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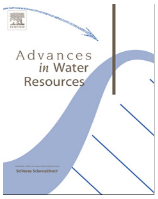

Stochastic modeling of hydrologic variability of geographically isolated wetlands: Effects of hydro-climatic forcing and wetland bathymetry

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ABSTRACT

We examined temporal variability in hydrology of geographically isolated wetlands (GIWs), and derived analytical expressions for probability density functions (*pdfs*) for water storage volume and water stage. We conceptualize a GIW as a non-linear reservoir, subject to stochastic "shot-noise" (Poisson rainfall inputs) modulated by recession through both evapotranspiration and drainage during inter-event periods. The analytical *pdfs* are defined by four key dimensionless parameters which characterize temporal variability of wetland hydrologic conditions: scaled aridity index (ϕ^*), mean daily stage jump (r), relative rate constants for the two recession processes (ε), and wetland shape coefficient (β). These parameters define the similarity or diversity of hydrologic regimes in GIWs at a location or at different sites by capturing the essential features of the landscape: stochastic hydro-climatic forcing, bathymetry, and groundwater or upland connectivity. We illustrate the utility of the analytical *pdfs* using observed data from an isolated wetland in Florida.

1. Introduction

1.1. Geographically isolated wetlands

Wetlands occupy only a small fraction of the landscape area (e.g., 4–6% globally, and <10% for most regions [1]), but play a disproportionately large role as essential aquatic habitats, especially for several endangered or threatened plants, and vertebrate and invertebrate species [2]. Wetlands also play a key role in provision of multiple other ecosystem and socio-economic services by serving as hydrologic and biogeochemical buffers in mitigating floods, attenuating exported loads of nutrients and sediments, and provision of food to rural communities [3,4]. Isolated wetlands are found in diverse regions of the world [5]. For example, several million wetlands are distributed over an area of ~750,000 km^2 of the Prairie Pothole Region in North America [6,7] and nearly 22,000 playas occur in the US Southern High Plains [8].

Due to increasing intensification of land uses for food production and urbanization, total wetland area and the ecological integrity of remnant wetlands have declined all over the world [9]. Such losses have prompted increasing regulatory and technical attention on retaining remnant wetlands, and creating new wetland habitats to restore socio-economic and ecological services that had been lost [2]. In managing and constructing wetlands, the focus is on ensuring that hydrologic variability, a major functional attribute of wetlands, should be restored to sustain target ecological functions (e.g., wildlife aquatic habitat). While much research has focused on experimental hydrologic observations of diverse wetland types and wetland classification schemes, development of a suitable quantitative theoretical framework to account for stochastic hydro-climatic forcing as a key control on wetland hydrologic conditions has been lacking. Here, we address this need.

Of many types of inland freshwater wetlands, our interest here is to examine geographically isolated wetlands (GIWs), defined as wetlands "that are completely surrounded by upland" [10]. It is recognized that *geographically isolated* wetlands at the landscape scale can be actually connected to downstream waters through groundwater connections, ephemeral stream channels, and occasional spillage from other wetlands [10]. Thus, we use the term GIWs to simply represent single depressions embedded into the

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landscape and not permanently connected to stream networks. These kinds of wetlands can be found in various forms such as vernal pools, prairie pothole wetlands, subtropical depression wetlands, and several others [11]. We identify three key factors for the hydrologic behavior of such GIWs: (1) hydro-climatic forcing (e.g., rainfall and evapotranspiration), which varies among regions; (2) wetland bathymetry as defined by the landscape topography shaped by its geologic and geomorphic history; and (3) hydrologic connectivity to uplands or shallow groundwater, which varies depending on regional hydrogeology. Of course, anthropogenic impacts on land-use and land-cover changes, as well as water management (e.g., drainage, irrigation, groundwater pumping) can also have major impacts on hydrological and ecological functioning of GIWs.

The hydrologic connectivity of wetlands to uplands and groundwater varies along a continuous gradient, depending on several factors. First, groundwater dynamics minimally influence the temporal variability of wetland stage when, for much of the period of interest, the water table depth is deep relative to the GIW pool bottom. The occurrence of shallow vs. deep groundwater, and the related fluctuations in water table are determined by regional geology and hydrology. Second, pedologic features, such as soil layering and saturated hydraulic conductivity (K_{sat}) of the soil layers, which can vary spatially and temporally, control the rate of water exchange between pool water and uplands. Third, depletion of soil water storage, via evapotranspiration, creates hydrologic gradients for driving water exfiltration from the pool. Fourth, when a pool bottom sediment layer of varying thickness and permeability is present, the hydrologic resistivity (R_h) of the layer also plays a role in water exchange between the pool and the surrounding landscape; note that $R_h = (d/K_r)$, where d is the thickness (L) of the bottom layer and K_r is its saturated hydraulic conductivity (LT^{-1}), with $0 \leqslant R_h < 20$ days [12]. Accretion of such bottom layers is the result of biological and geochemical processes within the wetlands, and also from accumulation of sediment collected from surrounding upland contributing area during surface runoff events [13].

One limiting case of hydrologic connectivity of wetlands to surrounding uplands is complete isolation (large R_h), when a sufficiently thick or an impermeable layer occurs all along the pool bottom as a result of accretion of sediment or organic material. The other limiting case is when $R_h \sim 0$, because a hydrologically restrictive bottom layer or soil horizons are absent, and the pool water can readily exfiltrate to, or infiltrate from the surrounding upland (or shallow groundwater) in response to the hydrologic potential gradient.

1.2. Monitoring and modeling hydrologic variability in GIWs

Of the large number of site-specific wetland monitoring studies (e.g., [14–18]), relatively few have focused on modeling hydrologic variations within a single wetland or among wetlands in a given landscape. Broadly, two types of modeling approaches are available: (1) spatially distributed or lumped, deterministic, numerical models and (2) stochastic analytical approaches. The first approach has been more common for describing complex wetland landscapes [19–21]. More recent papers have adopted high-resolution topographic maps and sophisticated numerical approaches for modeling hydrological dynamics to identify the spatial patterns and temporal persistence of saturated areas across specific wet-landscapes (e.g., [19]). However, it is difficult to extend information and data derived from such site-specific monitoring and modeling studies to other locations with distinctly different characteristics, or to develop a general theoretical understanding.

The second approach, based on eco-hydrological stochastic framework, incorporates the randomness of climate and rainfall to derive analytical expressions for the probability density functions (*pdf*s) of key hydrologic variables by calculating daily water balance using meteorological data and parameters describing wetland bathymetry, upland soil characteristics, and vegetation cover. Example applications cover a broad range of geophysical systems, including soil–water storage [22], water-table depth in large groundwater-dominated wetlands and soil–water storage in wetlands [23–25], wetland vegetation patterns [26], stage and discharge in stream networks [27,28], solute loads exported from the vadose zone to groundwater [29], and solute export and losses in stream networks [30].

Appropriate water-balance equations for the landscape hydrologic filtering of stochastic hydro-climatic forcing (e.g., rainfall) are written as a set of first-order stochastic differential equations and solved to yield the analytical *pdf*s for steady state conditions [23,24]. Thus, instead of empirical, site-specific data-trends and statistical analyses, these analytical *pdf* expressions allow for a more generalized, quantitative exploration of the contributions of and interactions among key drivers and stochastic forcing controlling hydrologic variability in wetlands. The stochastic modeling approach is used here to illustrate its general utility, and to understand the role of stochastic hydro-climatic forcing and wetland bathymetry to determine the temporal variability of hydrologic conditions in GIWs.

1.3. Scope of the present study

We present analytical expressions for the *pdf*s for pool water volume [$W(t)$] and pool water depth, or stage, [$h(t)$] in a GIW (Section 2), and explore in detail the sensitivity of the derived analytical *pdf*s to controlling parameters (Section 3.1). To serve as an initial test case, we focus on the hydrologic behavior of a GIW in Florida [31] during two distinct seasons, for which we estimate model parameters *a priori* from site-specific data. We then compare the empirical *pdf*s obtained using observed wetland stage data gathered during a monitoring campaign with the analytical *pdf*s we developed (Section 3.2). The scaled parameters in the analytical *pdf* expressions are interpreted in terms of likely wetland *hydrologic regimes* (Sections 4.1 and 4.2). In Section 4.3, we discuss the practical implications of our findings, as well as limitations and extensions of current work to more complex settings involving multiple GIWs distributed across a wetland landscape. Then we close with conclusions in Section 5.

2. Wetland stochastic model

2.1. Conceptual model of GIW hydrology

We conceptualize a GIW as a depression in the landscape within which water can accumulate, with its bathymetry defined by the landscape topography (Fig. 1). Water storage changes in a GIW are controlled by the balance or imbalance between water inputs and water losses. The rate of water losses from the wetland is controlled by evapotranspiration and exfiltration (i.e., drainage to uplands and/or groundwater), which are assumed to be mainly a function of the actual water storage in the wetland, $W(t)$. Inputs include rainfall, and recharge from groundwater and surface water. Here, we assume that rainfall is the dominant input, and there are no inputs from permanent or ephemeral surface stream networks. Moreover, rain falling on the contributing upland area, A_c, is assumed to be collected in the pool, while rain falling outside of this contributing area is not considered. Under these assumptions, the observed temporal fluctuations in wetland stage and volume are driven primarily by the stochasticity of the rainfall inputs, which typically produce a sudden increment (or “jump”) in pool stage or volume corresponding to each rainfall event, followed by