Journal of Hydrology 409 (2011) 710–723

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Trend-outflow method for understanding interactions of surface water with groundwater and atmospheric water for eight reaches of the Upper Rio Grande

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A R T I C L E   I N F O

Article history:
Received 20 January 2011
Received in revised form 29 August 2011
Accepted 2 September 2011
Available online 10 September 2011
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Erwin Zehe, Associate Editor

Keywords:
Surface water
Atmospheric water
Groundwater
Inflow
Outflow
Trend-outflow

S U M M A R Y

Atmospheric water, surface water, and groundwater interact very actively through hydrologic processes such as precipitation, infiltration, seepage, irrigation, drainage, evaporation, and evapotranspiration in the Upper Rio Grande Basin. A trend-outflow method has been developed in this paper to gain a better understanding of the interactions based on cumulated inflow and outflow data for any river reaches of interest. A general trend-outflow equation was derived by associating the net interaction of surface water with atmospheric water as a polynomial of inflow and the net interaction of surface water with groundwater as a constant based on surface water budget. Linear and quadratic relations are probably two common trend-outflow types in the real world. It was found that trend-outflows of the Upper Rio Grande reaches, Española, Albuquerque, Socorro–Engle, Palomas, and Rincon are linear with inflow, while those of reaches, Belen, Mesilla and Hueco are quadratic. Reaches Belen, Mesilla and Hueco are found as water deficit reaches mainly for irrigated agriculture in extreme drought years.

1. Introduction

Ground water, surface water and atmospheric water are the three basic components of the hydrologic system that define hydrologic landscapes (Winter, 2001). These three components are included in a hydrologic budget, water budget, or water balance for a surface water system, groundwater system or hydrologic system in various terms (Todd and Mays, 2005). Because of the inseparability of the three waters in an open hydrologic system such as a surface water system, it is very important to understand interactions of surface water with groundwater and atmospheric water in assessment of a surface water system such as the Upper Rio Grande hydrologic system in this paper. The interaction of surface water with groundwater and atmospheric water in this study is more integrated than the interaction of surface water and groundwater (Winter, 1995; Woessner, 2000; Sophocleous, 2002; Diiwu, 2004) and the interaction of surface water and atmospheric water (Sene and Plinston, 1994; Zhang et al., 2008; Tani, 2008).

The methodology for analysis of the more integrated interactions of surface water with groundwater and atmospheric water employed in previous studies can be summarized in the following six categories.

1. Hydrologic budget: Anderholm (1987) showed groundwater system hydrologic budget for Socorro Basin in the Upper Rio Grande, including surface water inflow and outflow, groundwater inflow and outflow, recharge from precipitation, and consumptive uses by human and ecosystem as well as storage changes. Grubbs (1995) and Sacks et al. (1998) showed the relationship of lake water inflow and outflow with precipitation and evaporation and net groundwater flow for Lake Five-O (a seepage lake) in Bay county and for 10 lakes in ridge areas of Polk and Highlands counties, Florida, respectively, by using hydrologic budget.
2. Baseflow routing: Determination of groundwater baseflow from recession analysis of a streamflow hydrograph, commonly referred to as hydrograph separation (Hall, 1968; Wahl and Wahl, 1988; Rutledge, 1992; Winter, 1995) is a typical approach to analyzing the impact of the interactions of surface water with groundwater and atmospheric water on the hydrograph if the interaction is not impacted by human water management. Mathematical digital filtering of hydrograph (Nathan and McMahon, 1990; Chapman, 1991; Arnold et al., 1995; Arnold and Allen, 1999) has become an alternative method for assessing groundwater-stream interaction.

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doi:10.1016/j.jhydrol.2011.09.004

3. Channel flow coupled with groundwater flow and contribution from atmospheric water: Hantush (2005) achieved a closed-form solution that related channel reach discharge with stream-aquifer exchange rates and atmospheric water contribution (precipitation and evaporation etc.) for an assumed stream-aquifer system and channel geometry with 16 parameters during and between storm events.
4. Numerical method: In fact any interaction of surface water and groundwater occurs under a certain climate condition. Recharge package and Evapotranspiration package within MODLOW (McDonald and Harbaugh, 1988) can contain the climate information. Weeden and Maddock (1999) simulated the complex interaction of the Rio Grande, canals, and drains with groundwater in the Rincon valley area and Mesilla basin, New Mexico and Texas using a modified version of the stream Routing package (Prudic, 1989; Hamilton and Maddock, 1993; S.S. Papadopulos and Associates, 2007). Other related groundwater flow models include those presented by O'Brien and Stone (1983), Kernodle et al. (1986), Kernodle et al. (1987), Frenzel and Kaehler (1992), Kernodle (1992). Rodriguez et al. (2008) simulated stream-aquifer interactions in a drainage basin through full conservative coupling of HEC-RAS. Cohen et al. (2006) found that Lakes and wetlands respond differently across watersheds in respond to climate change through application of their HYDRAT2D, which is a new quasi-two-dimensional numerical model of unsaturated/saturated flow that fully couples the surface–subsurface hydrologic cycle, including evapotranspiration.
5. Statistical method: Bailly-Comte et al. (2008) presented time-series analyses for assessing karst/river interactions during flooding periods. Correlation and spectral analyses are used to understand how a linear time-invariant system for a modification of surface flows in the river dissipates or enhances the flood wave energy during a flood.
6. Chemical method: Mencio and Mas-Pla (2008) assessed groundwater-surface water interactions in urbanized Mediterranean streams through multivariate analysis of 12 hydrochemical constituents. Increasing salinity levels downstream in semiarid and arid rivers were probably the consequences of the interactions of surface water with atmospheric water (through evapotranspiration from irrigated agriculture) and salty groundwater (through discharge) (Hogan et al., 2007). Choi and Harvey (2000) employed a coupled water and solute (chloride) mass balance approach to find both groundwater discharge and recharge other than just the net exchange.

A new method presented in this paper is to associate trend statistics of inflow and outflow for a stream reach derived from its hydrologic budget, which yields findings of net interactions of surface water with groundwater and atmospheric water within the reach. A case study in the Upper Rio Grande Basin demonstrates its applications in assessment of net interactions of surface water with groundwater and atmospheric water.

2. Study site

The Rio Grande is one of the longest rivers flowing through the semiarid or arid southwestern United States. With its headwaters in southern Colorado, the Rio Grande travels 3058 km south through New Mexico and eventually discharges into the Gulf of Mexico. In Texas the Rio Grande forms the international boundary between the United States and Mexico (Fig. 1).

This study will focus on the upper 1294 km of the Rio Grande (the Upper Rio Grande Basin, Fig. 1) from the headwater in Colorado to Fort Quitman in Texas. It is a highly stressed arid-region river in which chronic water shortages threaten agricultural production and limit economic development (Johnson et al., 2001). The pattern of water use in the Upper Rio Grande Basin is typical of irrigated rivers in arid climates (Phillips et al., 2007). The study covers approximately 105,084 km^2 of drainage area. Currently, 89% of the available Rio Grande water supply is used to support 3700 km^2 (370,000 ha) of irrigated agriculture (Fig. 1) (Ellis et al., 1993) and the remaining for municipal, industrial and environmental uses. Flooding, furrow or basin irrigation methods are widely used in the study area. The Rio Grande water is released from the reservoirs (Cochiti Dam and Lake, Elephant Butte Reservoir and Caballo Reservoir, see Fig. 1) along the Upper Rio Grande and then diverted to farm fields through irrigation delivery networks. Groundwater is also pumped to supplement surface water shortage, especially during drought periods (Hibbs et al. 1997). At some locations where surface water is not available, groundwater serves as a sole supply for agricultural production.

The irrigated agriculture is developed in seven alluvial basins in the Upper Rio Grande Basin (Fig. 1): 1. San Luis, 2. Española, 3. Albuquerque, 4. Socorro – Engle, 5. Palomas, 6. Mesilla, and 7. Hueco (Hearne and Dewey, 1988; Wilkins, 1998; Anderholm, 2002; Phillips et al., 2007). The basin-fill deposits are unconsolidated to poorly consolidated sand and gravel interbedded or intermixed with clay and silt (Wilkins, 1998). The thickness of the deposits is about 792 m in San Luis Basin; 1500 m in the Albuquerque–Belen Basin; 488 m in Palomas Basin; 610 m in Engle Basin; 732 m in Mesilla Basin; 793 m in Hueco Basin (Wilkins, 1986). Rocks in this region primarily include volcanic basalt, shale and sandstone (including limestone, gypsum and salt), and intrusive igneous rocks and metamorphic rocks (Wilkins, 1998). Groundwater mainly occurs in these alluvial basins (Hearne and Dewey, 1988; Wilkins, 1998; Anderholm, 2002). The recharge of the groundwater in the alluvial basins is from the mountain-front recharge, precipitation deep infiltration and surface water infiltration (Wilkins, 1998). The potentiometric surface in the basin-fill is about 2377 m in San Luis Basin; 2012 m in Espanola Basin; 1585 m in the Albuquerque–Belen Basin; 1463 m in Socorro–Engle Basin; 1189 m in Mesilla Basin; and 1099 m in Hueco Basin above sea level (Wilkins, 1986).

The average precipitation is 513 mm/a in San Luis basin (from rain gauge station #52432) in Colorado. The precipitation ranges from 193 to 323 mm/a in basins from Española to Hueco (Bartolino and Cole, 2002; Climatography of the United States No. 20 1971–2000). Annual potential evapotranspiration ranges from 1046 to 1209 mm in the Española and Albuquerque basins (Bartolino and Cole, 2002) and from 2728 to 2865 mm in basins from Socorro–Engle to Hueco (S.S. Papadopulos and Associates, 2007). The Rio Grande carries an average of about 1233 million m^3/a of surface water into the Upper Rio Grande Basin (S.S. Papadopulos and Associates, 2000). During the drought periods in 1950's, the Rio Grande carried an average of about 777 million m^3/a in the Española basin.

Atmospheric water, surface water, and groundwater interact with each other very actively through hydrologic processes such as precipitation, infiltration, seepage, irrigation, drainage, evaporation and evapotranspiration in the Upper Rio Grande Basin. This three-water interactions study was based on long-term monthly flow data measured at nine gauge stations: Lobatos, Otowi, Albuquerque, San Acacia, Elephant Butte, Caballo, Leasburg, El Paso, and Fort Quitman (Fig. 1) since 1930's. Flow data availability and data gaps are shown in Table 1. The flow data was collected by the US Geological Survey under federal QA/QC requirements.

For this study, the Upper Rio Grande was divided into nine reaches simply according to the above nine gauging station locations as shown in Fig. 1: San Luis, Española, Albuquerque, Belen, Socorro–Engle, Palomas, Rincon, Mesilla, and Hueco. The last eight reaches were selected for analysis of three-water interactions by using the trend-outflow method developed in this paper.