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Uncertainty in mass-balance estimates of regional irrigation-induced return flows and pollutant loads to a river

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ABSTRACT

Study region: Arkansas River in Colorado, east of the Rocky Mountains.
Study focus: Nonpoint source (NPS) flows and solute loads from irrigated lands can markedly shape the water environment. Describing their diffuse and variable characteristics over vast regions is critical to assessing compliance with regulatory and performance standards for streams, yet is particularly ambiguous. The nature and degree of this uncertainty is addressed here using a stochastic mass balance of return flow rates and solute loads along two reaches of Colorado's Arkansas River Valley. Measurement error, spatiotemporal variability, and trends in flow and concentration variables are considered, allowing assessment of return flow rates and mass loading rates of total dissolved solids, sulfate, selenium, uranium, and nitrate using probability intervals and other statistics.
New hydrological insights for the region: Time series of the statistics of daily NPS return flows and mass loading rates, within a four-year period, are estimated and discussed. Coefficients of variation in NPS mass loading rates range from about 32% to 134% for the five solutes considered. There is an estimated 95% probability that mass loading rates lie within a range equivalent to 109% to 405% of the temporally-averaged mean value, depending on the solute and the river reach. The sizeable uncertainty quantified in these findings should temper the interpretation, modeling, regulation, and management of irrigation-induced NPS loading in this and similar settings.

1. Introduction

Sediments and solutes in waters that traverse the surface and subsurface across broad agricultural landscapes are a leading contributor to stream pollution (USEPA, 1996, 2009, 2017, Novotny, 2003). Consequently, the management of nonpoint-source (NPS) pollution from agricultural lands has been a topic of intense study over the last two decades and is likely to consume much attention and resources in the decades to come (Xiang et al., 2017). For example, USEPA regulations for the adoption of total maximum daily loads (TMDL) to meet water quality standards in streams requires both the voluntary management of NPS loads as well as the compliance of point source loads with National Pollution Discharge Elimination System (NPDES) permits (Hoornbeek et al., 2013; USEPA, 2018). However, the sheer expanse and variability of diffuse NPS flows and their solute loads make them difficult to characterize and control. Estimating this ambiguity inherent to describing and predicting NPS loads is important to management decisions and investments. Walker and Selman (2014) recently highlighted this by citing the risk and uncertainty faced by point

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dischargers who wish to lower the cost of water treatment needed to comply with NPDES permits through trades with agricultural producers to reduce NPS loads. Determining just how much NPS return flow and solute loading are actually occurring along a river and then estimating the likelihood that a given course of action would reduce them, and by how much, can be elusive. Gathering necessary field data over the large scales associated with NPS flow and pollution assessment is difficult and resource-intensive. Mobilizing expansive field monitoring expeditions is time-consuming and costly. Collecting, preserving, and analyzing water samples for sediment and solute concentrations is especially demanding. Hence, available data often are sparse and intermittent, and significant uncertainty is cast over them by the considerable spatiotemporal variability that is typical of NPS flow and solute properties. Moreover, every individual measurement that is made at a given location and a given point in time is subject to error due to limitations in equipment and methodology. One strategy that can be used to increase information availability is to estimate relationships between those properties that can be more easily and frequently measured and those that are more difficult or expensive to measure. For example, regression equations that relate solute concentrations to flow and in-situ water quality parameters (e.g. electrical conductivity, pH) can be developed to allow such concentrations to be estimated at locations where flow and in-situ measurements are available but where water samples are not. However, the ambiguity in such regression models must also be accounted for.

River mass balance methods using field data on flows and concentrations can be beneficial in characterizing the magnitude and extent of existing (baseline) NPS return flows and pollutant loads along a river. They also can guide the calibration and testing of process-based distributed parameter (DP) models of the larger stream-aquifer system that encompasses the river. In such cases, the river NPS inputs (and outputs) from (or to) the adjacent landscape and groundwater aquifer, calculated using a river system mass balance, can be compared to landscape and aquifer NPS outputs (inputs) to (from) the river computed using the DP governing equations for flow and mass transport processes within the landscape-aquifer system. Anderson et al (2015) and Hill and Tiedeman (2007) point out that it is advisable that DP groundwater models be calibrated against estimates of groundwater flow, though such estimates are often uncertain, rather than solely against estimates of groundwater head. The approach of using a river mass balance to estimate groundwater flow and overland flow, in exchange with rivers, to calibrate DP models is most suitable under the following conditions:

(1) River mass balance estimates are used as targets for DP model-simulated values that are influenced predominately by landscape and aquifer system flow and transport processes, thereby promoting a higher degree of independence between the reciprocal computed inputs and outputs of the landscape-aquifer system and the adjacent river system; and
(2) River mass balance estimates are not the sole targets for DP model calibration, but are used in conjunction with other data, like groundwater levels, groundwater concentrations, river concentrations, evapotranspiration rates; etc.

Several investigators have used a mass balance approach to estimate NPS return flows and solute mass loading along a stretch of a river (Jaworski et al., 1992; Jain, 1996; Jha et al., 2005; Jain et al., 2007). Such studies commonly neglect the effect of storage changes and internal sinks and sources (associated with redox reactions, adsorption and settling, volatilization, etc.) within a river reach to calculate unknown mass loading to or from the reach as the difference between measured in-stream mass load fluxes at the downstream and upstream ends. Other researchers have used a variety of statistical methods to account for uncertainty, primarily related to the estimation of in-stream nutrient mass load fluxes, often near the outlet of a watershed. Harmel et al. (2006) examined uncertainty in several procedural categories for measuring key properties used in the calculation of in-stream solute mass fluxes: streamflow measurement, collection of water quality samples, sample preservation and storage, and laboratory analysis. Cumulative error within each category was estimated using a root mean square error propagation method and was found to be substantial under typical conditions. Jiang et al. (2014) used an error propagation method to account for flow and concentration measurement uncertainty, as well as uncertainty in interpolating between measurements, in describing the overall uncertainty in calculating in-stream river nitrate-nitrogen load fluxes. Rode and Suhr (2007) provide an assessment of component uncertainties in estimating concentrations and loads of not only nutrients but also some heavy metals and biological compounds at in-stream locations. Mueller-Price and Gates (2008) expanded the consideration of uncertainty from that associated with the estimation of in-stream mass load fluxes to that associated with the mass balance estimation of nonpoint source loads returning along river reaches from the landscape and aquifer. They used a stochastic mass balance to account for multiple sources of uncertainty common to describing NPS pollution in an application to irrigated regions of Colorado's Lower Arkansas River Valley (LARV).

Employing an approach similar to Mueller-Price and Gates (2008), the present paper uses a more extensive data set to consider both NPS flows and solute loads for two representative river reaches in the LARV and estimates them as stochastic time series of daily rates rather than as uncertain quantities within discrete multi-day sampling periods. This allows an examination of seasonal variability in estimated measures of uncertainty. Also, the time period considered here extends four years beyond the drought-affected years reported by Mueller-Price and Gates (2008), permitting a comparison of the conditions within the two periods. Moreover, the number of considered solutes is expanded here to include sulfate (SO_4), uranium (U), and nitrate (NO_3) as well as the previously-considered total dissolved solids (TDS) and selenium (Se). A variety of available field data are used to reconstruct estimates of stream flows and concentrations along with diffuse flows and loads that return from the irrigated landscape and aquifer. These data include gaged stream flows and water levels (main stem and tributaries), gaged canal diversions, surveys of stream cross sections, climatic variable records, measurements of electrical conductivity, EC (as specific conductance at 25 °C), and intermittent water quality samples.

Managing NPS pollution in Colorado's LARV has reached a critical stage. The Colorado Department of Public Health and Environment (CDPHE) is looking to administer TMDLs for Se, especially for the wastewater treatment plant of the City of Pueblo, due