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Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management

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SUMMARY

Policymakers in arid and semiarid basins face hard choices on water policies needed for adaptation to climate change. Hydro-economic modeling is a state-of-the art approach that can be used to guide the design and implementation of these policies in basins. A major gap in developments of hydro-economic modeling to date has been the weak integration of physically-based representations of water sources and uses such as the interaction between ground and surface water resources, to inform complex basin scale policy choices. This paper presents an integrated hydro-economic modeling framework to address this gap with application to an important and complex river basin in Spain, the Jucar basin, for the assessment of a range of climate change scenarios and policy choices. Results indicate that in absence of adequate policies protecting water resources and natural ecosystems, water users will strategically deplete reservoirs, aquifers and river flows for short-term adaptation to climate change, disregarding the impacts on the environment and future human activities. These impacts can be addressed by implementing sustainable management policies. However, these policies could have disproportionate costs for some stakeholders groups, and their opposition may undermine attempts at sustainable policy. These tradeoffs among water policy choices are important guides to the design of policies aimed at basin-wide adaptation to climate change.

1. Introduction

Policymakers in arid and semiarid basins face hard choices on water policy design for adaptation to climate change. Well-designed policies must account for complex environmental and economic tradeoffs, which point to the need for developing and using integrated tools capable to jointly address these tradeoffs based on sound science. Hydro-economic modeling is a state-of-the art tool to inform the design of integrated water policies at the basin scale. Hydro-economic models integrate the spatially distributed water sources, water storage and conveyance infrastructures, water-based economic activities, and water-dependent ecosystems into a unified framework. The advantage of this approach is the formulation of interrelationships among hydrologic, economic, institutional and environmental components for a comprehensive assessment of the tradeoffs among water policy choices (Harou et al., 2009).

Despite the significant advancement in hydro-economic modeling since the 1980s, several gaps remain unsettled in the literature, and progress in the development and application of hydro-economic models is needed to realize their full power to inform critical policy debates (Booker et al., 2012). One important gap not yet filled in the development of most hydro-economic models is the typically highly simplified modeling of interactions between groundwater and surface water flows. This linkage is important when aquifer systems are closely related to river flows making a sizable inflow or outflow contribution to basin resources. An earlier study by Burness and Martin (1988) suggests that the linkage between ground and surface water use requires detailed and careful attention to guide water policy design. They point out that the failure to account properly for river–aquifer linkage, when important, risks leading to misguided policy recommendations, either over-depleting or underusing basin water resources.

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This paper presents the development of a fully-integrated (holistic) hydro-economic modeling framework capable to address the tradeoffs among water policy choices for climate change adaptation. The contribution of this paper relative to prior literature stems from a more unified treatment of basin dynamics and the explicit specification of the interactions between ground and surface water flows. The modeling framework is solved in its entirety, and information among the economic and hydrological components over all periods and locations is jointly and simultaneously determined. This framework is applied to the Jucar basin in Spain to identify the tradeoffs among policy choices and the hurdles facing the implementation of sustainable management under various climate change scenarios.

The paper is organized as follows. First, a literature review on the specification of river–aquifer interaction in hydro-economic models is presented in Section 2, followed by the description of the modeling framework in Section 3. Model application is presented in Section 4, and the results in Section 5. Finally, Section 6 concludes with the summary and policy implications.

2. Literature review: hydro-economic modeling of river–aquifer interaction

This section reviews selected policy-oriented hydro-economic models at basin-level that include an economic objective function and representations of rivers and aquifers and the interaction between them. A more comprehensive literature review from hydraulic and hydrogeological views can be found in Sophocleous (2002), and Barthel and Banzhaf (2016).

Typically, aquifer dynamics and river–aquifer interactions have been simplified in hydro-economic models, because of the high level of complexity already involved in modeling whole river basins. Two simplifications are common. First, aquifers are mostly represented as simple single-tank units. Second, the linkage between aquifer and river flows is often represented using linear estimates relating the stream–aquifer flow with variables such as aquifer recharge, groundwater pumping, or water table levels. For example, Danskin and Gorelick (1985) present a combined ground and surface water economic management model that includes streamflow-recharge relationships based on field observations. McCarl et al. (1999) use regression-based forecasts of aquifer discharges that respond to recharge, pumping and water table levels. Cai et al. (2003) use a single-tank formulation and assume a linear relationship between aquifer discharge and water table levels. Ward and Pulido-Velazquez (2009) use single-tank formulation and estimate discharge as a proportion of recharge. Daneshmand et al. (2014) follow the same approach to optimize conjunctive management of water resources for mitigating impacts of droughts.

Some innovative studies in the hydro-economic literature have made progress in the representation of groundwater flow and river–aquifer interaction by incorporating spatially-distributed groundwater formulations into economic optimization frameworks. Pulido-Velazquez et al. (2008) present a holistic hydro-economic model with conjunctive ground and surface water use. They apply both the Eigenvalue and the Embedded Multi-reservoir methods to model groundwater dynamics and river–aquifer interactions. However, these methods have not been widely used in the literature. The study by Kuwayama and Brozovic (2013) develops an economic optimization model of agricultural groundwater use. It accounts for stream depletion using the Glover analytical solution, in order to test the effects of spatially differentiated groundwater pumping regulations. Although much work has been done to extend the applicability of analytical solutions to conditions that are typically found in the field, these solutions remain unable to address many practical applications, particularly basinwide analyses in which multiple users pump and divert water simultaneously and also numerous dimensions of water withdrawals, storage, and flows simultaneously yield economic benefits to a wide range of competing users (Barlow and Leake, 2012).

Several other studies have chosen to externally link separate hydrologic and economic sub-models. For example, Mulligan et al. (2014) evaluate groundwater management policies with coupled economic-groundwater hydrologic modeling. Medellín-Azuara et al. (2015) follow the same approach to analyze the effects of drought and groundwater overdraft, linking an economic model of agricultural production to a groundwater simulation model. Maneta et al. (2009) link an economic model of agricultural production to a detailed physically-based three-dimensional hydrodynamic model, to assess the effect of droughts. Dale et al. (2013) combine farmers' economic behavioral response functions and hydrological modeling to study conjunctive ground and surface water use. Although this approach brings in accurate hydrological details, it requires numerous iterations between the separate sub-models, together with simplified economic assumptions, which limit the comprehensiveness of the integrated environmental-economic analysis (Cai, 2008).

3. Modeling framework

An important contribution made by this paper is the development, application and use for policy analysis of a comprehensive multi-disciplinary modeling framework. This framework integrates several components including surface and groundwater hydrology, agronomy, land use, institutions, environment, and water-based economic activities. The framework is integrated, avoiding several of the simplified assumptions on both aquifer–river linkages and economic variables made in previous studies described above, as well as, bypassing iterations of temporary solutions passed among separate model elements. A description of each component of the framework as well as their integration is presented below. In all model equations, parameters are represented by lower case letters and variables are represented by capital letters.

3.1. Hydrology

The basin hydrology is represented by a node-link network based on the principle of water mass balance, defined in both flows and stocks. The flow variables tracked by the model are headwater inflow, streamflow, surface water diversion, groundwater pumping, water applied and consumed, return flow to streams and aquifers, stream–aquifer interaction, reservoir release, and reservoir evaporation. The stock variables tracked by the model are the reservoir and aquifer storage volume levels. The detailed formulation of the hydrological component is described in the Appendix A.

One important component of basin hydrology, considered in this paper, is groundwater flow, calculated with a finite-difference groundwater flow equation based on the principle of water mass balance and Darcy's law. The formulation is a special case of the one used in the USGS MODFLOW groundwater flow model (McDonald and Harbaugh, 1988).

An aquifer system is divided into n (1 row, n columns and 1 layer) connected cells (sub-aquifers), aqf, which are linked to n connected reaches of a river, $river$. The aquifer head, $H_{aqf,t}$, in each sub-aquifer aqf in time t is defined by the following equation (see Appendix A for details):

$$\begin{aligned} H_{aqf,t} = {} & [1/\{(s_{y,aqf} \cdot a_{aqf}/\Delta t) + c_{aqf,aqf-1} + c_{aqf,aqf+1} + c_{river,aqf}\}] \\ & \cdot [r_{aqf,t} - Q_{aqf,t} + (s_{y,aqf} \cdot a_{aqf} \cdot H_{aqf,t-1}/\Delta t) + c_{aqf-1} \cdot H_{aqf-1,t} \\ & + c_{aqf+1} \cdot H_{aqf+1,t} + c_{river,aqf} \cdot H_{river,aqf}]; \quad H_{aqf,0} = bz_{aqf,0} \end{aligned} \quad (1)$$