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Stream-aquifer and in-stream processes affecting nitrogen along a major river and contributing tributary

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ABSTRACT

This study assesses the spatio-temporal patterns of water and nutrient mass exchange in a stream-riparian system of a major river and a contributing tributary in an irrigated semi-arid region. Field monitoring is performed along reaches of the Arkansas River (4.7 km) and Timpas Creek (2.0 km) in southeastern Colorado during the 2014 growing season, with water quantity and water quality data collected using a network of in-stream sampling sites and groundwater monitoring wells. Mass balance approaches were used to identify temporal and spatial trends in flow, nitrogen (N), and salinity in stream-aquifer exchange. In the Arkansas River, percent decrease of N concentration along the study reach averaged 36% over the period, with results from a stochastic mass balance simulation indicating a 90% probability that 44% to 50% of NO_3-N mass in the study reach (109–124 kg/day/km) was removed by in-stream processes between 1 September and 8 November. Results suggest that contact with organic-rich river bed sediments has a strong impact on N removal. A greater decrease in concentrations of NO_3-N along the reach during the low flow period suggests the effect of both in-stream processes and dilution by inflowing groundwater that undergoes denitrification as it flows through the riparian and hyporheic zones into the river. In contrast, N concentration decreases in the smaller Timpas Creek were negligible. Results for the Arkansas River also are in contrast with other large agriculturally-influenced rivers, which have not exhibited capacity to remove N at significant rates. Results provide important insights across spatial and temporal scales and point to the need for investigating nutrient dynamics in large streams draining agriculturally-dominated watersheds.

1. Introduction

Nitrogen (N) often is a primary limiting nutrient in marine and aquatic environments and a requirement in plant and animal nutrition (Mueller et al., 1992; Novotny, 2002). Excess amounts of these nutrients from agricultural and urban diffuse pollution cause eutrophication in rivers, lakes, estuaries, and coastal ocean waters leading to toxic algal blooms, oxygen depletion, and loss of aquatic life (Mueller et al., 1992). The primary diffuse agricultural sources of N and P are over-application of industrial fertilizers and manure (Novotny, 2002). Nutrients are of particular concern in irrigated agriculture due to fertilizer use increase as the demand for food increases (Monteagudo et al., 2012). For example, irrigated agriculture and food production doubled between 1964 and 1999 in conjunction with a sevenfold increase in the use of N based fertilizer and a threefold increase in P based fertilizer (Tilman, 1999).

Many studies have indicated that river riparian areas play a major role in controlling nutrient mass flux from groundwater and wetland systems to the in-stream environment (Cooper, 1990; Duff et al., 2008; Jacobs and Gilliam, 1985; Peterjohn and Correll, 1984). To quantify this control and nutrient mass exchange, water and nutrient fluxes between the aquifer and the stream must be determined. Loading of solute mass from the aquifer to the stream often is estimated by applying the conservation of mass principle to a river reach during a defined time period (Jain, 1996; Jaworski et al., 1992; Teissier et al., 2008). Measurements of solute concentrations and water flow are taken at the upstream and downstream ends of the reach to provide an estimate of in-stream solute mass flux into and out of the reach, with differences attributed to either fluxes that leave or enter the reach along its length or to changes in dissolved mass stored within the reach (Martin and Gates, 2014; Teissier et al., 2008).

For many studies the mass balance approach has involved extensive data collection on many physico-chemical characteristics of the stream reach, including groundwater and surface water contributions, chemical reaction rates in bed sediments and soil media, hyporheic exchange, soil properties, and vegetative cover (Duff et al., 2008; House and Warwick,

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1998; Teissier et al., 2008). Many of these studies, however, are limited in their spatial scales. Studies performed on large, wide rivers (20 to 100 m wide) are performed over long distances, typically tens of kilometers, but lack detailed examination of groundwater-surface water exchange, relying on existing stream gaging infrastructure for sampling locations and data (House and Warwick, 1998; Teissier et al., 2008). In contrast, studies performed on smaller streams typically are confined to short reaches. Duff et al. (2008) collected detailed surface and groundwater data in three stream reaches about 1.0 km long, ranging in width from 4 to 11 m and discharge rates between 0.14 m^3/s and 0.41 m^3/s, but did not expand their findings to a larger river. Published attempts to quantify nutrient mass exchange and associated groundwater-surface water interactions in large, wide rivers are lacking, as well as those comparing exchange water and nutrient dynamics between large and small streams within a given region.

This study seeks to monitor and quantify in-stream N loadings and concentrations, groundwater N loadings, and associated groundwater-surface water interactions within a major river and a contributing tributary in a semi-arid irrigated agricultural region. The Lower Arkansas River Valley (LARV) in southeastern Colorado is an alluvial, irrigated valley that suffers from high concentrations of nutrients and salts in the coupled groundwater-surface water system (Gates et al., 2009) due in large part to irrigation and drainage practices. Previous regional-scale (>500 km^2) data collection and flow and contaminant transport modeling efforts (Bailey et al., 2015b; Gates et al., 2009) have indicated that riparian areas play a significant role in controlling nutrient mass flux from the aquifer to the Arkansas River and its tributaries. However, the water and nutrient mass exchanges within the riparian-stream system have not yet been quantified. To accomplish this, two study reaches were selected and instrumented to be monitored through an entire growing season (April–November 2014). The study focuses on a 4.7 km reach of the main stem of the Arkansas River (average discharge = 12.3 m^3/s) and a 2.0 km reach of a major tributary, Timpas Creek (average flow = 1.7 m^3/s) to compare and contrast channel and riparian processes in streams of different scale. The field monitoring network consists of in-stream sampling sites and groundwater observation wells, with collected data used to quantify groundwater-surface interactions and a nitrate (NO_3-N) mass balance. A NO_3-N mass balance for the Arkansas River study reach is performed to quantify the net daily loading of NO_3-N mass to/from the study reach of the Arkansas River, with a stochastic simulation approach used to account for uncertainty in the input variables and parameters.

2. Materials and methods

This section provides a description of the two reach-scale studies and the methods and instrumentation used to collect physical, hydrologic, and water quality data and to perform a nitrate (NO_3-N) mass balance for the Arkansas River reach.

2.1. Study reaches

The location of the two study reaches within the so-called upstream study region (USR) of the LARV (Morway et al., 2013) is shown in Fig. 1A, with a detailed map of the Arkansas River reach shown in Fig. 1B and a detailed map of the Timpas Creek reach shown in Fig. 1C. The USR is so designated since it lies upstream of John Martin Reservoir, in contrast to a downstream study region (DSR) referenced in Section 3.2.3. The Arkansas River study reach is 4.7 km long, has an average width of 75 m, and is surrounded by a mixture of irrigated fields, fallowed fields, and pasture with moderate riparian vegetation composed primarily of cottonwood, willow, tamarisk, and a variety of grasses. Soils along this reach are mostly sand, loamy sand, and silty clay loam. Twenty-three years (1992–2014) of streamflow data for this site, which were collected by the United States Geological Survey (USGS) and the Colorado Division of Water Resources (CDWR), show an average discharge of 12.3 m^3/s and a peak discharge of 233 m^3/s. The Timpas Creek study reach (Fig. 1C) is 2.0 km long, has an average width of 7.0 m, and is surrounded by fallowed fields, pasture, and irrigated fields. Riparian vegetation is present at the southern end of the reach but is sparse at the middle and northern end of the reach. Streamflow data collected at this location since 1965 by the USGS

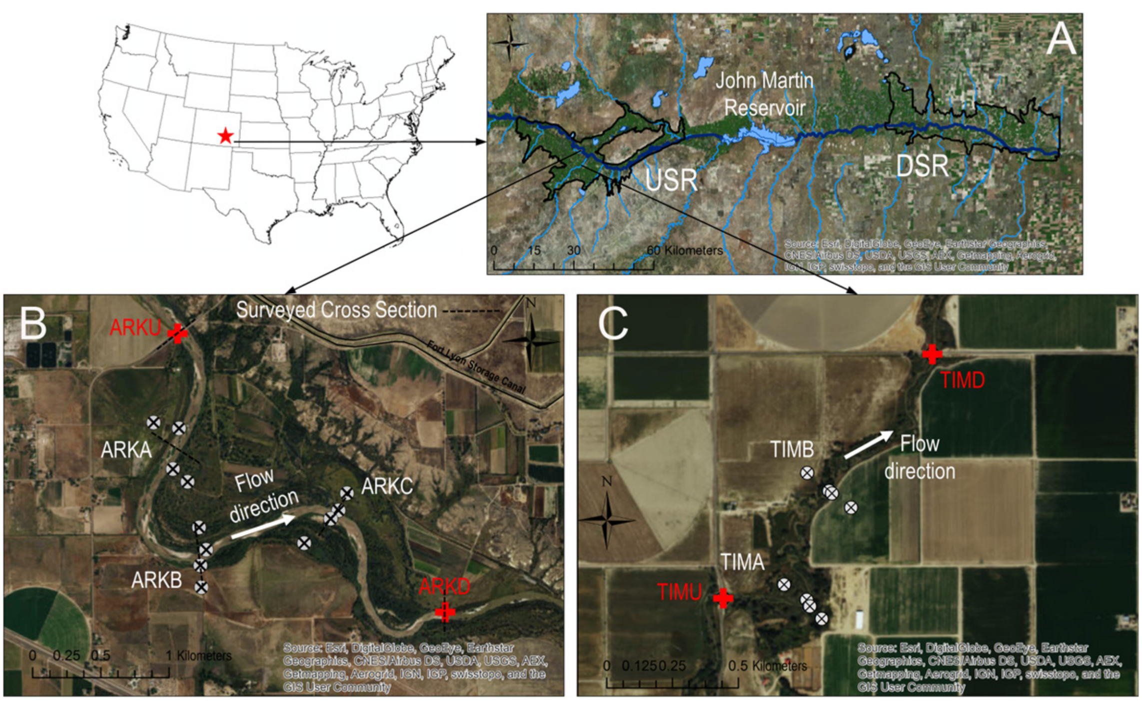

Fig. 1. (A) Lower Arkansas River Valley in southeastern Colorado, showing the locations of the Upstream Study Region (USR) and the Downstream Study Region (DSR); within the USR, short reaches along (B) the Arkansas River (4.7 km) and (C) Timpas Creek (2.0 km) are the focus of this study. Red crosses indicate stream gaging locations, and mark the upstream and downstream locations of each study reach; white circles indicate locations of groundwater monitoring wells in the riparian areas. The surveyed cross sections for the Arkansas River study reach are also shown in (B).