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Analytical modeling of irrigation and land use effects on streamflow in semi-arid conditions

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SUMMARY

Availability and uncertainty in input data are the primary constraints of groundwater modeling. Analytical models assimilate the key and important data, but capture the major traits of the watershed. We study a baseflow-dominated stream, Frenchman Creek in southwestern Nebraska, USA, which has experienced large streamflow reductions since the 1960s and is a subject of various actions on water rights appropriation. The new element of the model is simultaneous analytical consideration of groundwater pumping and land use change effects. Analytical stream depletion rate calculations by various methods show that pumping from the 462 irrigation wells in the basin consumed a large amount of baseflow. The simulated streamflow at the outlet of Frenchman Creek with minimal calibration compares favorably with observed streamflow and indicates the viability of an analytical approach to watersheds with limited hydrogeologic data.

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1. Introduction

Modeling of groundwater (GW)–surface water (SW) interactions to gain a better understanding of the hydrologic system is important in the Great Plains region of the United States where groundwater pumping for irrigation is widespread. This area has undergone tremendous land use changes from native rangeland to cropland. This proliferation of irrigation and land use change has led to streamflow and GW level declines throughout the Great Plains during the past century (McGuire, 2011). In order to better understand the effects of irrigation and land use changes on the water budget and streamflow and to predict and mitigate future declines, water resources management in the western USA rely on modeling the GW–SW interactions predominately using numerical models (e.g., Rossman and Zlotnik, 2013). Usually, natural conditions are highly complex and the model's ability to produce reliable outputs rests on the quality and quantity of input data. As well, model development is labor-intensive. Therefore, analytical models may be a good supplement or alternative for stream water budget assessment because they focus on key processes and are easy to implement and provide a water management tool for understanding the consequences of water management policies.

Analytical studies by Theis (1941), Glover and Balmer (1954), Hantush (1965), Jenkins (1968), Hunt (1999); Zlotnik et al. (1999); Butler et al. (2001) and others, and well summarized by Barlow and Leake (2012), focused largely on stream depletion by irrigation wells in various hydrogeological conditions. Jenkins' (1968) analysis became the standard analytical approach for stream depletion rate (SDR) assessment for water management in the Mid-West and other regions of the USA, but newer methods have not been compared with this technique in hydrological applications. Areas where SDR were assessed using analytical techniques may vary in magnitude from km^2 (e.g., Hunt et al. (2001), Kollet and Zlotnik (2003), Langstaff (2006), Fox (2004) and Fox et al. (2011)) to hundreds of km^2 (e.g., Foglia et al., 2013).

Abbreviations: FC, Frenchman Creek; GIS, geographic information system; GW, groundwater; NDNR, Nebraska Department of Natural Resources; RRGWM, Republican River Groundwater Model; SDR, stream depletion rate; SRR, stream recharge rate; SW, surface water.

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The influence of land use change on recharge and streamflow is also a concern (Dugan and Zelt, 2000; Sophocleous, 2005; Oudin et al., 2008; Wilcox et al., 2008; Zheng et al., 2009; Stonestrom et al., 2009; McMahon et al., 2011; Perez et al., 2011; Zeng and Cai, 2014), but the application of analytical techniques to this problem have not been fully explored yet. Knight et al. (2005) addressed the influence of land use practices; they evaluated the effect of GW recharge changes on baseflow to a stream in South Australia, but GW withdrawals for irrigation were not considered. Foglia et al. (2013) accounted for pumping and land use aspects, but utilized a more complex hydrological model of the watershed.

The goal of this study is to combine the analytical methods of the stream depletion and stream recharge analyses, considering the effects of GW pumping for irrigation and land use changes on streamflow and apply it jointly to Frenchman Creek (FC). Another goal of this study is to investigate conditions for application of more recent approaches in SDR evaluations by comparing Jenkins' and Hunt's methods.

2. Study area

Our study area is the salient example of declining streamflow and large land use changes over the last century like in many countries around the world. FC of southwestern Nebraska, USA, is a tributary of the Republican River (Fig. 1) and has been the subject of a number of hydrological studies and numerical models of various domains, scales, and complexity (Condra, 1907; Cardwell et al., 1963; Lappala, 1978; Peckenpaugh et al., 1995; Szilagyi, 1999, 2001; Burt et al., 2002; Republican River GW Modeling Committee, 2003; Zeng and Cai, 2014; Demissie et al., 2014).

Our study encompasses both the SW and GW basins of FC between the Imperial and Culbertson stream gages (Fig. 1). The SW basin area is 985 km^2 and the GW basin area is 1308 km^2. The semi-arid area receives an average of 500 mm of precipitation per year with 75% of that precipitation occurring in the growing season from April to September (National Climatic Data Center (NCDC), 2011, http://www.ncdc.noaa.gov). Land use in 2009 includes 50% rangeland, 15% dry cropland, 16% terraced land, and 16% irrigated land with a total of 462 irrigation wells. The remaining 3% of land is open water, riparian vegetation, roads, and municipalities (provided in table format by T. Tietjen, personal communication, 2011). From 1928, or predevelopment period, more than 450 irrigation wells have been installed (NDNR Wells, 2011, http://dnrdata.dnr.ne.gov).

The topography influences the land use. Along the flat FC valley, the dominant land use is irrigated crops. The valley is surrounded by rolling hills and steep canyons covered by native rangeland and terraced dry cropland. The western parts of the region are relatively flat or gently sloping and have a mixture of dry cropland and irrigated land.

The principal aquifer in the study area is the High Plains Aquifer, where GW generally flows from west to east until it discharges to FC as baseflow. FC has a flow-through regime above Enders Reservoir and is naturally a gaining stream below Enders Reservoir; receiving all GW that flows into the basin. There is no GW flow out of the basin (Fig. 2).

FC flows from west to east and is the central water body in the SW network between Imperial and Culbertson. Stinking Water Creek, the only significant tributary of FC, flows south and empties into FC at Palisade, Nebraska. Enders Reservoir, located 5 km downstream from the Imperial stream gage on FC, was constructed

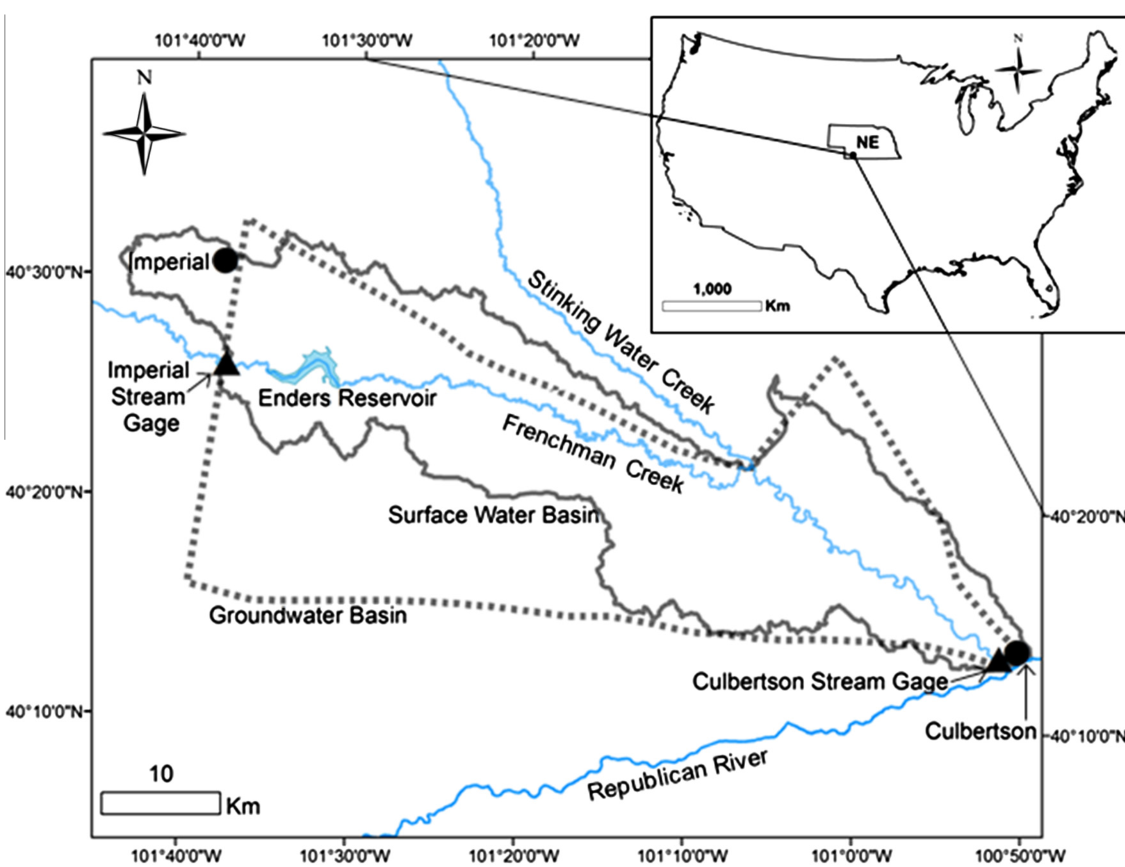

Fig. 1. The GW and SW basins of Frenchman Creek between the Imperial and Culbertson stream gages, Nebraska, USA.