Hydrological drivers of wetland vegetational biodiversity within Everglades National Park, Florida

M. Jason Todd¹, D. Pumo¹,², S. Azaele¹, R. Muneeperakul¹, F. Miralles-Wilhelm³, A. Rinaldo⁴,⁵, and I. Rodriguez-Iturbe¹


¹Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544
²Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, Università di Palermo, Viale delle Scienze, 90128, Palermo, Italy
³Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174
⁴Department IMAGE and International Centre for Hydrology “Dino Tonini,” Università di Padova, via Loredan 20, I-35131, Padova, Italy
⁵Laboratory of Ecohydrology, Faculté ENAC, École Polytechnique Fédérale, Lausanne, CH-1015, Switzerland

Importance of Wetlands

1) Provide hydrologic connectivity and storage
2) Harbors of biodiversity for variety of plants and animals
3) Maintenance of water quality and pollutant removal

Everglades

- Historically over 10,000 km², now half that
- 2nd Largest NP in the U.S. at nearly 5,700 km²
- Mosaic of different vegetative communities, but sawgrass dominant
- Today hydrologically altered landscape due to human modification and drainage
- Natural hydrology dominated by precip and ET, distinct wet and dry seasons

Figure 1. Map of Everglades National Park study area
Goal: To link hydrological dynamics and their influences on vegetational distribution and species richness across Everglades National Park

- Of growing interest due to human alteration and climate change
- Hydrology a driving force in shaping wetland communities
- Generally conducted at narrow spatial scales

Wetlands hydrologic structure can be defined by:
1) Number of distinct hydroperiods (wetting/drying cycles)
2) Duration of a hydroperiod
3) Average depth of water for a hydroperiod
4) Percentage of time a wetland remains inundated
   - All are random variables that differ in time and space

Vegetational structure can be defined by the dominant vegetation type within a given geographical area.
Data Sets

**Everglades Depth Estimation Network (EDEN)**
- Water-surface model which determines the median daily measure of water
- From 2000–present. We use from 2000–2007
- Depends on over 250 water-level gauging stations and ground surface elevation data
- Extrapolates values of water depth at ungauged locations using radial basis functions with multiquadric regression.
- Resolution is at 400mX400m
- Shown to provide an accurate high-resolution measure of water levels (Liu et al. 2009)

**Vegetation Dataset**
- Developed by Center of Remote Sensing and Mapping Science at the Univ. of Georgia and the South Florida Natural Resources Center, Everglades National Park
- Consists of 79 different vegetational communities
- Detailed map at 1:15,000 scale
- 20mX20m grid was created and dominant vegetation type (>50% of the vegetation within the polygon) extracted out for each pixel.
Each 20mX20m pixel defined by:

- Vegetation Type
- 4 hydrologic parameters of larger 400mX400m pixel
- Total of over 5 million data points
Figure X. Classification of hydrologic parameters across Everglades National Park including: a) Average number of hydroperiods per year; b) average depth of a hydroperiod (cm); c) average duration of a hydroperiod (d); and d) percent time of inundation.
Vegetation Dataset

- Total of 56 community types (Out of 79)
  - 52 Vegetative Communities
  - 3 Manmade
    - Canals
    - Roads
    - Structures and Cultivated Lawns
  - 1 Open Water

- Sawgrass by far most abundant (60.5% of all pixels)

- Thirteen vegetation types make up more than 92% of total landscape

- One exotic community (Brazilian Pepper) found within top 13

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>% Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawgrass</td>
<td>60.7</td>
</tr>
<tr>
<td>Mixed</td>
<td>6.5</td>
</tr>
<tr>
<td>Tall Sawgrass</td>
<td>5.8</td>
</tr>
<tr>
<td>Muhly Grass</td>
<td>4.1</td>
</tr>
<tr>
<td>Spike Rush</td>
<td>3.0</td>
</tr>
<tr>
<td>Red Mangrove</td>
<td>2.2</td>
</tr>
<tr>
<td>Bayhead</td>
<td>1.7</td>
</tr>
<tr>
<td>Pine Savanna</td>
<td>1.6</td>
</tr>
<tr>
<td>Willow Shrublands</td>
<td>1.5</td>
</tr>
<tr>
<td>Dwarf Cypress</td>
<td>1.5</td>
</tr>
<tr>
<td>Bay-Hardwood</td>
<td>1.4</td>
</tr>
<tr>
<td>Brazilian Pepper</td>
<td>1.2</td>
</tr>
<tr>
<td>Cattail Marsh</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Only those vegetation types constituting more than one percent of the total landscape listed
Sawgrass

Figure X. Relative abundance of sawgrass for a) number of hydroperiods per year b) mean depth per hydroperiod and c) mean duration per hydroperiod and d) percent time inundated for each bin. The red line indicates the relative abundance of sawgrass across the entire landscape. Black bars indicate bins which there were no data.
Muhly Grass

Figure X: Relative abundance of muhly grass for: a) number of hydropodics per year; b) mean depth per hydropod; c) mean duration per hydropod; and, d) percent time inundated for each bin. The red line indicates the relative abundance of muhly grass across the entire landscape. Black bars indicate bins where there were no data.
Red Mangrove Scrub

Figure X. Relative abundance of red mangrove scrub for a) number of hydroperiods per year, b) mean depth per hydroperiod and, c) mean duration per hydroperiod and; d) percent time inundated for each bin. The red line indicates the relative abundance of red mangrove scrub across the entire landscape. Black bars indicate bins in which there were no data.
Figure X. Relative abundance of bay-hardwood scrub for a) number of hydroperiods per year, b) mean depth per hydroperiod, c) mean duration per hydroperiod, and d) percent time inundated for each bin. The red line indicates the relative abundance of bay-hardwood scrub across the entire landscape. Black bars indicate bins with no data.
CV gives idea of how variable the distribution is from the mean.
- Lower CV = less variation from mean, evidence of less selection.
- Higher CV = increased variation from mean, evidence of more selection.

E.g. Muhly grass 11X more variation than sawgrass. Suggests Muhly grass strongly influenced by percent time inundated.

Coupling of graphical evidence w/ CV can help identify those communities most influenced by hydrologic parameters.

Figure X: Relative abundance of (a) sawgrass and (b) muhly grass related to percent of time inundated with associated coefficient of variation. The red line indicates the relative abundance of that vegetative community across the entire landscape.
Coefficient of Variation

Table 2. Coefficient of variation for vegetation types related to hydrologic parameter within the Everglades National Park.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Hydro</th>
<th>Depth</th>
<th>Duration</th>
<th>PercWet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawgrass</td>
<td>0.597</td>
<td>0.617</td>
<td>0.422</td>
<td>0.189</td>
</tr>
<tr>
<td>Mixed Graminoids</td>
<td>0.806</td>
<td>1.109</td>
<td>1.181</td>
<td>1.011</td>
</tr>
<tr>
<td>Tall Sawgrass</td>
<td>3.768</td>
<td>1.161</td>
<td>1.871</td>
<td>0.790</td>
</tr>
<tr>
<td>Muhly Grass</td>
<td>1.119</td>
<td>1.130</td>
<td>0.994</td>
<td>2.144</td>
</tr>
<tr>
<td>Spike Rush</td>
<td>1.363</td>
<td>2.162</td>
<td>1.977</td>
<td>0.928</td>
</tr>
<tr>
<td>Red Mangrove Sub</td>
<td>5.516</td>
<td>7.106</td>
<td>4.190</td>
<td>1.142</td>
</tr>
<tr>
<td>Bayhead</td>
<td>1.901</td>
<td>0.856</td>
<td>0.580</td>
<td>0.589</td>
</tr>
<tr>
<td>Pine Savanna</td>
<td>15.229</td>
<td>0.956</td>
<td>0.994</td>
<td>2.435</td>
</tr>
<tr>
<td>Willow Shrublands</td>
<td>0.818</td>
<td>0.820</td>
<td>0.732</td>
<td>0.819</td>
</tr>
<tr>
<td>Dwarf Cypress</td>
<td>0.963</td>
<td>0.946</td>
<td>0.943</td>
<td>1.473</td>
</tr>
<tr>
<td>Bay-Hardwood Sub</td>
<td>4.496</td>
<td>4.811</td>
<td>2.879</td>
<td>1.147</td>
</tr>
<tr>
<td>Brazilian Pepper</td>
<td>1.305</td>
<td>0.917</td>
<td>0.987</td>
<td>2.076</td>
</tr>
<tr>
<td>Cattail Marsh</td>
<td>2.387</td>
<td>1.035</td>
<td>4.943</td>
<td>0.961</td>
</tr>
</tbody>
</table>

Only those vegetation types constituting more than one percent of the total landscape listed.

Three highest values of CV for individual hydrologic parameter highlighted in green. Lowest value highlighted in grey.

- Some vegetation types appear to be structured by multiple hydrologic factors.
- Sawgrass lowest CV across all four variables.
- Average depth and percent of time inundated appear to be most discriminatory
  - All bins have data
  - Least skewed distributions
Relationship between % flooded and conditional mean depth
Conclusions

• Total of 56 community types in ENP with Sawgrass being most common by an order of magnitude

• Hydroperiod characteristics for the ENP can be calculated for a 7+ year period of record

• Vegetation communities display different patterns of relative abundances across a hydroperiod parameter.

• Two most discriminatory hydrologic variables:
  • Average depth
  • Percent time inundated

• Combining graphs with measures of coefficient of variance allows for differentiation of communities into hydrologically “selective” and “unselective”
Future Directions

• This work has shown evidence of hydrologic variation affecting vegetation distribution

• Changes in hydrology within ENP likely to be a result of:
  • Climate Change
  • Frequency and Intensity of Rainfall Events
  • Anthropogenic Control of Canals
  • Direct Impact on Hydrologic Parameters

• These modifications will have a hydrologic impact both temporally and spatially

Can we predict what effects hypothesized changes in hydrology will have on vegetation composition and distribution?
Humidlands

**WETLAND:** environment at the interface between **TERRESTRIAL** and **AQUATIC** ecosystems

**HUMIDLAND:** environment with shallow water table, where the ecosystem strongly depends on the **groundwater**

**EXAMPLES** of **HUMIDLANDS:**
- riparian zones
- coastal areas
- peatlands
- croplands
- unsubmerged wetlands, ...

![Diagram of a wetland ecosystem with text explaining the concepts of wetlands and humidlands, along with examples of such environments.](image-url)
Interactions and feedbacks

**Semi-arid ecosystems**
- Precipitation
- Soil moisture - rainfall feedback
- Nitrogen / Carbon Cycles
- Vegetation

**Humidland ecosystems**
- Water Table
- Soil Moisture
- Vegetation water stress
- Control on vegetation/roots

**Feedbacks**
- Soil moisture - rainfall feedback
- Vegetation water stress
- Control on vegetation/roots
Modelling Scheme

- Evapotranspiration
- Stochastic rainfall
- Capillary rise
- Lateral groundwater flow
- Recharge
TS/PH-6
Site status: Active (Active from March 2000)
Latitude: 25.21418102 Longitude: -80.6490792 Size: Approx. 1 ha
Watershed: Taylor Slough
Hydrography: Seasonally driven freshwater inputs and wind-driven estuarine inputs
Topography: Flat, with tidal creek topography Geology: Limestone bedrock
Soil: Wetland peat, >1 m thick
Vegetation: Mangrove forest
Habitat: Mangrove wetland, low/dwarf stature Climatology: Subtropical moist, with distinctive wet (June–Nov.) and dry (Dec–May) seasons

TS/PH-7
Site status: Active (Active from March 2000)
Latitude: 25.19080491 Longitude: -80.63910514 Size: Approx. 1 ha
Watershed: Taylor Slough
Hydrography: Seasonally driven freshwater inputs and wind-driven estuarine inputs
Topography: Flat, with tidal creek topography Geology: Limestone bedrock
Soil: Wetland peat, >1 m thick
Vegetation: Mangrove forest
Habitat: Mangrove wetland, low/dwarf stature Climatology: Subtropical moist, with distinctive wet (June–Nov.) and dry (Dec–May) seasons
### Period of observation considered for each site

For each site, a period in which simultaneous observations of rainfalls, evapotranspiration values and water table levels are available, has been considered.

<table>
<thead>
<tr>
<th>Site</th>
<th>From</th>
<th>To</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS/PH-6</td>
<td>08/14/2001</td>
<td>12/14/2004</td>
</tr>
<tr>
<td>TS/PH-7</td>
<td>08/14/2001</td>
<td>12/14/2004</td>
</tr>
</tbody>
</table>
Input estimation

For the estimation of $\alpha$, $\lambda$, and $E_p$, the mean values over the entire observed period, arising from the historical series (of precipitations and evapotranspiration respectively), have been

- Rainfall

From FCE-LTER (Florida Coastal Everglades – Long Term Ecological Research)

- Rain level is recorded at least every thirty minutes. Rain level data are collected using ISCO rain level gages attached to ISCO autosamplers, which also act as dataloggers, and are condensed into daily cumulative rainfall (cm/day).
The FCE–LTER database does not contain evapotranspiration observations. The PET (potential evapotranspiration data) have been obtained from the EDEN (Everglades Depth Estimation Network) database. For the two sites (TS/PH-6 and 7), a correspondent station (the closest) from the EDEN Network has been identified (E146), and the recorded PET data series relative to the same observation period as before, has been taken into account.

EDEN staff receives evapotranspiration (ET) data annually from the USGS approximately six months after the end of the calendar year. Daily potential evapotranspiration (PET) values (in millimeters) are extrapolated by location for each of the EDEN water level stations.
Vegetation: Mangrove forest

Species: Rhizophora mangle, Avicennia germinans, Laguncularia racemosa, Conocarpus erectus

Avicennia germinans: Evergreen shrub or small tree 3–12 (-25) m high; trunk 30–60 dm in diameter. Masses of small air roots 15–45 cm long sometimes hang from upper part of large trunks. Pneumatophores often rise 5–10 cm from the long horizontal roots. Bark dark gray or brown and smooth on small trunks, becoming dark brown, fissured, scaly, and thick. Leaves opposite, lanceolate or narrowly elliptical, 5–11 cm long, 2–4 cm wide, acute or blunt at tip, entire, thick, leathery. Fine hairs giving a grayish hue to foliage; both surfaces often with scattered salt crystals and salty taste. Petiole 3–15 mm long. Spikes or panicles headlike, upright at and near ends of twigs. Flowers several, crowded, sessile, 6 mm long, 10 mm across. Calyx cup-shaped, deeply 5-lobed; corolla tubular, hairy, white but yellowish at base, with 4 slightly unequal spreading, rounded, or notched lobes, stamens 4, 5 mm long in notches of corolla tube near base; pistil with imperfectly 4-celled ovary, slender style, and 2-forked stigma. Capsule elliptical, flattened, 2.5–3 cm long, often splitting into 2 parts. Seed 1, large, flattened, often germinating on tree (Little, 1983).

Laguncularia racemosa: Evergreen tree to 12 m tall and 30 cm diameter, with rounded or irregular spreading crown. Bark gray-brown, becoming rough and fissured; inner bark light brown. Pneumatophores often present. Leaves opposite, elliptical, 4–10 cm long, 2.5–5 cm wide, rounded at both ends, entire, glabrous, leathery, slightly fleshy, without visible veins. Petiole 10–13 mm long, stout, reddish, with 2 raised gland-dots near blade. Panicles at ends and sides of twigs, mostly branched and spreading, 3–10 cm long. Flowers mostly bisexual ca 5 mm long, bell-shaped, whitish. Petals, 5, rounded, whitish, 1 mm long, and stamens, 10. Pistil with inferior 1-celled ovary with 2 ovules, slender style, and tiny 2-lobed stigma. Drupes several, stalkless, obovoid, 12–20 mm long, flattened, ridged, gray-green with velvety hairs when immature, turning brownish. Seed 1, large, sometimes viviparous (Little, 1983).
• **Topography:**
The nearest Water Body is the sea (0 m a.s.l.). Then, for each of the four sites, the value of $y_0$ corresponds to the opposite of the terrain elevation of the ground surface in the same site. The elevation for each site has been taken from an High Accuracy Elevation Data map for the Lake Okeechobee Littoral Zone by USGS-Sofia, available in the web site of Global Change Master Directory (Goddard Space Flight Center – NASA).

From a modellistic point of view, $y_0$ can not be positive (the model does not account for water standing conditions), then for the sites SRS-3 and TS/PH-3, $y_0$ has been considered equal to 0.

<table>
<thead>
<tr>
<th>Site</th>
<th>$y_0$ Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS/PH-6</td>
<td>26 cm</td>
<td>0 cm</td>
</tr>
<tr>
<td>TS/PH-7</td>
<td>11 cm</td>
<td>0 cm</td>
</tr>
</tbody>
</table>
Model Input estimation: Soil

Geology: Limestone bedrock
Soil: Wetland peat, x 1 m thick

It has been considered a clay soil type with features taken from Rawls and Brakensiek (1989)

- \( m = \) pore size distribution = 0.131;
- \( K_s = \) saturated hydraulic conductivity = 0.06 \( \times 24 = 1.44 \) (cm/day);
- \( n = \) porosity = 0.475;
- \( h_d = \) Bubbling pressure head = -37.30 (cm);
- \( s_w = \) relative water content at wilting point = 0.272/n = 0.573;
## Input Data

<table>
<thead>
<tr>
<th></th>
<th>Site</th>
<th>TS/PH-6</th>
<th>TS/PH-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>cm</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>1/day</td>
<td>0.410</td>
<td>0.410</td>
</tr>
<tr>
<td>MAP</td>
<td>cm/year</td>
<td>171</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>PET</td>
<td>mm</td>
<td>3.97</td>
</tr>
<tr>
<td>$y_0$</td>
<td>cm</td>
<td>26</td>
<td>11</td>
</tr>
<tr>
<td>considered</td>
<td>cm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b$</td>
<td>cm</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>cm</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Water level is recorded at least hourly. Water level is measured with acoustic (and Pressure) water level gages that digitally record water height relative to the local soil surface. Ultrasonic water level recorders are placed at each site. The recorders collect water level readings every hour. The data is collected from the water level recorder using an HP 48G+ calculator on a monthly basis. To make a daily water level reading, all numbers are downloaded into Microsoft Excel, and all the readings from a day are averaged.
Historical series of water levels from 1999 to 2006 for the site TS/PH-6

- Total number of observation = 2620 days
- Number of “no data” values = 81 days
- number_stand_water_periods = 32
- mean_hydroperiod = 18.9 days
- mean_stand_water_amount = 4.45 cm
- upcrossing = 32
- downcrossing = 31
TS/PH-6 – Historical series for the observed period (08/14/01 – 12/14/04)
TS/PH-7 – Total historical series of water levels (from 04/07/96 – 09/30/06)
From FCE-LTER (Florida Coastal Everglades – Long Term Ecological Research)
Historical series of water levels from 1996 to 2006 for the site TS/PH-7

- Total number of observation = 3829 days
- Number of “no data” values = 7 days
- number_stand_water_periods = 46
- mean_hydroperiod = 2.9 days
- mean_stand_water_amount = 6.74 cm
- upcrossing = 46
- downcrossing = 46
TS/PH-7 – Historical series for the whole observed period (08/14/01 – 12/14/04)
TS/PH-7 – Historical series for 150 days (from 07/03/04 to 11/30/04)
Grid= 10 days x 10 days
TS/PH-7 – Historical series for 30 days (from 15/08/02 to 09/17/02)
Grid= daily
TSS/PH7 - Comparison between the cdf's arising from the model (red) and from the observed data (from 1996 to 2006)

- Red line: model cdf (b=10 cm)
- Blue circles: cdf from observed data (complete series)
- Green triangles: cdf from observed data (series without positive values)
Rainfall–driven water level fluctuation in wetlands

Marked Poisson process representing rainfall

Water level dynamics

Water loss function
Water loss function

Piecewise linear loss function

The “effective” loss due to evapotranspiration and topography-induced drainage

Reduced loss as WT gets deeper

Loss due to lateral surface flow

Assume fixed values for $D_0$ (say 200 cm) and tune $L_g$ and $k$.

(In reality, the underground loss function can be quite complicated, but it is significantly simplified here as our focus is on the aboveground part.)
Determine hydrological parameters

The probability density function (pdf) of water level, \( p(y) \), can be written as:

\[
p(y) = \frac{c}{\chi(y)} \exp \left( -\frac{y}{\alpha} + \lambda \int \frac{dy}{\chi(y)} \right)
\]

where \( \frac{\bar{\alpha}}{\alpha} \) = mean daily rainfall depth
\( \lambda \) = rainfall arrival rate
\( \chi(y) \) = water loss function
\( c \) = normalization constant

Using the observed values of \% flooded, conditional mean, and conditional variance, we can estimate \( L_0 \) and \( k \) to characterize the loss function of each pixel.
Examples of resulting probability density functions

\[ p(y) \]

\[ p(y) \]

\[ p(y) \]

\( y, \) water level aboveground (cm)

Wet ——————————— Dry
Application to climate change

Once $L_y$ and $k$ are known, we can predict $p(y)$ under climate change. For example, if $\lambda$ is 10% lower, $p(y)$ will change. Coupling this prediction with the relationships between vegetation communities and hydrological quantities established in the preceding analysis, we can make some predictions regarding changes in vegetation communities in the Everglades under climate change!
Rainfall variability

Histograms of $\alpha$ (mean daily rainfall) and $\lambda$ (arrival rate of rainfall events) based on raingage data obtained from Everglades Depth Estimation Network (EDEN) for Support of Biological and Ecological Assessments (http://sofia.usgs.gov/eden). The histograms include only raingages listed under Everglades National Park–East and Everglades National Park–West at EDEN.
Stochastic Modelling of Seasonality in Water Table

Seasonal evolution brings about:
1–Non-stationary effects
2–Presence of different scales:
   a–seasonal effects (order of a few months)
   b–water table fluctuations (order of few days)
Main results:
   a–pdf of water table depth
   b– autocorrelation and crossing properties of the process.
Figure 1: A schematic diagram of water fluxes that control the hydroperiod dynamics in wetland ecosystems.
Figure 3: A tentative schematic diagram showing the processes to be included in the plant-resource model (section III.4). The thick open arrows represent element exchanges with the surrounding environment and the thin arrows the internal cycling. The meanings of the symbols are: A = assimilation; R = respiration; IN = incoming fluxes of nutrients (e.g., atmospheric deposition and nitrogen fixation); OUT = outgoing fluxes of nutrients (e.g., denitrification); S = senescence; D = death; U = plant uptake; AL = allocation; DEC = decomposition; and H = humification.
Questions for Plant Model.

- Which traits do plants optimize in wetland environments to maximize assimilation. Consider:
  1. Fraction of carbon assimilation allocated to rhizome.
  2. Leaf nitrogen content.
  3. Specific leaf area (e.g., leaf area per unit leaf mass).

Plant is subjected to changes in the water regime. Specific consideration of hydroperiod dynamics and Rainfall regime.

Full interaction with nutrient dynamics.
Miao (Aquatic Botany, 2004) showed the differences among species in their allometric relationships between leaf and rhizome biomass.
Wright et al. (*Nature*, 2004) showed that the multiple regression with specific leaf area (leaf area per unit leaf mass) and leaf nitrogen can explain key important plant processes, e.g., net photosynthesis, dark respiration, and leaf lifespan.

**The Three Plant Traits:**
(2) Specific Leaf Area and (3) Leaf Nitrogen
Thank You!