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Improving global flood and drought predictions: integrating non-floodplain wetlands into watershed hydrologic models

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1. Introduction

The world's climate is changing rapidly. Future model projections suggest amplified storm intensities and frequencies across the globe, increasing human exposures to flooding (Blöschl *et al* 2017). Further, warming temperatures are leading to new and expanded periods and locations of extreme drought and water scarcity (Gosling and Arnell 2016). Projecting the extent of flood and droughts in response to a changing climate requires robust hydrologic models. These models must consider not only in-stream hydraulics but also watershed hydrologic processes—such as changes in soil and surface water storage, evapotranspiration, groundwater recharge, and runoff in the landscape draining to streams and rivers.

Long-standing challenges remain in hydrologic modeling, including (a) improving the specificity and fidelity of process-representations in hydrologic models and (b) parsimoniously representing small spatial heterogeneities across the landscape, their interactions, and their effects on large watershed-scale fluxes, e.g. streamflow (Wood *et al* 1988, Clark *et al* 2017). Non-floodplain wetlands (NFWs), wetlands outside of the floodplain and embedded within uplands (Mushet *et al* 2015), range in size up to ~5 ha (Lane and D'Amico 2016) and are primary examples of heterogeneous landscape areas of variable water storage and fluxes that have been traditionally ignored in watershed hydrologic models (Golden *et al* 2014, Jones *et al* 2019).

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Yet NFWs are often abundant across many landscapes (figure 1), making their water storage and cycling fundamental to estimating a watershed's water balance (Rains *et al* 2016, Lee *et al* 2018). However, even in areas of lower densities, missing this component of water balances could potentially lead to disproportionately large model errors (Rajib *et al* 2020). Consequently, integrating the hydrological processes of NFWs into watershed-scale hydrologic models is needed to minimize uncertainties in simulating the frequency, magnitude, and duration of floods and droughts into the future (Martin *et al* 2012, Shook *et al* 2021).

How do NFWs yield such an influence on watershed hydrologic dynamics (e.g. streamflow and evapotranspiration) and thereby the timing and magnitude of floods or droughts? NFWs receive water via overland or subsurface flows from upgradient areas and can store this water over long time periods (effectively serving as *hydrologic sinks* that contribute to groundwater recharge). They also allow temporary retention and delayed releases to surface waters and groundwater (creating *hydrologic lags*), and cycle through evapotranspiration, soil seepage, and overland and shallow groundwater discharge processes netting outgoing connections to other water bodies (becoming *hydrologic sources*; (Rains *et al* 2016)).

When cumulatively considering NFWs mosaicked and networked throughout a watershed, all three functions affect the amount and timing of downstream water transport and thereby decrease flood magnitudes (Cohen *et al* 2016). NFWs have therefore been described as watershed 'gatekeepers' because of their potential for attenuating rapid downstream event-driven flows (Phillips *et al* 2011)—and conversely their loss results in increased peak, or flood, flows (Fossey *et al* 2016, Evenson *et al* 2018, Ameli and Creed 2019).

Through sink, source, and lag functions NFWs therefore moderate flood and drought conditions across watersheds (Fossey and Rousseau 2016, Evenson *et al* 2018, Ameli and Creed 2019, Zeng and Chu 2021). In systems with a dense distribution of NFWs compared to their watershed's size (e.g. the Prairie Pothole Region of North America, (Lane and D'Amico 2016)), NFWs are key arbiters of the antecedent wetness of watersheds (Lee *et al* 2020, Cui *et al* 2021): the amount of water stored on the land's surface and in its soils. Ignoring these potentially large watershed-scale hydrologic sinks, lags, and sources —to the atmosphere via evapotranspiration and downgradient via overland or subsurface flows to other water bodies—in watershed hydrologic models increases model uncertainty and minimizes the accuracy of predicted flood and drought responses to future climate conditions.

In fact, the underrepresentation of NFWs in hydrologic models can lead to overprediction of floods (figure 2) and droughts. For example, when NFWs were integrated into a watershed model for the Pipestem River of North Dakota, United States (US), the system does not reach 50 or 100 year flood levels (figure 2). However, when this additional water stored on the landscape via NFWs is ignored, simulations suggest that 50 and 100 year floods will occur during the 5 year model time frame. Not considering NFWs in watershed models, therefore, could be consequential for accurate future infrastructure planning and for stream and stream corridor restoration activities, where flood frequency and flood interval projections are required.

Because these ‘little things mean a lot’ (McLaughlin *et al* 2014) and can change model outcomes when ignored (e.g. Rajib *et al* 2020), we propose a necessary re-envisioning and redevelopment of conventional watershed-scale hydrologic models to specifically incorporate NFW hydrology and hydraulics—including surface storage volumes, water residence times, and drainage areas. This is supported by the recent evolution of NFW-focused models demonstrating how NFWs cumulatively decrease peak flow conditions across watersheds of different sizes and physiographic regions (Evenson *et al* 2018, Ameli and Creed 2019, Yeo *et al* 2019).

Further, recent model simulations in the Upper Mississippi River Basin, a large ~0.5 million km^2 watershed in the United States, demonstrated that incorporating NFWs into a large river basin watershed hydrologic model (a) increased the accuracy of streamflow simulations across the basin, (b) improved the physical realism of watershed hydrologic processes, and (c) minimized model uncertainty (Rajib *et al* 2020). We therefore argue that pivoting toward integrating NFW hydrologic processes into watershed models projecting floods and droughts in response to a changing climate will improve simulation accuracy and minimize uncertainties.

2. NFW-integrated hydrologic modeling: evolutions and needs

Currently, most hydrologic models require modifications or methods to work around the model’s limited structure, using existing non-NFW parameters, to incorporate NFW watershed storage and their water fluxes to the atmosphere and to downstream waters (Golden *et al* 2014, Jones *et al* 2019). Some models, e.g. the Soil and Water Assessment Tool or the Precipitation-Runoff Modelling System (Hay *et al* 2018), allow for simulation of wetland volumes but are often volumetrically lumped across sub basin scales—though some new models allow for spatially explicit connections of individual NFWs (e.g. Wang *et al* 2021). Yet the standard remains that NFW-integrated downgradient fluxes to other surface waters (e.g. streams, rivers, wetlands) and NFW-based fluxes to the atmosphere are incorporated into models using existing parameters not directly related to NFW hydrologic or hydraulic processes (Jones *et al* 2019).

Model calibration of the hydrologic dynamics of the NFWs also needs to be improved. Most hydrologic models focus on calibration and verification at the outlet, or stream gauge. Considering the internal watershed hydrological processes of evapotranspiration and runoff into and out of the NFWs (Rajib *et al* 2018) could vastly improve future flood prediction efforts and decrease model biases. Integrating remotely sensed data or improved streamflow modeling will help in this capacity (e.g. (Hulsman *et al* 2021)).

Questions also remain regarding the degree of acceptable model error if NFWs are not included in a watershed hydrologic model. For example, if NFWs are ignored in a watershed modeling approach and this results in a 5% model error for streamflow simulations, how important is that 5% model error for the system being studied? Does a 5% model error result in watershed-relevant over- and under- predictions of floods and droughts? Does a 10% error? Additional research is needed in this area, particularly focusing on the interaction of NFW model-integration and non-stationary climate conditions.

Simultaneous with hydrologic model redevelopment is the need to use increasingly available high-resolution spatial (e.g. Light Detection and Ranging) and temporal (e.g. sub-daily flow measurements via sensors) data in current models. Integrating these data will improve predictive simulations while decreasing model uncertainty. These enhanced data-model applications will afford watershed managers more confidence in models used to predict flood and drought events. Nonetheless, data gaps remain. Large-scale, high-resolution spatial and temporal datasets across the world's watersheds are lacking. For example, no high-resolution (i.e. meter or submeter-scale) continental US, European, or global-scale topographic data currently exist—and streamflow monitoring is on the decline (e.g. the extent of US Geological Survey gage stations continues to be reduced (US Geological Survey 2020). These short-comings need to be addressed alongside model refinements.

3. Improving watershed management with NFW-integrated modeling

How would improving watershed hydrologic models with NFW hydrologic processes help future watershed management under a changing climate? First, NFW-integrated hydrologic models would simulate sinks, lags, and sources of water with greater spatial accuracy than traditional modeling approaches. Without including NFW hydrologic processes, simulated water on the landscape may be in the wrong place—particularly when modeling large river basins (Rajib *et al* 2020). For example, areas that are NFW-dominated may show water paucities where they do not exist. Therefore, targeting areas of the landscape for flood or drought management absent NFW-integrated hydrologic modeling may produce erroneous information that is unsupportive of sustainable watershed management.

Second, getting the correct amount of water in the right places across the landscape in model simulations will lead to improved modeling of NFW biogeochemical reactions. NFWs are biogeochemical reactors on the landscape (Marton *et al* 2015, Cohen *et al* 2016) that receive and chemically process water, and thereby influence downstream water quality (Golden *et al* 2019). For example, NFWs on the landscape exhibit strong nutrient attenuation capacities (Cheng and Basu 2017, Cheng *et al* 2020), translating to decreases in downstream nutrient loads and concentrations (Mengistu *et al* 2020). Simulating water volumes and residence times of NFWs therefore assists in targeting appropriate areas in the watershed for nutrient-based water quality management.

The good news is that progress is happening, i.e. the figurative dam is starting to break. Hydrologic models projecting the extent to which NFWs impart downstream flood reductions—particularly across large river basins—are beginning to emerge (Evenson *et al* 2016, Grimm and Chu 2020, Rajib *et al* 2020, Wu *et al* 2020, Zeng *et al* 2020). Further, sustainable water futures under a changing climate demands watershed-scale, nature-based solutions to flood and drought management—including NFW storage (Thorslund *et al* 2017, United Nations 2018). Improving our hydrologic models for projecting floods and droughts is a key step toward this sustainable future, and this is beginning to happen. The next step is to convince the hydro-geoscience community to simultaneously modify models for NFW-integration while using high-resolution spatial and temporal data for future flood and drought predictions.

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Data availability statement

No new data were created or analyzed in this study.

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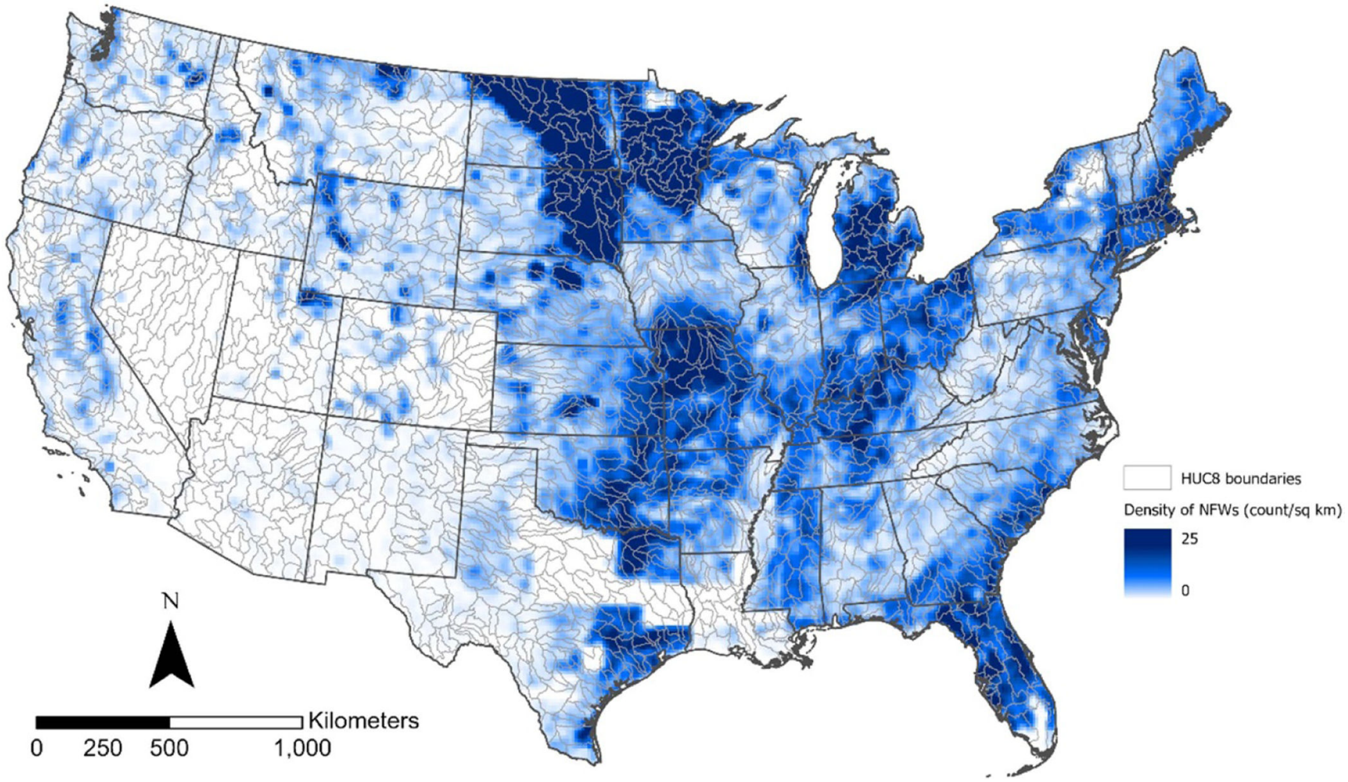

Figure 1.

NFWs are extensive across portions of the US, presented here with 8-digit hydrologic unit code boundaries. For example, NFWs are abundant in the upper Midwest—and other parts of the Midwest, Florida, and New England. Even in areas with lower densities, missing this part of the water balance in model simulations could potentially have disproportional effects on simulated flood and drought projections. We use the National Wetlands Inventory Version 2 data (www.fws.gov/wetlands/data/Wetlands-Product-Summary.html) to document NFW density. We identified NFWs using the method developed by Lane and D'Amico (2016).

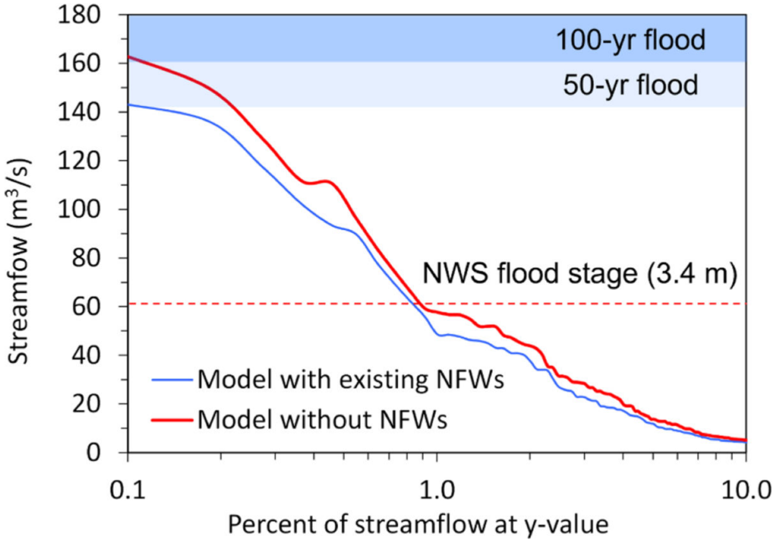

Figure 2.

Whether NFWs are included in watershed hydrologic models can affect estimates of flood stage frequencies and the frequency and discharge of 50 and 100 year floods, both of which can have consequences for sustainable community and infrastructure planning. In this example, if NFWs—and the associated additional water stored on the landscape—are ignored in the model (model without existing NFWs), simulated model output suggests that 50 and 100 year floods will occur during the 5 year (2009–2013) model time frame. However, with NFWs integrated into the model, those simulated flood stages are not reached. The example shown here is from a ~1800 km^2 watershed in North Dakota, US (USGS Pipestem Creek gage 06469400). The flood stage at the USGS gage location was derived from the National Weather Service (NWS), and values of flood frequency and volumes were estimated from model simulations (Rajib *et al* 2018). The NWS flood stage over a 10 year record is >3.4 m.