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# Quantifying wetland–aquifer interactions in a humid subtropical climate region: An integrated approach

Itza Mendoza-Sanchez [a,b], Mantha S. Phanikumar [a,*], Jie Niu [a], Jason R. Masoner [c], Isabelle M. Cozzarelli [d], Jennifer T. McGuire [e]

[a] Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA
[b] Escuela Superior de Ingeniería y Arquitectura, Instituto Politécnico Nacional, Mexico City 07740, Mexico
[c] US Geological Survey, Oklahoma City, OK 73116, USA
[d] US Geological Survey, Reston, VA 20192, USA
[e] Department of Biology, University of St. Thomas, St. Paul, MN 55105, USA

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SUMMARY

Wetlands are widely recognized as sentinels of global climate change. Long-term monitoring data combined with process-based modeling has the potential to shed light on key processes and how they change over time. This paper reports the development and application of a simple water balance model based on long-term climate, soil, vegetation and hydrological dynamics to quantify groundwater–surface water (GW–SW) interactions at the Norman landfill research site in Oklahoma, USA. Our integrated approach involved model evaluation by means of the following independent measurements: (a) groundwater inflow calculation using stable isotopes of oxygen and hydrogen ($^{16}O, ^{18}O, ^{1}H, ^{2}H$); (b) seepage flux measurements in the wetland hyporheic sediment; and (c) pan evaporation measurements on land and in the wetland. The integrated approach was useful for identifying the dominant hydrological processes at the site, including recharge and subsurface flows. Simulated recharge compared well with estimates obtained using isotope methods from previous studies and allowed us to identify specific annual signatures of this important process during the period of study (1997–2007). Similarly, observations of groundwater inflow and outflow rates to and from the wetland using seepage meters and isotope methods were found to be in good agreement with simulation results. Results indicate that subsurface flow components in the system are seasonal and readily respond to rainfall events. The wetland water balance is dominated by local groundwater inputs and regional groundwater flow contributes little to the overall water balance.

## 1. Introduction

The hydrologic regime of a wetland is the result of a complex interplay between climate and wetland characteristics (Winter, 1998). To evaluate the capacity of a wetland to degrade contaminants, it is necessary to conduct long term studies that include observations and modeling at different scales in time and space. Quantifying the responses of an aquifer–wetland system to climate, soil and vegetation is useful to understand a wide range of natural processes such as the intensity and duration of groundwater recharge, the extent and location of aquifer–wetland interfaces, the origin of contaminants entering or exiting the wetland, and the dominant hydrological processes in riparian ecosystems. Interactions between GW–SW may be a dominant component of the water budget since inland wetlands are usually connected with the groundwater system (Winter, 1998). A number of studies examined the hydrologic regime of wetlands in the past (Choi and Harvey, 2000; Doss, 1993; Devito et al., 1996; Eser and Rosen, 1999; Hunt et al., 1999; LaBaugh et al., 1998; Mills and Zwarich, 1986; Ramberg et al., 2006). Earlier studies have quantified GW–SW fluxes based on field measurements or field estimations of each component of the water budget (Choi and Harvey, 2000; Doss, 1993; Devito et al., 1996; Mills and Zwarich, 1986; Ramberg et al., 2006). LaBaugh (1986) concluded that for accurate quantification of hydrologic components it is necessary to measure all components including GW contributions. Long-term field measurement of water budget components is demanding due to the amount of resources needed to accurately measure all components. On the other hand climatic variables are available for long periods of time because they are routinely measured at weather stations (e.g., NOAA or USGS). Since wetland hydrologic regimes result from an interplay of climate and wetland characteristics

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* Corresponding author. Address: 1449 Engineering Research Court, Room A130, Michigan State University, East Lansing, MI 48824, USA. Tel.: +1 (517) 432 0851; fax: +1 (517) 355 0250.

*E-mail addresses:* imendozas@ipn.mx (I. Mendoza-Sanchez), phani@msu.edu (M.S. Phanikumar), niujie@msu.edu (J. Niu), jmasoner@usgs.gov (J.R. Masoner), icozzare@usgs.gov (I.M. Cozzarelli), jtmcguire@stthomas.edu (J.T. McGuire).

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(Winter, 1998), it is appealing to rely on readily available climatic measurements for long-term studies.

Simple models based on the concepts of mass balance, storage and flow rates, called bucket models or lumped parameter models, are attractive due to their simplicity and their ability to describe fundamental hydrological processes. Groundwater investigations of contaminated sites often use distributed, multi-dimensional models (e.g., Phanikumar et al., 2005) rather than bucket models which are more common in rainfall runoff investigations. Distributed models need extensive data and detailed site characterization which can be expensive and time consuming. Some studies have used numerical groundwater flow models to quantify GW–SW interactions (Green, 1991; Krabbenhoft et al., 1990; Lapen et al., 2005; Loheide et al., 2009; Poiani et al., 1996). These models require extensive installation of wells and piezometer readings at different depths for the area of study (Choi and Harvey, 2000). A network of monitoring wells is generally not available at a number of sites where long-term evaluation of GW–SW interactions is not the primary objective. For these sites, it would be attractive to develop a simple long-term bucket model describing fundamental hydrological processes that does not require extensive field data (e.g., detailed subsurface heterogeneity).

Bucket models have been used extensively in the past. For example, Muneepeerakul et al. (2008) used a mechanistic model linking dynamics of plant growth, soil moisture, and water table fluctuations, to understand how hydrologic and vegetation processes in natural wetlands are altered in response to rainfall variability. Krasnostein and Oldham (2004) used a bucket model to predict water storage in wetlands, and to evaluate the water balance of a permanently inundated wetland. Farmer et al. (2003) used a bucket model to conduct a "downward" analysis to explore climate and landscape interactions that cause differences in water balance between different catchments. While state variables in some process-based bucket models described observed data reasonably well (Krasnostein and Oldham, 2004; Farmer et al., 2003), to the best of our knowledge the flux estimates were not evaluated using independent field observations. The specific objectives of the present paper are therefore: (1) to quantify GW–SW interactions and fluxes in a wetland–aquifer system at a local-scale; (2) to understand the relative importance of local groundwater flow, recharge, and ET over time; and (3) to integrate long-term (e.g., annual and decadal scale) model results with short-term (e.g., daily) measurements to evaluate the importance of vegetation in different environments (e.g., catchment, wetland) on ET fluxes. We developed a simple bucket model of wetland aquifer interactions and tested its ability to describe key hydrologic fluxes using different types of data including GW–SW fluxes, and recharge and evapotranspiration (ET) rates on a daily scale. The model uses readily available meteorological data as input and allows quantifying groundwater inflow and outflow to and from the wetland, as well as their seasonal variability.

## 2. Site description

To test the bucket model we use field data collected at the Norman Landfill Research Site. The site is ideal for this research in that extensive geochemical data, evaporation rates, piezometric data and GW–SW fluxes have been measured at the site (Cozzarelli et al., 2011; Masoner and Stannard, 2010). The site is located in Cleveland County, Oklahoma, USA (Fig. 1) and is on the south side of the City of Norman and includes a former municipal landfill that received wastes from 1922 to 1985, at which time it was closed and capped with locally obtained clay, silt, and sand materials. The landfill was not lined and a leachate plume extends downgradient from the landfill in the direction of regional groundwater flow (Becker, 2001), which is towards the wetland and the Canadian River. The climate of the site is between humid subtropical and semi-arid, with an average annual temperature of 16 °C, and average maximum and minimum temperatures of 23 °C and 9 °C respectively during the period 1997–2009. The hottest month is July with an average temperature of 28 °C. The coldest month is January with an average temperature of 3.5 °C and the average annual precipitation is 88 cm.

As reported by Cozzarelli et al. (2011), the Canadian River alluvium is 10–12 m thick and predominantly composed of fine- to medium-grained sand beds with interbedded, discontinuous layers of clayey silt and gravel at depths between 3 and 5 m below the ground surface. Measured hydraulic conductivity of the unconfined alluvial aquifer ranges from $8.4 \times 10^{-7}$ to $2.8 \times 10^{-4}$ m/s with a median value of $6.6 \times 10^{-5}$ m/s (Scholl and Christenson, 1998). The aquifer is underlain by the Hennessy Group, a shale and mudstone confining unit. A potentiometric surface map of the area made in 1995 (10 years after the landfill was capped) shows regional groundwater flow toward the Canadian River with a hydraulic gradient of about 1.4 m/km south of the landfill (Scholl and Christenson, 1998).

The present study focused on local interactions between groundwater and the wetland. The specific study area includes the area of the wetland (actual area inundated) of 8800 $m^2$ and the riparian catchment area of 38,755 $m^2$ shown in Fig. 1. The wetland is approximately 700 m long and 15–25 m wide and is 50–100 m from the southern toe of the landfill. The wetland is situated in a previous location of the main river channel and is aligned perpendicular to the groundwater flow path. Water level in the wetland is an expression of the regional water table with the wetland pool elevation usually being lower than the up-gradient groundwater elevation. Dry periods have been observed during summer when the water table drops below the wetland bottom. It has been reported that the wetland has no apparent surface-water sources and is mainly fed by groundwater discharge and precipitation (Cozzarelli et al., 2011; Masoner et al., 2008; Báez-Cazull et al., 2007). The wetland system is a shallow stream, with ponded areas or wetlands caused by beaver dams. A road that intersects the upstream section of the wetland (Fig. 1) acts as a dam that limits surface flow from upstream ponded areas. At the down gradient end of the wetland there is a beaver dam, isolating the wetland to pools downstream. Seepage measurements showed that the groundwater connectivity along the direction of the wetland is insignificant. Cozzarelli et al. (2011) reported that the hydrologic conditions at the site have created a leachate plume that migrates underneath the wetland toward the Canadian River and also interacts with the wetland (see Fig. 2 in Cozzarelli et al. 2011). Therefore in this study it is assumed that groundwater flow and precipitation are the dominant inputs into the wetland.

The riparian area near the landfill is densely vegetated with shallow-rooted vegetation, also found in the wetland area and deep-rooted vegetation dominated by at least three species of phreatophytes namely: willow, cottonwood, Eastern red cedar, and salt cedar (Burgess, 2004; Scholl et al., 2005). The wetland vegetation is composed of a mixture of native and introduced species including: common reed, western ragweed, Bermuda grass, Johnson grass, bundleflower, Ravenna grass, giant cane, sandbar willow and black willow (Burgess, 2004; Masoner et al., 2008; Zume et al., 2006).

## 3. Materials and methods

Readily available meteorological data and initial water levels were used as inputs to the model described in the next section. Measured soil properties were used to constrain parameters. Evaporation pan data were used for comparison of this flux with