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Key Points:
- A novel "rating curve transformation" approach to model hydroperiod (flooding frequency) in lotic wetlands and floodplains is presented
- The method is applied to infer predrainage flows and hydroperiods in the Everglades based on historical accounts of peat soil elevation
- Results address a central knowledge gap on historic Everglades hydrology and provide guidance for flow restoration in the Everglades

Supporting Information:
- Supporting Information S1

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Doing ecohydrology backward: Inferring wetland flow and hydroperiod from landscape patterns

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Abstract Human alterations to hydrology have globally impacted wetland ecosystems. Preventing or reversing these impacts is a principal focus of restoration efforts. However, restoration effectiveness is often hampered by limited information on historical landscape properties and hydrologic regime. To help address this gap, we developed a novel statistical approach for inferring flows and inundation frequency (i.e., hydroperiod, *HP*) in wetlands where changes in spatial vegetation and geomorphic patterns have occurred due to hydrologic alteration. We developed an analytical expression for *HP* as a transformation of the landscape-scale stage-discharge relationship. We applied this model to the Everglades "ridge-slough" (RS) landscape, a patterned, lotic peatland in southern Florida that has been drastically degraded by compartmentalization, drainage, and flow diversions. The new method reliably estimated flow and *HP* for a range of RS landscape patterns. Crucially, ridge-patch anisotropy and elevation above sloughs were strong drivers of flow-*HP* relationships. Increasing ridge heights markedly increased flow required to achieve sufficient *HP* to support peat accretion. Indeed, ridge heights inferred from historical accounts would require boundary flows 3–4 times greater than today, which agrees with restoration flow estimates from more complex, spatially distributed models. While observed loss of patch anisotropy allows *HP* targets to be met with lower flows, such landscapes likely fail to support other ecological functions. This work helps inform restoration flows required to restore stable ridge-slough patterning and positive peat accretion in this degraded ecosystem, and, more broadly, provides tools for exploring interactions between landscape and hydrology in lotic wetlands and floodplains.

1. Introduction

Feedbacks between water flow and landscape configuration, mediated by organisms, are a common foundation of self-organized patterned landscapes, impacting, for example, semiarid woodland [*Rietkerk et al.*, 2004], coastal mudflats [*Weerman et al.*, 2010], reticulate coral reefs [*Schlager and Purkis*, 2015], floodplain forests [*Corenblit et al.*, 2015], and both subtropical [*Larsen et al.*, 2011] and boreal [*Eppinga et al.*, 2009] peatlands. Our focus here is on lotic wetlands and floodplains, where vegetation and landform arrangement exert strong controls on the magnitude and direction of flow [*Larsen et al.*, 2007; *Murray-Hudson et al.*, 2014], thereby impacting the pattern and frequency of flooding (hydroperiod, *HP*) [*Harvey et al.*, 2009; *Kaplan et al.*, 2012], which in turn is the dominant driver of vegetation diversity and organization [*Foti et al.*, 2012; *Todd et al.*, 2010; *Robertson et al.*, 2001; *Lenssen et al.*, 1999]. Parsimonious descriptions of the reciprocal relationship between hydrologic behaviors and landscape pattern are integral for developing restoration plans and setting restoration goals.

Equally integral to setting and achieving ecological restoration goals is an understanding of historical system attributes. For systems with no contemporary reference, knowledge about historical function (and how it has degraded) is critical for reestablishing target ecological processes [*Hobbs*, 2004; *Zedler*, 2000]. For wetland ecosystems with altered hydrology (e.g., from drainage or diversion of water), restoration is often explicitly motivated by "getting the water right" [*Boesch et al.*, 2006]. However, sparse and unreliable historical evidence on hydrology (flow volume and timing, *HP*, velocity) can critically constrain planning and implementation of specific restoration efforts. Where such historical data are scarce or speculative, alternative methods to characterize predisturbance hydrological conditions are needed.

One such approach is development and application of analytical or numerical models of interactions among climate, hydrology, and wetland landscape characteristics (e.g., vegetation type and patterning). For example, ecohydrological models of soil moisture, water level, nutrients, sediments, and vegetation growth have been used to investigate groundwater-surface water-vegetation interactions [*Chui et al*., 2011; *Muneepeerakul et al*., 2008], productivity [*Grant et al*., 2012], landscape pattern evolution [*Lago et al*., 2010; *Larsen and Harvey*, 2010], and inundation [*Horritt and Bates*, 2001] in wetlands and floodplains. While these models offer insight about reciprocal ecohydrological feedbacks in response to variations in climate and management [*Larsen et al*., 2007; *Siegel*, 1983], most are explicit in space and time [e.g., *Chui et al*., 2011; *Min et al*., 2010; *Marani et al*., 2006; *Townsend and Walsh*, 1998], limiting their applicability for restoration if historical data are unavailable.

In general, a lack of reliable historical information about ecohydrological processes (e.g., flow volume and timing, vegetation type, and patterning) can be an impediment to effective wetland restoration planning and implementation, and further to an understanding of the origins of, and controls on, landscape patterns. To address this challenge, we developed a novel inverse-ecohydrological approach to infer historic flows from attributes of landscape pattern. The approach couples landscape-scale stage-discharge relationships (i.e., rating curves) with statistical distributions of observed flows and water levels. Unlike spatially distributed numerical models, this rating curve transformation (RCT) method approach does not require intensive parameter inputs. We applied the RCT method to estimate predrainage flows in the ridge-slough landscape of the Florida Everglades, a lotic peatland in south Florida that has been drastically degraded due to hydrologic modifications [*Watts et al*., 2010]. Specifically, we estimated the magnitude of flow required to support inundation of sufficient duration to maintain positive peat soil accretion (and thus stable landscape patterning) under a variety of landscape configurations. We refer to this as "doing ecohydrology backward" in the sense that proposed historical peat elevations implicitly indicate a historical hydrologic regime that would be sufficient to maintain net neutral or positive vertical accretion in that configuration. While this termonology is similar to the previously introduced 'doing hydrology backward' approaches in catchment hydrology [*Kirchner*, 2009; *Krier et al*., 2012], our approach is substantially different from previous methods and applies to lotic wetlands and floodplains.

In addition to providing an alternative method to modeling interactions between hydrology and landscape pattern in lotic wetlands, the RCT method lays out a general inverse-modeling framework in which flow and water level data from a contemporary (potentially altered) landscape can be used to gain insights on flow and *HP* under historical (undisturbed) conditions. Finally, this study addresses a central knowledge gap and provides guidance for hydrologic restoration of the Everglades, one of the most extensive and expensive landscape and hydrologic restoration projects in history [*Schrope*, 2001; *Sklar et al*., 2004].

2. Study Area: The Everglades Ridge and Slough Landscape

The Everglades is a large freshwater system that was, prior to modern development, a hydrologically interconnected mosaic of wetland habitats spanning more than 10,000 km^2 [*Light and Dineen*, 1994]. The modern Everglades is dramatically altered [*Sklar et al*., 2005; *Chimney and Goforth*, 2001], with over a century of water management (drainage, compartmentalization, impoundment) and urban development leading to a 50% loss of wetland area and dramatic changes in the hydrology of the wetlands that remain [*Davis and Ogden*, 1994; *Ogden et al*., 2005; *Sklar et al*., 2005]. In this context, the widespread loss of flow path connectivity [*Larsen et al*., 2012; *Yuan et al*., 2015], unique geomorphologic features [*Larsen and Harvey*, 2010; *Cohen et al*., 2011; *Kaplan et al*., 2012], and attendant ecosystem functions [e.g., *Liston*, 2006; *Williams and Trexler*, 2006; *DeAngelis et al*., 2010] have emerged as restoration priorities.

The Everglades "ridge and slough" (RS) landscape covered ca. 55% of the area of historical Everglades and remains one of the most important features of the greater Everglades system [*McVoy et al*., 2011]. The RS landscape is a patterned peatland comprising higher-elevation ridges (dominated by the emergent sedge *Caladium jamaicense)* and lower elevation sloughs (dominated by emergent, submerged, and floating-leaved herbaceous plants and periphyton) organized into distinct patches oriented in the historical flow direction [*Davis and Ogden*, 1994; *Science Coordination Team (SCT)*, 2003; *McVoy*, 2011] (Figure 1). Maintenance of two distinct patch types, illustrated by strongly bimodal peat elevations in the best conserved regions [*Watts et al*., 2010], is thought to arise via local feedbacks among hydroperiod (*HP*, the frequency of inundation), primary productivity, and organic matter respiration. These local feedbacks yield two stable peat accretion equilibria [*Larsen et al*., 2007; *Heffernan et al*., 2013], with higher-elevation ridges balancing high primary productivity with high organic

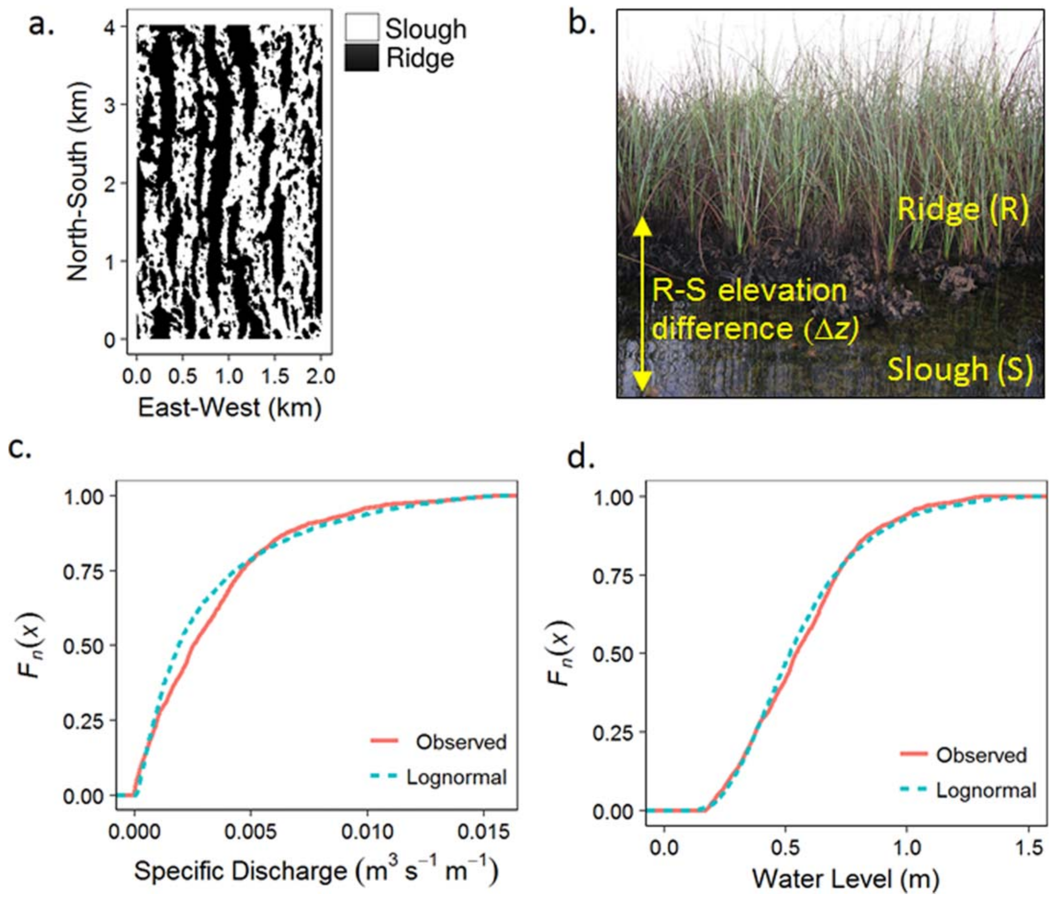

Figure 1. (a) Aerial view of the reference landscape, located in Water Conservation Area 3A (WCA-3A) in the central Everglades, illustrating well-conserved ridge-slough patterning; (b) photo depicting ridge-slough soil elevation differences (Δz) in the well-conserved landscape, with contemporary $\Delta z \sim 0.25$ m; (c, d) observed cumulative density function of specific discharge and water level in the benchmark landscape (red line), along with the best fit log-normal distributions (dashed blue line).

matter respiration rates due to relatively shorter *HP* (85–90% inundation) [*Watts et al*., 2010], and lower elevations sloughs achieving the same long-term accretion rate despite far lower production due to lower respiration driven by near-continuous inundation. While the processes that created and maintained flow-oriented ridge-slough patterning continue to be debated [*Ross et al*., 2006; *Larsen et al*., 2007; *Cheng et al*., 2011; *Cohen et al*., 2011; *Heffernan et al*., 2013; *Acharya et al*., 2015; *Casey et al*., 2016], there is consensus that hydrology controls pattern self-organization and that loss of spatial pattern is associated with loss of ridge-slough elevation differences [*Yuan and Cohen*, 2016; *Watts et al*., 2010; *Todd et al*., 2010], which in turn impacts landscape hydraulics [*Harvey et al*., 2009; *Heffernan et al*., 2013].

Water management activities that began in the early 1900s have substantially reduced and altered the natural flow regime of the Everglades. Limited data inform predrainage flows, but the available evidence suggests that drainage and compartmentalization have lowered landscape flows by as much as 60% [*Smith et al*., 1989; *Marshall et al*., 2009]. This alteration prompted myriad negative impacts to the RS landscape. Three primary measures of RS patterning have been dramatically altered: patch anisotropy (ε, defined as the ratio of the spatial autocorrelation ranges in the N-S and E-W directions), ridge density (*%R*), and mean peat elevation difference between the ridges and sloughs (Δz). Patch anisotropy in the best conserved portions of the contemporary RS landscape ranges from 3.5 to 6.0, which trends toward random, isotropic ridge organization (i.e., $\varepsilon \sim 1.0$) with hydrologic alteration [*Casey et al*., 2016]. Ridge densities have also been dramatically altered from a historical range of 32–55% areal coverage [*Wu et al*., 2006] to ridge dominated (i.e., $\%R > 55\%$) conditions where the landscape has been overly drained and slough-dominated (i.e., $\%R < 25\%$) where it has been overly impounded [*Nungesser*, 2011].

While most attention on pattern loss in the Everglades has focused on landscape pattern in two dimensions, defined largely by %*R* and ε [e.g., *Larsen and Harvey*, 2010; *Nungesser*, 2011; *Casey et al*., 2016], drastic changes are often manifest most clearly in spatial and temporal variation of the vertical dimension of peat elevations. Under the best conserved conditions, the observed mean elevation difference between ridges and sloughs (Δz) is ca. 0.25 m [*Watts et al*., 2010] (Figure 1b). Rapid loss of organic soils due to respiration and wildfires in response to wetland drainage [*Ingebritsen et al*., 1999] has dramatically flattened the landscape in many areas [*Nungesser*, 2011], often resulting in unimodal elevation distributions and lowered elevation variance [*Watts et al*., 2010]. Crucially, historical accounts suggest that the ridge-slough elevation differences in the predrainage Everglades were as high as 0.6–0.9 m [*SCT*, 2003; *McVoy et al*., 2011], suggesting that even the best conserved contemporary landscape has undergone dramatic topographic flattening, a contention supported by analytical modeling [*Heffernan et al*., 2013]. Restoration thus needs to consider the hydrologic conditions necessary to sustain three-dimensional (horizontal and vertical) pattern geometry.

The Comprehensive Everglades Restoration Plan (CERP) aims to improve ecological condition across the Everglades by restoring the surface water flow regime and reinstating, to the extent possible, historical spatiotemporal patterns of water depth and *HP* [*Ogden et al*., 2005; *Choi and Harvey*, 2016]. Although this goal offers clear objectives (i.e., "get the water right"), lingering uncertainties remain. Centrally, how much flow is required to restore historical *HP*s? Under the contemporary flow regime, *HP* in the best conserved ridge-slough landscapes is approximately 0.87 (i.e., approximately 318 days) [*Watts et al*., 2010; *Kaplan et al*., 2012]. However, whether a similar *HP* regime previously existed, particularly given historically larger Δz, is not known. To enable higher ridge elevations (i.e., $\Delta z > 0.25$ m) in the predrainage landscape would likely require flows substantially higher than currently observed in order to maintain *HP* similar to values currently observed where the RS patterning is best conserved. Although higher flow conditions are supported by historical inferences [*Marshall et al*., 2009; *McVoy et al*., 2011], establishing flow restoration targets is challenging due to substantial uncertainties on predisturbance flow estimates [e.g., *Smith et al*., 1989].

3. Methods

Hydrology of lotic wetlands and floodplains is clearly influenced by the magnitude of boundary flows (i.e., inputs). However, in extremely low-relief settings (such as the Everglades), the ability of the landscape to convey water, quantified by specific discharge (flow rate Q per unit width, also known as discharge competence, q, m^3 s^{-1} m^{-1}), is strongly affected by spatial arrangement of the landscape elements, including topographic variance and the density and spatial organization of vegetation [*Cohen et al*., 2011; *Kaplan et al*., 2012]. For a given flow Q, different landscape geometries will produce different q, water depth (h), and *HP* based on these properties [*Cohen et al*., 2011; *Heffernan et al*., 2013]. This implies each landscape configuration exhibits a characteristic landscape-scale rating curve (RC), which, in turn, directly informs *HP*.

Our model application and evaluation is focused on the RS landscape, where *HP* is likely the primary driver of self-organized vegetation pattern emergence and maintenance [*Foti et al*., 2012; *Cohen et al*., 2011; *Watts et al*., 2010]. Following from above, we observe that two RS landscapes with different spatial geometries, subject to the same hydrologic input *Q*, will have different water stage (h) responses and hence different *HP* [e.g., *Kaplan et al*., 2012]. Thus, we posit that the h-distribution in a known, reference landscape can be used to calculate the h-distribution of another, unknown landscape subject to the same flow by equating their respective rating curve relationships. In this study, we use a reference landscape [*Kaplan et al*., 2012] in the best conserved region of ridge-slough patterning in central Water Conservation Area 3A (WCA-3A) of the Everglades (Figure 1a). Ridge density in this domain is 54.5%, with ridge patches elongated in the flow direction (patch anisotropy, $\varepsilon \approx 4.5$) [*Kaplan et al*., 2012] and elevated above adjacent sloughs ($\Delta z = 0.25$ m). These Δz values are the highest observed in the contemporary Everglades [*Watts et al*., 2010], but are not necessarily representative of historical conditions, when ridges may have been significantly taller [*SCT*, 2003; *McVoy et al*., 2011]. For our analysis, we assume the observed 2-D patterning in this reference landscape is similar to historical conditions, but that Δz has declined [*McVoy et al*., 2011]. We used numerous realizations of synthetic RS landscapes with varying spatial attributes (%*R*, ε, and Δz) created using sequential indicator simulation [*Journel and Deutsch*, 1998] following *Kaplan et al*. [2012].

Our methods, detailed below, are summarized as follows: (1) develop an analytical expression for *HP* by transforming rating curves for each landscape using a common power function to describe each rating curve (section 3.1); (2) estimate rating curve parameters by fitting to the observed *Q-h* relationship determined by steady state simulations of sheet flow through each landscape (section 3.2); (3) evaluate estimates of *HP* from this rating curve transformation (RCT) against estimates from both numerical simulations and observations in the reference landscape (section 3.3); and (4) develop probability distributions of *HP* in the RS landscape under current and restored-flow scenarios to infer flow requirements to meet target *HP* regimes for each value Δz across a variety of landscape configurations (section 3.4).

3.1. The Rating Curve Transformation (RCT) Method: Theory

Rating curves are models of *Q-h* relationships used to estimate discharge in open channels (e.g., streams, rivers, and canals) using measured water level data [*Ocio et al*., 2017; *Rantz et al*., 1982b]. They are commonly described by a power-function relationship of the form $Q = a(h\text{-}c)^b$, where *c* denotes the water level corresponding to effective zero *Q*, *a* is a scale coefficient, and *b* is a exponent that determines the slope of the curve [*Van Eerdenbrugh et al*., 2016; *Domeneghetti et al*., 2012; *Rantz et al*., 1982b]. The term *h-c* signifies the combined influence of physical channel attributes (e.g., spatial geometry and vegetation resistance) on the *Q-h* relationship [*Rantz et al*., 1982a]. The power function parameters can be related to Manning's coefficients that describe channel physical properties (geometry and roughness/resistance) that control discharge [*Leon et al*., 2006; *Rantz et al*., 1982b]. The steady state *Q-h* relationship in the RS landscape is well described with a power function rating curve [*Kaplan et al*., 2012]. Our RCT method combines this power function expression with statistical distributions of *Q* and *h* to derive an analytical expression for *HP*.

Given a distribution of daily water depths in sloughs (i.e., stage, *h*), ridge *HP* is the cumulative density of the *h*-distribution above Δz. That is, *HP* is the zeroth truncated moment of the *h*-distribution with lower-truncation point Δz. If the *h*-distribution follows a defined functional form (e.g., lognormal), this truncated moment can be calculated directly from the observed mean and variance [*Jawitz*, 2004].

Two landscapes with the same imposed *Q* but different pattern configurations (i.e., *%R*, *e*, and Δz) will have different *q* and *h*, and hence different rating curves, such that

$$Q = a_1(h_1 - c_1)^{b_1} = a_2(h_2 - c_2)^{b_2}, \tag{1}$$

where subscript 1 refers to a reference landscape (for which we have time series of *Q*, *q*, and *h*) and subscript 2 refers to any other landscape for which we want to estimate *HP*.

To facilitate the derivation of analytical expressions for the moments of the random variables *Q* and *h*, we introduce $h_{i,s} = h_i - c_i$ such that equation (1) becomes

$$Q = a_1\left(h_{1,s}\right)^{b_1} = a_2\left(h_{2,s}\right)^{b_2}. \tag{2}$$

Solving for the unknown $h_{2,s}$ and taking the logarithm yields

$$\ln h_{2,s} = \ln\left(\frac{a_1}{a_2}\right)^{\frac{1}{b_2}} + \frac{b_1}{b_2}\ln h_{1,s}. \tag{3}$$

Here we assume h_i to be a lognormal random variable such that $h_{i,s}$ in equations (2) and (3) is a shifted lognormal random variable. The distribution of *h* observed in the reference landscape (Figures 1c and 1d) comports with the lognormal distribution, providing strong support for this assumption. Recognizing equation (3) to be of the general form $Y = \alpha + \beta X$, we note that for lognormal *X*, *Y* is also lognormal with $\mu_{\ln Y} = \alpha + \beta\mu_{\ln X}$ and $\sigma_{\ln Y} = \beta\,\sigma_{\ln X}$, where μ and σ, respectively, denote the mean and standard deviation of the distribution. Thus, because $h_{1,s}$ is lognormal, $h_{2,s}$ is also lognormal with

$$\mu_{\ln h_{2,s}} = \ln\left(\frac{a_1}{a_2}\right)^{\frac{1}{b_2}} + \frac{b_1}{b_2}\mu_{\ln h_{1,s}}, \tag{4}$$

$$\sigma^2_{\ln h_{2,s}} = \left(\frac{b_1}{b_2}\right)^2 \sigma^2_{\ln h_{1,s}}. \tag{5}$$

Equations (4) and (5) thus relate the distributions of water levels in the reference and unknown landscapes by means of landscape-specific rating curve parameters *a* and *b*. The shifted lognormal distribution assumption for *h* also means an expected value $E[h_{i,s}] = E[h_i] - c$, and variance $\mathrm{Var}[h_{i,s}] = \mathrm{Var}[h_i]$, whereas for a lognormally distributed variable X, the expected value and variance are $E[X] = \exp(\mu_{\ln X} + \sigma^2_{\ln X})$ and $\mathrm{Var}[X] = [\exp(\sigma^2_{\ln X}) - 1]E[X]^2$, respectively. Substituting these in expressions for $E[h_{i,s}]$ and $\mathrm{Var}[h_{i,s}]$ and rearranging the resulting expression yields the parameters of the $h_{1,s}$ distribution in terms of the given h_1 distribution parameters

$$\mu_{\ln h_{1,s}} = \ln\left[\exp\left(\mu_{\ln h_1} + \frac{\sigma^2_{\ln h_1}}{2}\right) - c_1\right] - \frac{\sigma^2_{\ln h_{1,s}}}{2}, \tag{6}$$

$$\sigma^2_{\ln h_{1,s}} = \ln\left[\frac{\left[\exp\left(\sigma^2_{\ln h_1}\right) - 1\right]\ \exp\left(2\mu_{\ln h_1} + \sigma^2_{\ln h_1}\right)}{\left[\exp\left(\mu_{\ln h_1} + \frac{\sigma^2_{\ln h_1}}{2}\right) - c_1\right]^2} + 1\right]. \tag{7}$$

The parameters of the h_2 distribution in the unknown landscape can now be similarly obtained in terms of the $h_{2,s}$ distribution parameters as

$$\mu_{\ln h_2} = \ln\left[\exp\left(\mu_{\ln h_{2,s}} + \frac{\sigma^2_{\ln h_{2,s}}}{2}\right) + c_2\right] - \frac{\sigma^2_{\ln h_2}}{2}, \tag{8}$$

$$\sigma^2_{\ln h_2} = \ln\left[\frac{\left[\exp\left(\sigma^2_{\ln h_{2,s}}\right) - 1\right]\ \exp\left(2\mu_{\ln h_{2,s}} + \sigma^2_{\ln h_2}\right)}{\left[\exp\left(\mu_{\ln h_{2,s}} + \frac{\sigma^2_{\ln h_{2,s}}}{2}\right) + c_2\right]^2} + 1\right]. \tag{9}$$

Finally, HP for a given ridge elevation, Δz, is obtained as the lower truncated zeroth moment, m_0, of the lognormal h_i distribution [*Jawitz*, 2004]

$$HP = m_0(\Delta z,\ \infty) = \frac{1}{2}\left(\mathrm{erf}\left[\frac{\ln(\Delta z) - \mu_{\ln h_i}}{\sigma_{\ln h_i}\sqrt{2}}\right]\right), \tag{10}$$

where erf is the Gauss error function. Hydroperiod is calculated by first solving equation (7) followed by equation (6) to obtain the mean and variance of the shifted water level distribution observed in the reference landscape ($h_{1,s}$). These values are then used in equations (4) and (5) to estimate the statistics of the shifted water level distribution in the unknown landscape ($\mu_{\ln h_{2,s}}$ and $\sigma^2_{\ln h_{2,s}}$). Finally, equations (8) and (9) enable calculation of mean and variance of water level in the unknown landscape ($\mu_{\ln h_2}$ and $\sigma^2_{\ln h_2}$), and equation (10) is used to calculate HP.

The analytical expressions in equations (8)–(10) indicate that the RCT method developed here only requires the mean and variance of the h-distribution in the reference landscape, along with rating curve parameters from reference and unknown landscapes, to calculate HP in any unknown landscape. This represents a major advantage over detailed numerical modeling approaches, which require extensive inputs (e.g., rainfall, evapotranspiration, etc.) to simulate water flow and daily water levels necessary for calculating HP.

3.2. Rating Curve Development and Parameterization

A prerequisite to implementing equation (10) to calculate HP is parameterization of rating curves as continuous functions of landscape pattern attributes (*%R*, ε, and Δz). To achieve this for the RS landscape, we followed and expanded upon the approaches of *Kaplan et al.* [2012] and *Acharya et al.* [2015]. They simulated steady state sheet flow using a spatially distributed, two-dimensional, hydrodynamic, surface-water flow model, SWIFT2D [*Schaffranek*, 2004] to obtain *Q-h* relationships for the reference landscape and 840 synthetic RS landscapes. In these previous studies, the synthetic landscapes were generated with sequential indicator simulation [*Journel and Deutsch*, 1998] and consisted of *%R* between 10 and 90%, and ε ranging from 1 to 6, while Δz was fixed at 0.25 m based on *Watts et al.* [2010]. Steady Q from each landscape was then simulated under a range of fixed boundary conditions (h) using SWIFT2D. We expanded on this approach by varying Δz from 0.1 to 0.9 m in the synthetic landscapes (Δz values of 0.1, 0.25, 0.5, 0.75, and 0.9 m). For simplicity, we fixed *%R* = 50% based on observations of relatively consistent ridge density across the best conserved RS landscapes [*Casey et al*., 2016], but allowed ε to vary. For each Δz class, we generated 120 2 × 4 km synthetic landscapes, with ε ranging from 1.0 (isotropic ridges) to 8.0 (ridges highly elongated in the flow direction), for a total of 600 landscapes. For each landscape, steady state Q was simulated using SWIFT2D under fixed-head boundary conditions ranging from 0.10 to 3.0 m. The resulting *Q-h* relationships in both the synthetic and reference landscapes (with varying Δz) were used to construct the rating curves. Further details on this modeling framework can be found in *Kaplan et al*. [2012].

Steady state flow simulations from SWIFT2D yielded unique RCs for each landscape based on particular Δz and ε combinations. A power function model (equation (1)) was fitted to simulated *Q-h* relationships for each landscape, yielding parameters (*a*, *b*, and *c*) for each Δz and ε combination. RC parameters *a*, *b*, and *c* were then regressed against ε for each value of Δz, enabling parameter estimation for any landscape (reference or synthetic) of given horizontal and vertical pattern attributes. These functional relationships, embedded in the RCT approach (equations (4)–(10)), are ultimately used to calculate *HP* for any RS landscape with given Δz and ε values.

3.3. RCT Method Validation

The *HP* estimates obtained from the RCT method, HP_{RCT}, were evaluated using two sets of data. First, HP_{RCT} estimates were compared with the "true" *HP* observed over a 20 year period in the reference landscape determined using water surface and ridge elevation data from the Everglades Depth Estimation Network (Site 64; available at http://sofia.usgs.gov/eden/). Next, we compared HP_{RCT} with *HP* estimates from SWIFT2D, HP_{S2D}. The HP_{S2D} values were calculated using the daily contemporary flow time series in the reference landscape, reported by *Kaplan et al*. [2012]. Comparison of HP_{RCT} and HP_{S2D} for the synthetic landscapes was performed for Δz and ε that spanned the range of values in the contemporary landscapes as well as the range thought to exist in the historical, undisturbed Everglades.

3.4. Inferring Hydroperiod Under Historical Landscapes and Restoration Flows

The effect of flow restoration on *HP* was explored by enumerating the probability distribution of *HP* under a range of imposed restoration flow scenarios using both current and historical ridge elevations. For this analysis, we imposed $\varepsilon = 4.5$, based on the observed anisotropy in the reference landscape. We considered restoration flow scenarios (q_r) from 1 to 4 times the contemporary mean flow (q_m) to include the range of possible predrainage flow regimes that may have existed in the Everglades. For each q_r, the corresponding lognormal distribution parameters were determined using the observed variance in mean daily q_m, and these parameters were used to generate random samples of q_r ($n = 6000$). Randomly generated q_r were converted to mean water level in the reference landscape, h_r, using corresponding RC parameters. Next, the lognormal *h*-distribution parameters $\mu_{\ln h_r}$ and $\sigma^2{}_{\ln h_r}$ for each h_r were calculated in similar manner to the *q*-distribution, and *HP* was calculated using equation (10). The resulting *HP* estimates for q_r:q_m were then used for each Δz value to develop cumulative distribution functions (CDFs), which were used to calculate the likelihood of meeting the "target" *HP* of 0.87. These likelihood estimates suggest mean flow volumes required to sustain long-term target *HPs* under historical ridge-slough elevation differences. The target *HP* was chosen based on observed values in the reference landscape over a 20 year stage record [*Watts et al*., 2010; *Kaplan et al*., 2012], as well as the simulated value for synthetic landscapes with similar spatial geometry; it implies that ridges are, on average, inundated 318 days per year.

4. Results

4.1. Rating Curve Parameterization

Specific discharge simulated with SWIFT2D increased with stage in the reference landscape ($\%R = 54.5\%$, $\varepsilon = 4.5$) and responded clearly to varying Δz (Figure 2). The power function RC (equation (1)) fitted the simulated discharge well at water levels greater than Δz, while for lower water levels (i.e., when $h < \Delta z$), equation (1) results in zero discharge. This is due to the nature of the RC formulation (equation (1)), which implies $Q = 0$ for $h < c$, although flow paths through connected sloughs may convey small volumes of water even when $h < \Delta z$ [*Kaplan et al*., 2012]. However, since our primary interest is in estimating *HP* (i.e., the proportion of time when $h > \Delta z$), we are most interested in agreement between RCs and simulated results when ridges are inundated. Under these conditions, there was excellent agreement between SWIFT2D simulations and RC predictions across ridge heights (Figure 2).

Parameterization of the RCs revealed that fitted parameters (*a*, *b*, and *c*) were influenced interactively by both Δz and ε, with the largest effects of ε at highest Δz (Figure 3). All three RC parameters were best fit by power-function relationships with ε within each Δz class (see supporting information). In contrast, within any ε class, the relationships between Δz and the RC parameters were best described by a higher-order

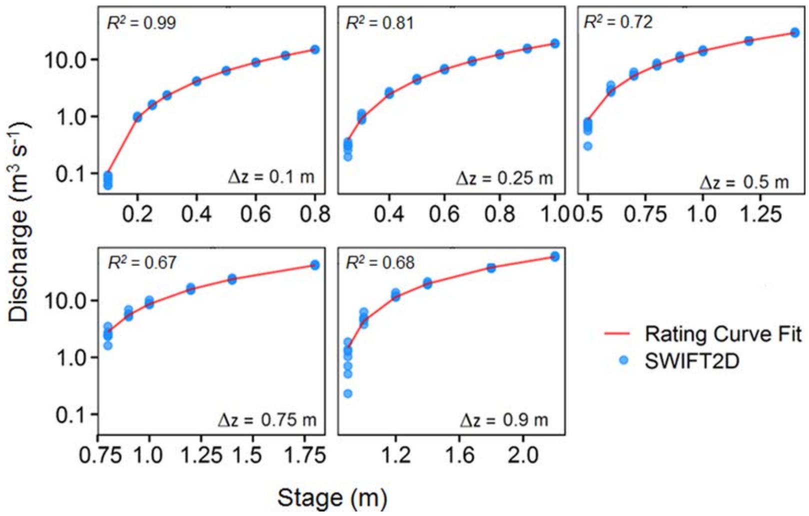

Figure 2. Rating curve fits for synthetic landscapes with spatial attributes similar to the reference landscape (ridge density = 50% and anisotropy = 4.5) and ridge-slough elevation differences (Δz) ranging from 0.1 to 0.9 m. (note: *y* axis shown in log scale).

polynomial function. Therefore, we modeled these parameters as functions of ε for individual Δz class. Specifically, each parameter ($p = a$, b, or c) was fit by $p = \alpha_p \varepsilon^{\beta_p}$ for each value of Δz (supporting information Table S1 and Figures S1 and S2).

4.2. Evaluation of the RCT Method

The results showed excellent association ($R^2 = 0.98$) between yearly HP_{S2D} and HP_{RCT} estimated in the reference landscape (Figure 4a), supporting the suitability of our analytical approach in subsequent analyses. While the RCT method tended to slightly underestimate *HP* during the driest years relative to the measured values in the reference landscape, agreement with the observed values during majority of the years was strong. Additionally, the long-term HP_{RCT} estimated over the 20 year period of record was also equal to the observed value in the reference landscape (0.87 ± 0.1).

Agreement between the overall *HP* estimates based on the 20 year simulation period from the two methods was also strong ($R^2 = 0.84$) for synthetic landscapes across the range of Δz explored here, with the exception of very low ridge heights, for which *HP* values were often close to or equal to unity (Figure 4b). Similar to the reference landscape, the RCT method also tended to slightly underestimate *HP* for landscapes with high Δz and slightly overestimate *HP* at high ε/low Δz (Figure 4b). Nonetheless, these comparisons suggest the RCT method accurately reproduces HP_{S2D} estimates, and thus reliably predicts pattern-varying *HP*.

4.3. Effect of Ridge Elevation on Hydroperiod

Contemporary flow simulations from 600 synthetic landscapes showed that average SWIFT2D-estimated hydroperiods (HP_{S2D}) decreased with Δz following a power function, with further variance within Δz classes

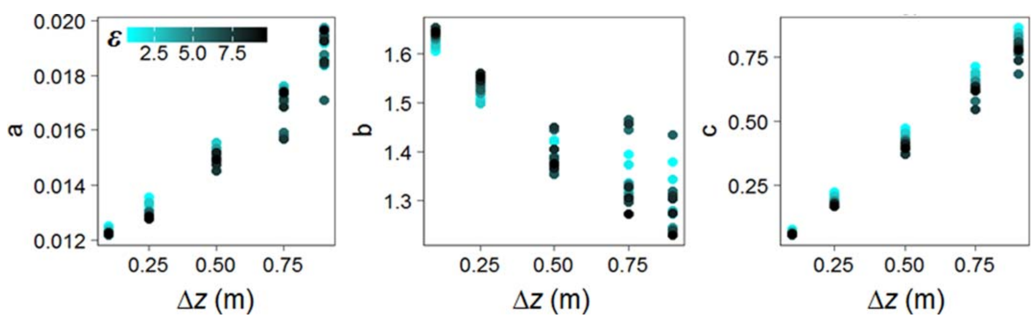

Figure 3. Relationships between ridge height (Δz, m) and the rating curve parameters *a*, *b*, and *c* across a range of anisotropy (ε) values.

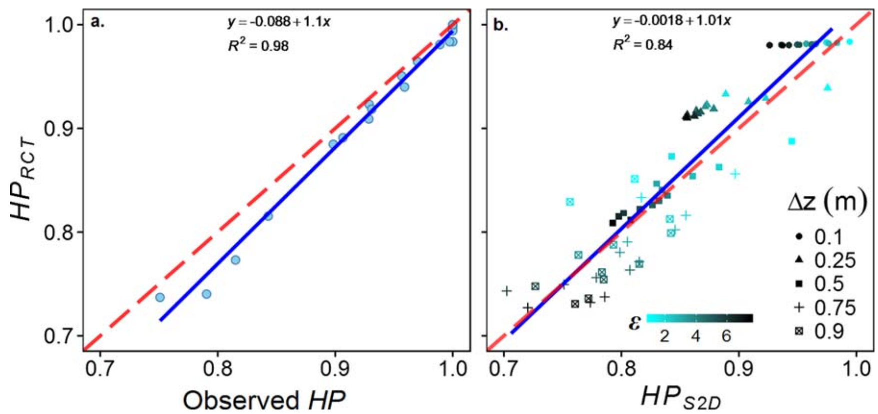

Figure 4. (a) Observed hydroperiod (*HP*) versus rating-curve transformation estimates (HP_{RCT}) for the reference landscape (Figure 1a). (b) Comparison of HP_{RCT} to hydroperiod simulated by the SWIFT2D model (HP_{S2D}) for synthetic landscapes spanning values of ε and Δz. The red dashed line is the 1:1 line, and the blue solid line is the best fit linear relationship.

driven by ε (Figure 5). Higher Δz reduced ridge inundation for a given discharge, as expected, and higher ε (i.e., more connected sloughs) decreased *HP* for a given Δz because of improved discharge competence. HP_{S2D} estimates also reveal the relative strength of ε and Δz effects. Variance in HP_{S2D} estimates attributable to ε were largest for landscapes with moderate Δz (between 0.25 and 0.75 m) and smaller for those with extremely low or high ridges. HP_{S2D} estimates using contemporary *Q* values for $\Delta z \geq 0.75$ m indicate that the inundation frequency would be less than 290 days, resulting in a much drier environment than required for sustained peat accretion in ridges, and thus reduction in Δz over time.

4.4. Effect of Flow on Hydroperiod

Analyses of HP_{S2D} and HP_{RCT} (Figure 4) are based on contemporary flow and suggest substantially reduced *HP* (<300 d/yr) would ensue for landscapes with $\Delta z > 0.25$ m without commensurate flow increases. Estimated CDFs of HP_{RCT} indicated the *HP* distribution is strongly controlled by interactions between Δz and flow (Figure 6). At a given flow, increasing Δz yields a more evenly distributed *HP* regime, with the mean shifted toward the drier (i.e., lower *HP*) environment. Increasing flow shifts the *HP* distribution under each Δz toward wetter conditions and narrower CDF distributions. In general, increasing flows across the range of explored q_r:q_m values produce steeper CDFs (Figures 6b–6d) that also show strong effects of Δz on the probability of achieving a *HP* similar to that observed in the conserved, real landscapes (0.87).

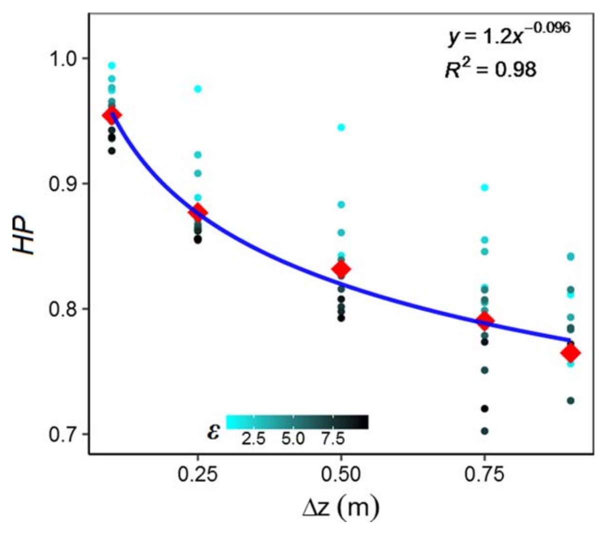

Figure 5. Effect of ridge-slough elevation difference (Δz) on *HP* simulated using SWIFT2D (HP_{S2D}) for synthetic landscapes with 50% ridge coverage and variable anisotropy (ε) under current flow conditions. Red circles indicate mean values across all levels of ε. The blue line is the best-fit power function.

The CDFs of HP_{RCT} for each Δz class under different restoration flows (i.e., q_r:q_m between 1 and 4) also provide an important insight into the magnitude of flow required to sustain the target *HP*. For contemporary flow (q_r:$q_m = 1$), 62% of years meet the *HP* target for $\Delta z = 0.25$ m, whereas fewer than 10% of years meet that target when $\Delta z = 0.9$ m (Figure 7). The probability that *HP* exceeds the target in a given year (i.e., $p[HP] \geq 0.87$) is a nonlinear function of flow (defined vis-à-vis contemporary flow), approaching unity as q_r:q_m increases, particularly for lower ridge heights (Δz). Under contemporary flow ($q_r/q_m = 1.0$), *p* is substantially below 0.5 (i.e., the target is not met in more than 50% of years) for $\Delta z > 0.25$ m (Figure 7), which is the

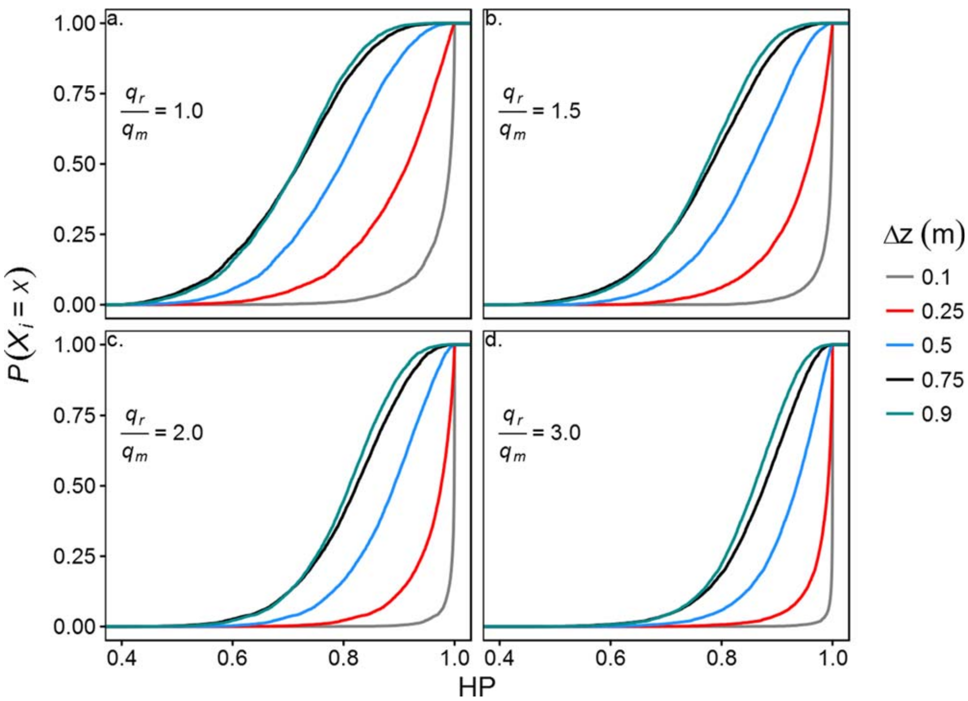

Figure 6. Cumulative distribution functions of ridge hydroperiod (*HP*) for four flow enhancement scenarios (i.e., ratios between restoration and mean contemporary flow, $\frac{q_r}{q_m}$, ranging from 1.0 to 3.0) and five values of ridge-slough elevation difference (Δz).

contemporary RS elevation difference in the best conserved RS landscape. As expected, the probability of meeting the target *HP* increases significantly for higher Δz when q_r:$q_m > 1.0$, indicating that sustaining an optimum *HP* regime (i.e., $P \geq 0.5$) with ridges markedly higher than the current landscape requires doubling contemporary flow for $\Delta z = 0.5$ m, and tripling flow for $\Delta z = 0.75$ m (Figure 7). Given assertions of ridge elevations in the predevelopment Everglades between 0.6 and 0.9 m [*SCT*, 2003; *McVoy*, 2011], our results suggest that dramatic enhancement to current flow would be required to maintain *HP* in the range necessary to sustain ridge peat accretion.

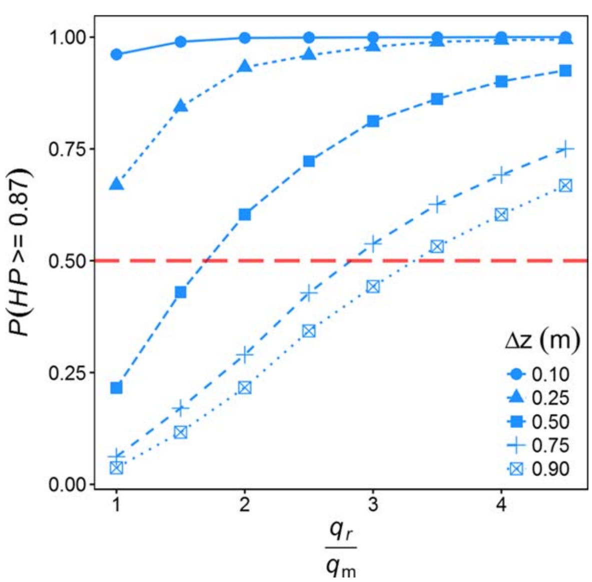

Figure 7. Probability of meeting the target ridge hydroperiod $P(HP \geq 0.87)$ in a given year as a function of flow enhancement scenario $\left(\frac{q_r}{q_m}\right)$ ratios for landscapes with varying ridge-slough elevation difference (Δz). We assume that long-term ridge peat accretion is sustained when the *HP* target is met in 50% of years (i.e., $P[X \leq x] = 0.5$) indicated by the red dashed line.

5. Discussion and Conclusions

5.1. The RCT Method: Applications

The RCT method developed and applied in this study provides a novel approach to understanding the dynamic interplay between landscape attributes and *HP* in lotic wetlands and floodplains. An advantage over previous modeling approaches is that the RCT method can be used to easily estimate *HP* for landscapes with different spatial attributes and under various flow regimes. Application of RCT method to the dramatically altered Everglades RS landscape to provided valuable inferences of likely *HP* regimes under alternate pattern configurations (e.g., higher Δz and modified ε) and restoration flow scenarios. These results help address a challenging knowledge gap about the ecohydrology of the predrainage Everglades.

In contrast to computationally intensive, spatially distributed hydrodynamic modeling, the RCT method takes advantage of the statistical properties of observed hydrologic variation, which often follow a lognormal distribution [*Stedinger*, 1980; *Moyeed and Clarke*, 2005]. While the development of landscape-scale rating curves does require one-time, numerical modeling of flow in unknown landscapes, this can be achieved by simulating steady state conditions under imposed water level boundary conditions and does not require the data on rainfall and other weather variables that are needed for transient numerical simulations. Once the rating-curve relationships are established, they can be easily regressed against the most important landscape attributes (such as ε and Δz in the case of the RS landscape) for the parameterization of the RCT method. In this sense, the RCT method is substantially easier to implement and is not limited by the lack of detailed inputs required for spatially distributed models.

Other potential applications of the RCT method include downstream flooding prediction following structural changes that alter a river's rating curve (i.e., bridge and culvert addition or removal) and floodplain inundation prediction following geomorphological changes in river and floodplain cross sections that do the same. While a variety of numerical methods exist to predict changes in stage as a function of cross section (e.g., HEC-RAS) [*Brunner*, 1997], our RCT method requires minimal input variables and parameters to quickly assess the effect of different hydraulic geometries on hydrologic regime. By benchmarking the RCT method against SWIFT2D, we showed it can provide reliable *HP* estimates across landscape configurations.

5.2. Flow Inferences From Historical Landscape Patterns

In addition to the development of the RCT method, other overarching objectives of this study were to estimate the likely magnitude of historical flows based on historical accounts of landscape geometry and to better understand how the RS landscape would respond to higher (restoration) flow regimes. Central to this analysis was the choice of a target *HP* value that represents a stable or increasing carbon balance [*DeBusk and Reddy*, 2003; *Sulman et al*., 2012]. Contemporary estimates of mean annual ridge *HP* in the best conserved portion of the RS landscape range from 310 to 340 days [*Ross et al*., 2006; *Cohen et al*., 2011; *Kaplan et al*., 2012], though some studies report higher values based on specific sampling periods [e.g., *Givnish et al*., 2008]. Given year-to-year variation in ridge *HP* reported from short-term field studies, our assumption of long-term mean *HP* target of 0.87 (318 days) was based on the 20 year flow and *HP* record developed by *Kaplan et al*. [2012], coupled with ridge elevation data from *Watts et al*. [2010]. From field studies of soil respiration, the estimated 30–50 dry days per year in ridges are critically important for predicting total annual respiration. Respiration rates as a function of water depth were indistinguishable between ridges and sloughs [*Watts*, 2013], with both exhibiting marked increases in respiration for water depths below zero. This suggests that achieving the same net carbon balance in both ecosystem types requires dry ridge days to offset markedly higher ridge primary production [*Heffernan et al*., 2013]. This disproportionate importance of dry days to the overall carbon balance means even small shifts in the number of dry days are likely to impact long-term peat accumulation, and thus for divergence in ridge and slough soil elevations. Little work has been done on the cumulative implications to local peat accretion of small changes in *HP*. As such, our assumption that sustained peat divergence between ridges and sloughs requires meeting the 0.87 *HP* target in 50% of years should be viewed with appropriate caution. Future work that explicitly integrates C dynamics into this *HP* modeling framework would allow exploration of landscape pattern sensitivity to this assumption.

Besides finding strong effects of Δz on *HP*, our study also complements previous results by *Kaplan et al*. [2012] and *Acharya et al*. [2015] by further demonstrating that for any given flow, a characteristic *HP* regime develops in a particular RS landscape as a result of nonlinear interactions among 3-D landscape geometry attributes: *%R*, *e*, and Δz. Together, these properties constitute the hydraulic geometry of the RS system and dictate the magnitude and variation of discharge competence, and hence *HP*. Here we explored effects of Δz on *HP* only for *%R* = 50% because this patch density approximates mean ridge-density in the best conserved RS landscapes [*Wu et al*., 2006]. However, we expect similar relationships in landscapes with %R from 35–55% and conserved anisotropy ($\varepsilon \approx 4.0$ to 6.0). For landscapes with very high or low *%R* [*Wu et al*., 2006; *Yuan et al*., 2015; *Casey et al*., 2016; *Nungesser*, 2011], effects of ε and Δz on *HP* are likely minimal because of inherently high or low corresponding specific discharge.

5.3. Restoration Flows and Hydroperiods

Inferences about restoration flows necessary to meet a target *HP* regime strongly depend on historical accounts of higher ridge elevations. Increasing Δz from 0.25 to 0.50 m would require flow twice what is currently observed to meet long-term target *HP*. This increases to roughly 3 times contemporary flow for $\Delta z = 0.75$ and 0.9 m (the upper bound of plausible historic ridge elevations). Although data on predrainage flows are limited, these inferences are in close agreement with indirect estimates suggesting 2.5–4.0 times greater historical flow than in the current system [*Marshall et al*., 2009, 2014; *Choi and Harvey*, 2016]. Similar estimates were also obtained by *Smith et al*. [1989] who reported freshwater flow from Everglades to Florida Bay may have declined by up to 60% due to hydrologic alteration. Thus, our analysis suggests that under plausible scenarios of higher predrainage flows, it was possible for markedly taller ridges to maintain a *HP* environment suitable for stable spatial patterns and ecosystem functions.

While we provide inferences on mean flows required to sustain target *HP* under a historical landscape configuration, temporal distribution of flows is also important for maintaining landscape patterns. There is strong evidence that water management in the Everglades has affected not only the magnitude of flow but also the temporal distribution, with the largest flow deficits during the dry seasons [*Marshall et al*., 2009; *Fennema et al*., 1994]. Historical flow may also have been spatially variable over the large extent of the historical ridge-slough landscape, resulting in different *HP* patterns at different locations [*Fennema et al*., 1994; *Said and Brown*, 2013]. Despite this potential spatial variation, we note that ridge-slough restoration is currently focused on WCA-3A (location of our reference landscape), because that is where restoration efforts are likely to be most tractable in the short term. Caution applying these results for ridge-slough settings outside the central Everglades is warranted. It is also crucial to highlight that because *HP* is central to development and maintenance of both 2-D and 3-D spatial patterning, these results may have important implications for determining restoration flows required to induce ecologically desirable changes in contemporary RS landscapes.

Finally, a key challenge in landscape and ecosystem restoration is our limited ability to predict overall system response to restored conditions. In the Everglades RS landscape, feedbacks between flow (or *HP*) and landscape attributes (%*R*, ε, and Δz) are nonlinear, making restoration responses difficult to predict. Whether historical landscape properties, such as higher ridge-elevation and patch anisotropy, will reemerge in response to restored higher flows in the RS landscape remains an open question. For example, *Choi and Harvey* [2016] used hydrologic simulations to show that even modest flow restoration may induce desired landscape response and lead to improved ecosystem functions. This indicates that the RS ecosystem could be substantially improved even if flow restoration to sustain the target *HP* for $\Delta z = 0.75$ m (i.e., ca. 3 times contemporary flow) is not possible. Furthermore, *Watts et al*. [2010] provided evidence for the existence of alternate, stable peat-elevation states mediated by *HP*, suggesting that flow restoration may change the trajectory of landscape recovery toward new, stable peat-elevation equilibria with taller ridges. In contrast, many ecosystems demonstrate hysteretic trajectories of degradation and recovery [*May*, 1977; *Scheffer et al*., 2001; *Suding et al*., 2004]. Loss of RS patterning in the Everglades (i.e., reduced anisotropy, connectivity, and slough coverage) has been observed over a relatively short time [*Casey et al*., 2016], and these newly degraded landscapes may be resilient to flow restoration efforts without more direct intervention. As restoration proceeds, observational and modeling studies are needed to assess the success of restoration flows in meeting system goals and to inform adaptive management.

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