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Research papers

Analysis of managed aquifer recharge for retiming streamflow in an alluvial river

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ABSTRACT

Maintenance of low flows during dry periods is critical for supporting ecosystem function in many rivers. Managed aquifer recharge is one method that can be used to augment low flows in rivers that are hydraulically connected to an alluvial groundwater system. In this study, we performed numerical modeling to evaluate a managed recharge operation designed to retime streamflow in the South Platte River, northeastern Colorado (USA). Modeling involved the simulation of spatially and temporally variable groundwater-surface water exchange, as well as streamflow routing in the river. Periodic solutions that incorporate seasonality were developed for two scenarios, a natural base case scenario and an active management scenario that included groundwater pumping and managed recharge. A framework was developed to compare the scenarios by analyzing changes in head-dependent inflows and outflows to/from the aquifer, which was used to interpret the simulated impacts on streamflow. The results clearly illustrate a retiming of streamflow. Groundwater pumping near the river during winter months causes a reduction in streamflow during those months. Delivery of the pumped water to recharge ponds, located further from the river, has the intended effect of augmenting streamflow during low-flow summer months. Higher streamflow is not limited to the target time period, however, which highlights an inefficiency of flow augmentation projects that rely on water retention in the subsurface.

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1. Introduction

Alluvial rivers are increasingly viewed as groundwater-dependent ecosystems (Stanford and Ward, 1993; Trush et al., 2000; Hancock et al., 2005; Larned et al., 2015). Groundwater inputs are necessary to sustain streamflow in most alluvial rivers, and the temperature and chemical composition of inflowing groundwater is an important control on the presence/types of riverine biota and rates of ecosystem processes (Boulton and Hancock, 2006). Many alluvial rivers worldwide have experienced a reduction in streamflow due to anthropogenic impacts such as diversions and groundwater pumping. Of particular concern is the diminishment of low flows during dry periods, which has the potential to alter the distribution of riparian and aquatic species and can lead to sedimentation and water quality problems (Smakhtin, 2001; Rolls et al., 2012). Flow management in alluvial rivers requires conjunctive use strategies that recognize the interconnection of groundwater and surface water (Winter et al., 1999).

Previous modeling studies in the water management literature have explored conjunctive use strategies aimed at improving streamflow conditions. For example, Barlow et al. (2003) performed simulation-optimization modeling to identify alternative groundwater pumping scenarios that minimized summer streamflow depletion in an alluvial river in the northeastern USA. Fleckenstein et al. (2004) evaluated the potential effects of reduced groundwater pumping on fall streamflows, critical for supporting Chinook salmon runs, in the Cosumnes River of California. Khan et al. (2014) demonstrated how enhanced subsurface water storage could increase dry season flow and decrease monsoonal season flow in rivers of the Ganges Basin. Managed aquifer recharge is a way to potentially increase streamflow in rivers that are hydraulically connected to permeable alluvial aquifers. Barber et al. (2009) conducted groundwater modeling to evaluate a proposed managed recharge project in the Spokane Valley-Rathdrum Prairie aquifer; the purpose of the project was to increase summer low flows in the Spokane River, which have been declining over the past several decades. For different recharge locations and water application

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strategies, they estimated the amount of time required for recharge water to impact stream/groundwater interaction areas.

The timing issue represents a particular challenge when evaluating the efficacy of streamflow augmentation projects that rely on managed aquifer recharge. Transmission of hydraulic head perturbations between the recharge site and stream depend on hydraulic properties and the geometry of the aquifer, which is often complex (Miller et al., 2007; Bredehoeft, 2011). Furthermore, increases in streamflow, produced by increased hydraulic heads at the stream-aquifer interface, are generally not limited to target low-flow periods; these effects are spread out in time due to the diffuse nature of groundwater system response. This results in some level of system inefficiency (Thomas et al., 2011). Given these complexities, accurate predictions of streamflow response to recharge may require spatially distributed numerical modeling.

In this study, we conducted numerical flow modeling to evaluate the performance of an existing managed recharge site in northeastern Colorado (USA) that is designed to retime streamflow; during winter months, groundwater is pumped from alluvial wells adjacent to the river and delivered to recharge ponds located further from the river, with the intent of increasing hydraulic heads and streamflow during the summer months. To accurately assess the hydraulic performance of the system and the impact on streamflow throughout the year, we employ a model that simulates head-dependent groundwater-surface water exchange and incorporates a streamflow routing component. We develop a general analysis framework to quantify the impact of the recharge operation on all seasonal head-dependent flows in the aquifer water budget, including groundwater-surface water exchange with gaining and losing stream reaches. Seasonal changes in streamflow, relative to a natural base case scenario, are quantified and interpreted.

2. Study area and hydrogeologic setting

The Tamarack Ranch State Wildlife Area is in the South Platte River valley in northeastern Colorado (Fig. 1). A managed aquifer recharge system has been operated at Tamarack since 1996, following a three-state agreement between Colorado, Wyoming, and Nebraska to improve streamflow conditions on the Platte River. The U.S. Fish and Wildlife Service identified the need to increase low flows to protect four threatened or endangered species: the whooping crane (*Grus americana*), interior least tern (*Sterna antillarum*), piping plover (*Charadrius melodus*), and pallid sturgeon (*Scaphirhynchus albus*). Colorado's obligation under the agreement involves the use of managed aquifer recharge to deliver additional streamflow across the Nebraska border between April and September.

In 2012–2013, the managed aquifer recharge system at Tamarack included four ponds, located in upland eolian sand deposits, at distances up to 1.4 km from the South Platte River (Fig. 2). Ten extraction wells are used to pump alluvial groundwater to the recharge ponds from December through March (when surface water demand is low), with the objective of increasing streamflow between April and September. Project design with pond locations was initially based on analytically derived streamflow depletion factors (Jenkins, 1968) which allow for simplified estimates of streamflow response to recharge at varying distance from the river (Flory and Halstead, 2002).

The South Platte River flows from west to east at a gradient of 1.3 m km^{-1} in the study area and is characterized by an incised channel and a flat channel bottom. The incised channel and heavily vegetated banks result in increased depth but not increased width with increased discharge (Donnelly, 2012). The stream is flanked on both banks by a forest of riparian phreatophytic vegetation, up to 1 km wide. The riparian forest is dominated by the plains cottonwood (*Populus deltoides*) and, to a lesser extent, the peach-leaved willow (*Salix amygdaloides*). Little to no shrub canopy is present and the undergrowth is primarily tall slough grass (*Spartina pectinata*) (Kittel et al., 1998). Areas away from the stream channel are vegetated eolian sand deposits consisting of well-sorted loose wind-blown sand (Scott, 1978). The eolian sand hills provide an ideal location for recharge ponds due to the high permeability of the sands that directly overly the alluvial aquifer (Warner et al., 1986).

Groundwater flows from west to east in Quaternary alluvium that underlies the eolian sand deposits. The alluvium consists of a heterogeneous mixture of well sorted to poorly sorted sand, gravel, and clay lens deposits (Bjorklund and Brown, 1957;

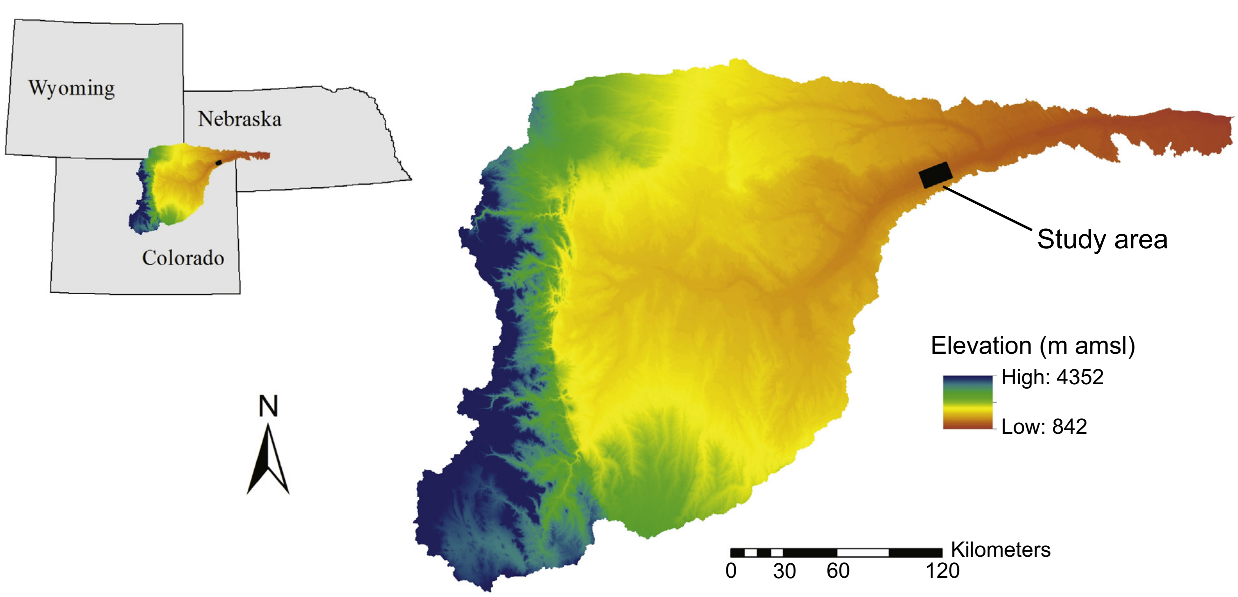

Fig. 1. Location of study area within the South Platte River Basin.

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