Journal of Hydrology 529 (2015) 240–256

Contents lists available at ScienceDirect

Journal of Hydrology

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

Geographically isolated wetlands and watershed hydrology: A modified model analysis

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 14 July 2015
Accepted 25 July 2015
Available online 31 July 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Toffolon, Associate Editor

Keywords:
Geographically isolated wetlands
Non-floodplain wetlands
Non-adjacent wetlands
Hydrologic connectivity
Watershed model
Soil and Water Assessment Tool (SWAT)

SUMMARY

Geographically isolated wetlands (GIWs) are defined as wetlands that are completely surrounded by uplands. While GIWs are therefore spatially isolated, field-based studies have observed a continuum of hydrologic connections between these systems and other surface waters. Yet few studies have quantified the watershed-scale aggregate effects of GIWs on downstream hydrology. Further, existing modeling approaches to evaluate GIW effects at a watershed scale have utilized conceptual or spatially disaggregated wetland representations. Working towards wetland model representations that use spatially explicit approaches may improve current scientific understanding concerning GIW effects on the downstream hydrograph. The objective of this study was to quantify the watershed-scale aggregate effects of GIWs on downstream hydrology while emphasizing a spatially explicit representation of GIWs and GIW connectivity relationships. We constructed a hydrologic model for a ~202 km^2 watershed in the Coastal Plain of North Carolina, USA, a watershed with a substantial population of GIWs, using the Soil and Water Assessment Tool (SWAT). We applied a novel representation of GIWs within the model, facilitated by an alternative hydrologic response unit (HRU) definition and modifications to the SWAT source code that extended the model's "pothole" representation. We then executed a series of scenarios to assess the downstream hydrologic effect of various distributions of GIWs within the watershed. Results suggest that: (1) GIWs have seasonally dependent effects on baseflow; (2) GIWs mitigate peak flows; and (3) The presence of GIWs on the landscape impacts the watershed water balance. This work demonstrates a means of GIW simulation with improved spatial detail while showing that GIWs, in-aggregate, have a substantial effect on downstream hydrology in the studied watershed.

1. Introduction

"Geographically isolated" wetlands (GIWs) are wetland systems typically surrounded by uplands. These systems characteristically have limited or unobservable surface hydrologic connections with other surface water bodies (Tiner, 2003; Winter, 2003). GIWs support an array of ecological processes including surface water storage and recharge (Pomeroy et al., 2014), watershed biogeochemical cycling (Creed et al., 2003), and biodiversity (Leibowitz and Nadeau, 2003). Despite these benefits, approximately 30–90% of the spatial extent of global wetlands – including GIWs and wetlands in general – has been lost to anthropogenic activities (Junk et al., 2013). Further, regulatory protection for these systems has been challenged within the United States. A ruling from a 2001 US Supreme Court case, the Solid Waste Agency of Northern Cook County (SWANCC) vs. US Army Corps of Engineers (531 US 159 2001) held that "isolated," intrastate, non-navigable waters could not be regulated under the Clean Water Act as "waters of the United States" based solely on the presence of migratory birds (Downing et al., 2003). The subsequent Rapanos vs. US Army Corps of Engineers ruling ("Rapanos," 547 US 715 2006) determined that protection for these systems would be afforded only if the waters significantly affect, either alone or in combination with similarly situated waters, navigable-in-fact waters – waters for which regulatory protections are undisputed. These decisions, the loss of wetlands globally, and limited watershed-scale studies on GIW systems, have led to a substantial research need for methods capable of quantifying the magnitude, extent, and duration of

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http://dx.doi.org/10.1016/j.jhydrol.2015.07.039
0022-1694/

GIW connections with downstream waters. A step toward addressing these key questions involves quantifying the potential aggregate effects of GIWs on downstream hydrographs.

Our understanding of GIWs and the processes governing their connective relationships with downstream surface waters are informed, in part, by previous work examining the hydrologic effects of wetlands in general (e.g., Vining, 2002; Bullock and Acreman, 2003; Quinton et al., 2003; Acreman and Holden, 2013). However, few studies have provided targeted evaluations of the effects of GIWs on downstream hydrology (but see, as examples, Leibowitz and Vining, 2003; Wang et al., 2008; Viger et al., 2010; Almendinger et al., 2011; Wilcox et al., 2011; McLaughlin et al., 2014; Pomeroy et al., 2014). Models using available long-term data – or supplementing current understanding in the absence of such abundant data – are important tools in quantifying aggregate GIW hydrologic effects. Watershed-scale simulation models show clear potential to quantify these effects due to their explicit representation of hydrologic and hydraulic dynamics (Golden et al., 2014).

A limited number of mechanistic modeling-based studies have provided important assessments of the influence of GIWs and/or landscape depressions on watershed-scale hydrologic processes, primarily using conceptual landscapes and/or lumped parameter modeling approaches. McLaughlin et al. (2014), for example, depicted GIWs within an idealized landscape by coupling soil moisture, upland water table, and wetland stage models. They found that increasing total wetland area and decreasing individual wetland size decreased landscape water table variation. Further, the number of wetlands within the landscape was shown to significantly affect wetland–groundwater interactions. Pomeroy et al. (2010) and Pomeroy et al. (2014) utilized the Prairie Hydrological Model (PHM), a modified version of the Cold Regions Hydrological Model (Pomeroy et al., 2007), to simulate the hydrologic influence of prairie pothole depressions within the Canadian plains. Pomeroy et al. (2014) incorporated a conceptual, network-based model of synthetic wetlands parameterized via the separate physically-based Wetland Digital Elevation Model Ponding Model (Shook et al., 2013; Pomeroy et al., 2014). Pomeroy et al. (2014) demonstrated that removal of all simulated depressions within the PHM resulted in a 55% increase in total flow volumes throughout their simulation period. Additionally, Vining (2002) utilized the Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1995) to simulate prairie pothole depressions within the Starkweather Coulee basin, North Dakota, USA. The PRMS model depicts closed basin depressional storage via an aggregate representation of all depressional storage within a simulated hydrologic response unit (HRU) where a constant proportion of HRU uplands drains to the depression reservoir (Vining, 2002; Viger et al., 2010). Vining (2002) simulated a 49% decrease in streamflow by increasing the quantity of closed-basin depressional area within the utilized PRMS model. Viger et al. (2010) similarly applied PRMS in the Upper Flint River basin, Georgia, USA and determined that wetlands decrease daily streamflow values for all but the lowest of streamflow values.

Additional studies have evaluated the watershed-scale hydrologic effects of GIWs and/or landscape depressions using the Soil and Water Assessment Tool (SWAT), a widely-utilized hydrologic model (Neitsch et al., 2009; Gassman et al., 2014). Almendinger et al. (2011), for example, applied SWAT to examine the influence of closed-basin depressional areas upon hydrologic flows and sediment yields in the Willow River watershed, Wisconsin, USA and Sunrise River, Minnesota, USA. Almendinger et al. (2011) characterized wetlands at the subbasin scale using the model's wetland and pond representations. SWAT subbasins are composed of a series of HRUs simulated as de-spatialized entities such that a constant, uniform fraction of each HRU is routed to the wetland or pond reservoir. Wang et al. (2008) designed and tested a "hydrologic equivalent wetland" (HEW) representation for SWAT to evaluate wetland hydrologic functions within the Otter Trail River Watershed in Minnesota, USA. A HEW is defined using calibrated parameters that describe the aggregate functional attributes of wetlands at the subbasin-scale. Wang et al. (2008) determined that, compared to a SWAT model with no wetland representation, HEW-model simulations had substantially decreased probabilities of streamflow exceedance, particularly for higher streamflow values. Other SWAT applications have utilized the model's "pothole" representation and found that the inclusion of depressional areas in simulations improves model performance in landscapes dominated by these systems, such as in the Midwestern Corn Belt, USA, and the Northern lowlands of Germany (Du et al., 2005, 2006; Kiesel et al., 2010). The pothole representation of wetlands provides improved spatial resolution in SWAT because it is simulated at the HRU-scale (compared to alternative subbasin-scale wetland representations) yet is nonetheless limited by the lumped parameterization and processing of HRUs within the model. These studies provide useful insights to the hydrologic effects of GIWs at broad spatial scales using conceptual or spatially-aggregated GIW representations. The development of spatially explicit representations of GIWs and their downstream connectivity dynamics is a particularly important research direction that capitalizes on these previous efforts to advance our understanding of GIWs and their hydrological effects. Furthermore, such critical work is needed in Coastal Plain watersheds, and indeed other areas with abundant wetland resources, as only limited studies on GIW connectivity and downstream hydrological effects have occurred yet abundant GIWs and GIW complexes exist (e.g., Golden et al., 2015).

The objective of this study was to assess the aggregate hydrologic effects of GIWs on downstream hydrology in a Coastal Plain watershed of the Southeastern United States. We placed particular emphasis on developing a more spatially explicit representation of GIWs and GIW-watershed connectivity relationships while quantifying these effects. We satisfied our objective via a twofold approach. Firstly, we constructed a SWAT model to represent a $\sim$202 km^2 drainage basin in the Nahunta Watershed, North Carolina, USA. We modified the representation of GIWs within the SWAT model to incorporate additional spatial detail in depiction of GIWs and GIW connectivity relationships. The modified SWAT model: (1) Explicitly incorporated a spatial data layer of the basin's GIWs to apply an alternative HRU definition; and (2) Allowed for subsurface inflow routing to our modified GIW representations as an extension of the SWAT model's "pothole" representation. We then calibrated the modified SWAT model to USGS streamflow observations at the watershed outlet. The modified and calibrated SWAT model constituted our "Baseline model." Secondly, we executed a series of scenarios that removed all or sub-sets of GIWs from the Baseline model to assess changes in watershed water balances and the downstream hydrograph relative to the Baseline simulation. Our approach and results advances current scientific understanding of the watershed-scale hydrologic impacts of GIWs and demonstrates a more spatially explicit representation of GIWs in models for future GIW-based hydrologic research in other watersheds and systems.

2. Methods

2.1. Study area and wetland identification

The study area watershed was delineated by United States Geological Survey (USGS) station #02091000 at Nahunta Swamp near Shine, North Carolina, USA (Fig. 1A). The Nahunta watershed covered approximately 202 km^2 and was dominated by agriculture