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Appraising options to reduce shallow groundwater tables and enhance flow conditions over regional scales in an irrigated alluvial aquifer system

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SUMMARY

Some of the world's key agricultural production systems face big challenges to both water quantity and quality due to shallow groundwater that results from long-term intensive irrigation, namely waterlogging and salinity, water losses, and environmental problems. This paper focuses on water quantity issues, presenting finite-difference groundwater models developed to describe shallow water table levels, non-beneficial groundwater consumptive use, and return flows to streams across two regions within an irrigated alluvial river valley in southeastern Colorado, USA. The models are calibrated and applied to simulate current baseline conditions in the alluvial aquifer system and to examine actions for potentially improving these conditions. The models provide a detailed description of regional-scale subsurface unsaturated and saturated flow processes, thereby enabling detailed spatiotemporal description of groundwater levels, recharge to infiltration ratios, partitioning of ET originating from the unsaturated and saturated zones, and groundwater flows, among other variables. Hybrid automated and manual calibration of the models is achieved using extensive observations of groundwater hydraulic head, groundwater return flow to streams, aquifer stratigraphy, canal seepage, total evapotranspiration, the portion of evapotranspiration supplied by upflux from the shallow water table, and irrigation flows. Baseline results from the two regional-scale models are compared to model predictions under variations of four alternative management schemes: (1) reduced seepage from earthen canals, (2) reduced irrigation applications, (3) rotational lease fallowing (irrigation water leased to municipalities, resulting in temporary dry-up of fields), and (4) combinations of these. The potential for increasing the average water table depth by up to 1.1 and 0.7 m in the two respective modeled regions, thereby reducing the threat of waterlogging and lowering non-beneficial consumptive use from adjacent fallow and naturally-vegetated lands, is demonstrated for the alternative management intervention scenarios considered. Net annual average savings of up to about 9.9 million m^3 (8000 ac ft) and 2.3 million m^3 (1900 ac ft) of non-beneficial groundwater consumptive use is demonstrated for the study periods in each of the two respective study regions. Alternative water management interventions achieve varying degrees of benefits in each of the two regions, suggesting a need to adopt region-specific interventions and avoid a 'one-size-fits-all' approach. Impacts of the considered interventions on return flows to the river were predicted to be significant, highlighting the need for flow augmentation to comply with an interstate river compact and portending beneficial impacts on solute loading.

1. Introduction

Irrigated agricultural development in an alluvial river valley can often lead to shallow water tables due to excessive water application, seepage from earthen canals, and inadequate drainage systems, creating a number of challenging difficulties. Over time, these high water tables become salinized, contributing not only to waterlogging (inadequate soil pore aeration) but also to salinization of soils and diminishing crop yield. High water tables cause recharge from irrigation to seep back to streams, and these return flows can dissolve salts and other chemical constituents as the water moves through the underlying aquifer, further increasing constituent loads. Also, as shallow groundwater flows laterally, it raises water tables beneath uncultivated and fallow land where substantial amounts of shallow groundwater may be non-beneficially consumed (herein, "non-beneficial consumptive use" signifies water evaporated and transpired without directly contributing to economic agricultural production). Groundwater solute concentrations increase beneath both cultivated and uncultivated

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land due in part to this evaporative upflux from shallow water tables (Gates et al., 2006; Ghassemi et al., 1995; Morway and Gates, 2012; Niemann et al., 2011).

Physically-based computational models often are used to investigate strategies for reducing waterlogging and salinization associated with shallow groundwater. For example, in northern India, Kumar and Singh (2003) employed a calibrated and tested model to investigate water-management scenarios aimed at reducing wide-spread waterlogging. Later, Singh et al. (2006) used a hydrological model to study the potential for waterlogging and salinity reduction through improved water management and reduction of canal seepage in India. In the Yaqui Valley of Mexico, Schoups et al. (2005a) used a hydrologic/agronomic model coupled with an optimization model to explore crop yield responses to increased reliance upon groundwater resources in a time of drought. In China's Yellow River Basin, Xu et al. (2010) used a lumped-parameter model to investigate management and infrastructure rehabilitation alternatives for current irrigation practices to relieve water scarcity and to curb waterlogging and salinization in the upper part of the basin. A wide range of options were investigated: reduced canal seepage, rehabilitated control structures, improved water delivery scheduling, deficit irrigation, adjusted crop patterns, land leveling, and modernized irrigation methods (e.g., drip or sprinkler irrigation). Scenarios were simulated through adjustment of assorted empirical coefficients in the lumped-parameter model and demonstrate the potential for lowering the water table by as much as 0.71 m using a combination of interventions. In the United States, a number of regional-scale waterlogging and salinity studies have been carried out in the San Joaquin Valley of California. Gates and Grismer (1989) and Gates et al. (1989) describe a groundwater flow and salt transport model that was used to help determine "economically optimal irrigation and drainage strategies for long-term regional management." Schoups et al. (2005b) present a regional-scale model that includes flow in both the saturated and unsaturated zones, as well as a reactive salt transport component, run over a 57-year period to simulate historic trends in salinity concentrations observed in both the shallow and deep aquifers.

The Lower Arkansas River Valley (LARV) in southeastern Colorado (Fig. 1) has a long history of rich agricultural production but is vulnerable to a number of the irrigation-related problems typical of intensively irrigated valleys. As such, it has been the focus of several investigations over recent decades. Several models of the LARV were developed in the second half of the 20th century (Brendle, 2002; Goff et al., 1998; Konikow and Bredehoeft, 1974a,b; Konikow and Person, 1985; Lefkoff and Gorelick, 1990; Person and Konikow, 1986). Gates et al. (2002) published steady-state results from a three-dimensional model that was more expansive and more spatially and temporally resolved than the earlier models. Burkhalter and Gates (2005, 2006) used transient models to evaluate management scenarios intended to mitigate waterlogging, salinization, non-beneficial consumptive use, and salt loading to streams in a portion of the LARV. Simulated management options included reduced canal seepage, reduced recharge from over-irrigation (improved water management), improved drainage facilities, and combinations of these. Results suggested the potential for dramatic improvements in crop productivity, water conservation, and improved water quality in the LARV.

This paper provides a record of the calibration, testing, and application of regional-scale ($\sim$$10^4$–$10^5$ ha) models of the irrigated alluvial aquifer system of the LARV with the aim of discovering how to alter regional water tables and groundwater flow to establish conditions that enhance and sustain agricultural production, conserve water, and improve the riverine environment of the LARV. This effort builds upon the work of previous modeling studies of the LARV by developing detailed representation of hydrologic conditions and water-budget components over an expanded spatial and temporal extent, and by drawing upon substantially richer observation data sets for calibration. Though the potentially harmful effects of irrigated agricultural production on water supplies are related to both water quantity and water quality, a model that simulates only the flow of water, and not the transport of salts, can be very useful for better understanding existing groundwater table and flow conditions. Such conditions are of direct concern themselves, and include depth to the water table, upward flow lost to non-beneficial consumptive use, and the rate and timing of groundwater return flow to streams. Moreover, the accurate simulation of these groundwater table and flow conditions is a prerequisite for eventual solute transport modeling.

For model construction and calibration, a database is built from extensive field data gathered over 9 years from two regions, selected to be broadly representative of the entire LARV. To maximize the use of this unique dataset, the following major distinguishing features are implemented in the regional models described herein: (1) model calibration and testing are improved by using a diverse set of observations applied to both representative valley regions: groundwater hydraulic head, groundwater return flow, seepage from earthen canals, actual evapotranspiration (ET) within the soil zone, upflux to ET from the water table under naturally vegetated and fallow land, and estimates of ratios of water table recharge to infiltrated irrigation water; (2) the modeled period is extended 6 years longer than in previous studies (Burkhalter and Gates, 2005, 2006) and now includes wet, dry, and near-average hydrological conditions; (3) unsaturated-zone flow processes are simulated over the regional scale using the unsaturated-zone flow (UZF1) package (Niswonger et al., 2006) developed for MODFLOW; (4) a water allocation algorithm is created that attempts to realistically recreate spatiotemporal irrigation patterns while honoring historical canal diversion records; (5) MODFLOW-NWT (Niswonger et al., 2011) is used for greater numerical stability during calibration (alleviating cell wetting and drying problems); (6) spatially-varying estimates of precipitation and potential ET rates are used in place of uniform estimates for each region; (7) highly resolved land-use and crop-planting classification are employed to more accurately account for actual ET; (8) an improved representation of the timing of seepage losses from earthen canals is used; and (9) hundreds of stratigraphic logs simultaneously guide and constrain spatially variable model parameter values. This paper presents an approach for detailed simulation and evaluation of alternative management scenarios that are designed to conserve both water quantity and quality, but with consideration limited herein to water quantity-related issues. General results for this study may be evaluated for transferability to similar irrigated agricultural regions, and the approaches are presented as guidelines for studies of other such settings.

2. Study area

Situated on the High Plains (Fig. 1) in semi-arid southeastern Colorado, the broad and thin alluvial aquifer of the LARV is underlain by a series of sedimentary formations of late Cambrian to Tertiary age (Darton, 1906). The lower formations, consisting of marine-derived shale, are relatively impermeable and serve as the lower boundary of the groundwater models (Moore and Wood, 1967; Person and Konikow, 1986). The Dakota sandstone formation underlies the alluvium in an area near the Colorado-Kansas border. Because of lower potentiometric heads in the sandstone as well as moderate porosity, recharge from the overlaying alluvium may occur (Voegeli, 1965). However, relative to the much larger fluxes present in the shallow alluvium, this interaction is assumed negligible. The alluvium is in good hydraulic connection with the Arkansas River (Konikow and Bredehoeft, 1974a; Person and Konikow, 1986).