwater flow and stream-aquifer interaction may be adequate in some parts of a basin for a certain time period, there is no guarantee that this assumption will hold throughout the entire simulation period and model domain, or under water management scenarios that induce significantly different stresses on the system.

Alternatively, more complex surrogate models such as ANNs can be used to adequately address the non-linearities inherent in groundwater flow (Peralta et al., 2014; Triana et al., 2010). ANN models can be trained with calibrated finite-difference or finite-element groundwater simulation models. For instance, Triana et al. (2010) trained ANN using results from a calibrated MODFLOW-MT3DMS finite-difference model for the Lower Arkansas River Basin in Colorado, U.S.A., to represent the quantity and quality of stream-aquifer flow exchanges in a river basin management model. They reported good agreement between ANN-predicted and MODFLOW-MT3DMS model results. They reported coefficient of correlations, r^2, of 0.92 and 0.99 for stream–aquifer exchange flows and total dissolved solid concentrations of these flows, respectively.

This paper describes a linked groundwater simulation and reservoir system analysis model. The linked model employs a generalized, full-featured, three-dimensional finite element groundwater simulation model, and a generalized reservoir system analysis model that uses a network flow algorithm to represent the reservoir-river system, along with a mixed integer linear programing solver. The new approach combines the power of a fully functional, three-dimensional groundwater flow model with the