Assessment of Wind and Vegetation Interactions in Constructed Wetlands

Mohamed Moustafa *,† and Naiming Wang‡

South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, USA; nwang@sfwmd.gov
* Correspondence: zmoustafa@sfecc.us; Tel.: +1-686-8800
† This author has retired.

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Abstract: Meteorological data from vegetated and un-vegetated wetlands during wet and dry seasons, were collected and analyzed to evaluate the role of wind and vegetation on wetlands’ hydrology. Wind speed diminished by as much as 40%, accompanied by a measurable change in wind directions in the vegetated compared to the open water site. Wind speed and direction means were significantly different (p < 0.001 and <0.01), for vegetated and non-vegetated wetland, respectively. Cattails (Typha sp.) and open water estimates of wind drag coefficients using the log wind profile, were 0.016 and 0.009 for dry season, and 0.012 and 0.005 for wet season, respectively. Wind set up near the wetland outlet was more pronounced at shallow water depth (<20 cm). Measured velocity profile during inflow discharge event with a wind speed of 0.53 ms⁻¹, showed two-layer flows; wind-generated surface water flow opposite to a sub-surface inflow. This opposing surface flow increases hydraulic residence time and improve nutrient uptake. Conversely, wind-generated flows aligned with inflow discharges, accelerates water flow towards the outlet, reduce the duration of water-biotic interactions, and decrease nutrient uptake.

Keywords: constructed wetland; vegetation; drag coefficient; hydraulic residence time (HRT); wind; wind stress; wind velocity

1. Introduction

Aquatic vegetation is an integral part of all natural and constructed wetlands and plays a vital role in treating both urban and agricultural runoff as well as wastewater. Aquatic plants assimilate nutrients for growth and reproduction, provide surface area for microbial growth, stabilize the soil, act as a filter to trap submerged detritus and sediment, induce resistance to flow, and decrease the ability of the water to carry sediments [1–5].

In south Florida, permanent features such as above ground reservoirs (flow equalization basin (FEB)) and large constructed wetlands (stormwater treatment area (STA)) are used to store and remove phosphorus (P) from stormwater runoff. Presence of emergent aquatic vegetation (EAV) in wetlands in those features reduces prevailing wind speed similar to the presence of trees, forests, and obstacles on land [6]. The key role of aquatic vegetation in both features is to remove phosphorus from agriculture runoff to acceptable levels before water is released southward into the Northern Everglades. However, the presence of EAV in those features induce resistance to flow, which causes delays of water deliveries within and in-between features [7].

Previous research has identified hydraulic factors that have the greatest impact on wetland treatment efficiency, mainly the duration of water-biotic interactions [8], water depth, hydraulic loading rate (HLR), and hydraulic residence time (HRT). However, HRT (how fast/slow water moves through a wetland) is the key factor that determines treatment efficiency and the quality of water at the wetland.

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Water flow through a wetland is affected by the presence of aquatic vegetation (both emergent and submersed), and their associated properties such as vegetation type (rooted, floating, etc.), size, density, and stem flexibility. The mere presence of aquatic vegetation (e.g., emergent and submersed) may cause short circuiting, which is expected to occur particularly in large constructed wetlands (STAs). Short circuiting in a wetland leads to a short contact time with resident biota, and consequently reduces nutrient uptake and performance [1,9].

Despite the vast amount of research in literature regarding the interaction between prevailing winds and aquatic vegetation in general, little information is available to quantify EAV effects on wind speed and directions in large constructed wetlands (i.e., STAs and FEBs), and very little attention has been given to quantifying the interaction between prevailing wind and EAV by calculating roughness length or drag coefficient. Research involving wind effects on wetlands includes both laboratory and field observations. Laboratory experiments showed that the presence of emergent macrophytes significantly enhanced vertical transport, particularly gas transfer across the air–water interface [11]. The gas transfer coefficient also increased as wind speed increased.

In south Florida, previous field studies focused primarily on wetland water flow under hurricane conditions [12]. Sediment resuspension (measured by sediment traps) increased significantly in open water areas compared to areas protected from wind by emergent vegetation [13]. In addition, numerous studies measured drag coefficients of solid objects (e.g., cones, hemisphere, cubes, and pyramids) placed on flat surfaces in wind tunnels and flumes, while others used direct field measurements to calculate wind drag on trees for modeling purposes [14,15]. Furthermore, [16] reported that seasonal variations, up to 5-fold increases in surface roughness lengths, is due to the difference of growing seasons for natural surfaces including wetlands.

Most of the research involving wind effects on wetlands focused largely on high and low frequency of meteorological stressors that impact wetlands in different ways. Severe impacts due to low frequency and high magnitude events such as hurricane and big storms, may last for decades and cover exceptionally large areas [17]. Most high frequency and low magnitude events, such as rainfall, evapotranspiration (ET), inflow discharges and winds, exert a regular, almost predictable, influence on wetlands’ ecosystem in terms of primary production, nutrient uptakes, and cycling. However, extraordinarily little is known about the impact of high frequency and low magnitude winds on wetlands in terms of vegetation resistance and wetland hydrology. Therefore, the major goals of this experiment are to answer the following questions, (1) What are the impacts, if any, of winds and EAV on wetland hydrology? (2) Determine if other weather parameters/stressors are being impacted due to the presence of EAV, (3) and if so, which ones are being impacted the most, and what are the implication of such change? Project objectives also included estimating drag coefficients to quantify the direct interaction of wind and EAV in wetlands.

Weather parameters were measured at three locations during wet and dry season in south Florida. Two weather stations were deployed in adjacent vegetated (EAV) and non-vegetated wetlands during wet and dry seasons (Figure 1). The third location is a permanent station (ENR 308) located at the standard ten-meter height (26°37′22.4″ N and 80°26′21.38″ W). Results obtained from the combined dataset of all three stations were used to assess winds and EAV interactions on wetlands hydrology and estimate cattail drag coefficients. Observed wind and water velocity measured in a large constructed wetland during a discharge event, were combined to illustrate the impact of prevailing winds (high frequency and low magnitude) on wetland hydrology.
Figure 1. Experimental site: The test cells are shallow, rectangular-shaped wetlands approximately 2000.00 m$^2$ located within the boundaries of STA-1W (26°37′22.9″ N and 80°25′36.6″ W) treatment Cell 3. Two test cells (approximately, 70 × 30 m) were used in this experiment. Cell #12 is dominated by emergent aquatic vegetation (EAV) while Cell #13 is void of vegetation (control). All cells depicted in this figure have the same dimension.

2. Materials and Methods

2.1. Data Collection

Metrological data were collected using an Airmar 150WX Ultrasonic weather station (www.fondriest.com, Fairborn, OH, USA). The Airmar 150WX is a compact weather station ideal for moving platforms and wetland environments. The sensor outputs apparent and true wind speed and direction, barometric pressure, air temperature, and GPS location. The Airmar weather station is rated for use on buoy platforms (IPX6 waterproof) and measures wind speed and direction with integrated 10 Hz GPS and 2-axis compass, tilt, temperature, pressure, and humidity sensor modules. Sampling intervals for all parameters were set at 15 min.

The initial monitoring period lasted for almost one month (wet season), between 12 June through 10 July 2014, while the second sampling interval covered approximately five months (dry season) between 2 November 2014 through 12 March 2015. The temporary weather stations were located at the center of each test cell (Figure 1), less than 25 m apart, and were placed at the same exact height above water level (~2 m). The nearby permanent weather station (ENR 308) is set at the standard ten-meter height, approximately eight meters higher than the Airmar weather stations located at the test cells.
2.2. Wind Stress

For practical applications and when observed wind speed is less than 10 m s\(^{-1}\), it is reasonable to use an empirical formula \cite{18} to calculate wind stress as follow:

\[
\tau = C_D \rho_{air} U_{10}^2 \tag{1}
\]

where \(U_{10}\) = wind speed at 10 m above the water surface; \(\rho_{air} = 1.22\ \text{kg m}^{-3}\), air density; and \(C_D = 0.0013\) dimensionless drag coefficient; a typical value which gives \(\tau\) in units of \(\text{N m}^{-2}\), or Pascals (Pa).

2.3. Wind Drag Coefficients

2.3.1. Power Law Wind Profile

The wind profile power law describes the relationship between wind speeds at two different heights \cite{19,20}. Most application of the wind profile power law are conducted to assess wind power at specific heights for wind turbines \cite{21}, and applications of atmospheric pollution dispersion models \cite{22}. Because the wind profile at atmospheric boundary layer (0–2000 m) is generally logarithmic in nature, it is best approximated by using the log wind profile equation, which accounts for surface roughness and atmospheric stability. However, when surface roughness or atmospheric stability information is lacking, the wind profile power law is commonly used:

\[
\frac{u}{u_r} = \left( \frac{z}{z_r} \right)^\alpha \tag{2}
\]

where \(u = \text{wind speed (ms}^{-1})\) at height \(z\) (meters) above ground level and \(u_r\) is the wind speed measured at a reference height \(z_r\) (meters); reference height in this experiment is ten meters (ENR 308 station); and \(\alpha\) is an empirically derived coefficient and is approximately = 0.143 for neutral stability in atmospheric conditions. The exponent value is almost constant, particularly if the difference between the two wind speed heights is less than 50 m \cite{21}.

2.3.2. Log Wind Profile

The simplest form to represent wind drag is to use a constant value like the one used in Equation (1). However, a more accurate and reliable approach would be to use a logarithmic wind profile above the surface \cite{23}. For this field experiment, the neutral atmospheric stability conditions apply:

\[
U_z = \frac{u_*}{k} \ln \left( \frac{z - d}{z_o} \right) \tag{3}
\]

where \(U_z\) is the mean wind speed at height \(z\) (meters) above the ground surface, \(u_*\) is the friction or shear velocity (ms\(^{-1}\)), \(k\) is the Von Karman constant (approximately = 0.41), and \(d\) is the height in meters above the ground surface that equals to the depth of an air layer trapped in vegetation at which wind speed is zero as a result of flow obstacles. For cattail in this case, it is approximated at \(2/3\) of the average height (2.0 m) of the obstacles \((2/3 \times 2.0 = 1.33\ \text{m}; \ [23])\); \(z_o\) is the roughness length, which is a corrective measure to account for the effect of the roughness of a surface or an obstacle (EAV in this case) on wind flow. The wind speed at the standard ten-meter height, measured at the ENR 308 station, is determined from the wind speed at 10 m:

\[
U_{10} = \frac{u_*}{k} \ln \left( \frac{Z_{10} - d}{Z_o} \right) \tag{4}
\]
While wind speed at the top of vegetation (lower height compared to standard 10-m height) is calculated as follows:

\[
U_2 = \frac{u_*}{k} \ln \left( \frac{Z_2 - d}{Z_0} \right)
\]  

(5)

Dividing Equation (3) by (4) results in a ratio of wind speeds:

\[
\frac{U_{10}}{U_2} = \frac{\ln(Z_{10} - d) - \ln z_0}{\ln(Z_2 - d) - \ln z_0}
\]  

(6)

Which can be rearranged to derive roughness length \(Z_0\) (m):

\[
z_0 = e^{\frac{U_{10} \ln \left( \frac{Z_{10} - d}{Z_2 - d} \right) - U_2 \ln \left( \frac{Z_{10} - d}{Z_2 - d} \right)}{\ln^2 \left( \frac{Z_{10} - d}{Z_2 - d} \right)}}
\]  

(7)

We can then calculate wind drag coefficient using wind speed at the standard ten-meter heights:

\[
C_D = \frac{k^2}{\ln^2 \left( \frac{Z_{10}}{z_0} \right)}
\]  

(8)

Drag coefficients were calculated using Equations (2) and (8) along with wind speed measurements from the ENR 308 (ten-meter height), vegetated wetland (cattail height = 2.0 m), and non-vegetated wetland/control (30 cm water depth).

2.4. Wind Setup

In general, surface water moves in the direction of wind causing a rise of water level at the downwind side of an inland water body. However, no previous studies have calculated wind setup in a wetland, presumably due to lack of practical methods, and most likely is the fact that wind friction is commonly considered to be part of variability of overall marsh flow frictions [24]. However, [25] described several methods to calculate wind setup for lakes and coastal areas. A simplified formula that gives a reasonably good estimate is given by [26]:

\[
S = \frac{UL^2F_u}{4.985D}
\]  

(9)

where

- \(S\) = wind setup (m),
- \(U\) = wind speed (m/s),
- \(F_u\) = wind fetch (km), and
- \(D\) = average depth over the wind fetch (m).

To assess the impact of wind set up at the wetland outflow, an overland flow equation following a general power law relationship can be used [24, 27]:

\[
Q = WaD^b
\]  

(10)

where

- \(Q\) = outflow (m\(^3\)/s),
- \(W\) = mean flow width (m),
- \(D\) = average depth (m),
- \(a\) = empirical parameter, and
- \(b\) = empirical exponent parameter. Walker and Kadlec [27] suggest using 3 to 4 for typical STA or wetland cell.
The relative increase of outflow discharge due to wind setup can be estimated based on Equation (11) as:

\[
\frac{Q_s}{Q} = \left( \frac{D + S}{D} \right)^b
\]

where

\(Q_s\) = outflow with wind setup (m³/s), and
\(S\) = wind setup (m).

2.5. Wind Stress

At the experiment site, water flows in a northerly direction (i.e., from south to north) between inflow and outflow structures. Observed wind vectors (speed and directions) were decomposed into two components, one aligned north–south and the other east-west direction to match water-flow alignment between inflow and outflow structures. Wind stress calculated using Equation (1), was also decomposed along these two directions, which resulted in a north-south and east-west stress component, pushing water along those directions (Table 1).

### Table 1. Wind Stress descriptive statistics at vegetated (Cell 12) and non-vegetated (Cell 13) wetland during the dry season between 2 November 2014 and 12 March 2015, and during the wet season between 12 June and 10 July 2014.

| Statistic | Wind (U), X-axis | Wind (V), Y-axis | Stress (U), X-axis | Stress (V), Y-axis | Wind (U), X-axis | Wind (V), Y-axis | Stress (U), X-axis | Stress (V), Y-axis |
|-----------|-----------------|-----------------|-------------------|-------------------|-----------------|-----------------|-------------------|-------------------|
| **Vegetated Cell 12** | | | | | | | | |
| Mean | −0.02850 | −0.29500 | 0.00175 | 0.00195 | −0.441505 | −0.364305 | 0.00380 | 0.00440 |
| Median | 0.00000 | −0.24630 | 0.00025 | 0.00025 | −0.468855 | −0.304675 | 0.00113 | 0.00122 |
| Mode | 0.39850 | −0.04890 | 0.00010 | 0.00020 | 0.000000 | 0.000000 | 0.00054 | 0.000000 |
| Standard Error | 0.01980 | 0.02040 | 0.00020 | 0.00020 | 0.02863 | 0.03127 | 0.00018 | 0.00018 |
| Standard Deviation | 1.02770 | 1.05800 | 0.00760 | 0.00910 | 1.48486 | 1.62170 | 0.00910 | 0.00919 |
| Minimum | −8.49470 | −9.42390 | 0.00000 | 0.00000 | −9.99391 | −7.37184 | 0.00000 | 0.00000 |
| Maximum | 6.86070 | 6.17180 | 0.11450 | 0.14090 | 7.82518 | 12.17352 | 0.15841 | 0.23504 |
| Range | 15.35540 | 15.59560 | 0.11450 | 0.14095 | 17.81909 | 19.54536 | 0.15841 | 0.23504 |
| Size | 2689 | 2689 | 2689 | 2689 | 2689 | 2689 | 2689 | 2689 |
| **Open Water Cell 13** | | | | | | | | |
| Mean | 0.26252 | 0.06584 | 0.00050 | 0.000385 | 0.480665 | 0.143305 | 0.00412 | 0.00147 |
| Median | 0.39392 | 0.10396 | 0.000295 | 0.000145 | 0.567325 | 0.094215 | 0.00134 | 0.00021 |
| Mode | 0.39392 | 0.16278 | 0.00025 | 0.0004 | 0.59088 | 0.000000 | 0.00055 | 0.00000 |
| Standard Error | 0.00440 | 0.00430 | 0.00002 | 0.00003 | 0.01377 | 0.00853 | 0.00006 | 0.00003 |
| Standard Deviation | 0.49166 | 0.48026 | 0.00252 | 0.00341 | 1.53806 | 0.95335 | 0.00719 | 0.00032 |
| Minimum | −5.93339 | −14.55484 | 0.00000 | 0.00000 | −7.56200 | −7.59884 | 0.00000 | 0.00000 |
| Maximum | 12.21926 | 4.44495 | 0.23656 | 0.33998 | 7.28222 | 5.79160 | 0.09069 | 0.09158 |
| Range | 18.14635 | 18.99980 | 0.23656 | 0.33998 | 14.84422 | 13.39044 | 0.09069 | 0.09158 |
| Size | 12,482 | 12,482 | 12,482 | 12,482 | 12,482 | 12,482 | 12,483 | 12,483 |

1—X-axis is oriented north–south direction (north is positive); 2—Y-axis is oriented east–west direction (east is positive); 3—units are in Pa; 4—units m s⁻¹; and 5—statistically significant difference at \(p < 0.001\).

To illustrate wind impacts on wetland hydrology and the generation of wind ripples in open water areas in constructed wetlands, we measured surface water velocities in Cell 3 of STA-2 where submerged aquatic vegetation (SAV) dominated, using a portable current meter (YSI, Handheld ADV FlowTracker©, San Diego, CA, USA). Velocity measurements were taken during a flow discharge event of 14.16 m³/s, which is the average discharge observed during previous field experiments.

2.6. Data Analysis

Descriptive statistics with graphical techniques were used to identify seasonality or trends, and describe relationships, if any, in time series observations. All analyses were performed with the raw data (i.e., every 15 min), and hourly means calculated from the original observations. Statistics were calculated with JMP (Version12, SAS Institute Inc., Cary, NC, USA) and SigmaPlot (Version 13, SPSS,
Inc. Chicago, IL, USA). The level of significance (\(\alpha\)) was set at 0.05 or lower as indicated for all analyses. Wind speed probability distributions were calculated to reveal the temporal characteristics of the data sets [28,29]. WRPLOT View software was used to determine wind vector and wind classes from field observations and display wind rose plots (http://www.weblakes.com/company/index.html, Waterloo, Canada) that depict the frequency of occurrence of winds in each of the specified wind-direction sectors and wind-speed classes for a given location and time period.

3. Results

3.1. Wind Speed and Direction

The overall wind speed during the wet season ranged between 0.10 and 11.80 m s\(^{-1}\) with a mean of 0.90 m s\(^{-1}\), and between 0.10 and 12.80 m s\(^{-1}\) with a mean of 1.85 m s\(^{-1}\) for vegetated and open water wetland sites, respectively. During the dry season, the overall wind speed ranged between 0.10 and 19.00 m s\(^{-1}\) with a mean of 0.62 m s\(^{-1}\), and between 0.00 and 8.10 with a mean of 1.52 m s\(^{-1}\) for vegetated and open water wetland site, respectively.

Observed wind speed and direction in vegetated and non-vegetated sites were significantly different for both dry and wet seasons (Table 2 and Figure 2). Wind speed means of the vegetated wetland during both seasons were half their counterparts in the non-vegetated site (Table 2). Wind direction in vegetated wetland was significantly different from the open water one (Figure 2). Open water wetland’s 25th and 75th percentiles of wind speed covered a much wider range compared to the vegetated one during both wet and dry season (Figure 2). However, 25th and 75th percentile of wind direction covered the same range, more or less, during both seasons. The difference in both mean and median values between the two groups is statistically significant (Table 2).

**Figure 2.** Box and Whisker plot for Wind Speed and Direction during the study: Panel (a) represents wind direction for dry season (November 2014 through March 2015); Panel (b) represents wind speed during wet season (June to July 2014); Panel (c) represents wind direction for wet season; and Panel (d) represents wind speed during dry season. Statistical significance values are also displayed on each panel.
Table 2. Descriptive statistics of all measured weather parameter in vegetated (Cell 12) and non-vegetated (Cell 13) wetlands during the dry season between 2 November 2014 and 12 March 2015 and the wet season between 12 June and 10 July 2014.

| Wet Season: 12 June through 10 July 2014 | Vegetated Cell 12 | Open Water Cell 13 |
|----------------------------------------|-------------------|-------------------|
| **Descriptive Statistics**             | **Air Temp.**     | **Relative Humid.** | **Dew Point** | **Wind Dir.** | **Wind Sp** | **Baro. Pressure** | **Air Temp.** | **Relative Humid.** | **Dew Point** | **Wind Dir.** | **Wind Sp** | **Baro. Pressure** |
|                                        | °C                | °C                | °C            | Deg.       | m s⁻¹     |                 | °C            | %               | °C            | Deg.       | m s⁻¹     |                 |
| Mean                                   | 26.38             | 77.96             | 21.82         | 213.23     | 0.90       | 1020.82        | 25.93         | 77.76           | 21.45         | 190.57     | 1.85       | 1020.49        |
| Median                                 | 25.03             | 84.00             | 21.93         | 236.00     | 0.60       | 1022.69        | 25.20         | 82.00           | 21.60         | 198.00     | 1.50       | 1021.10        |
| Standard Deviation                     | 4.06              | 13.89             | 1.56          | 98.82      | 1.21       |                 | 11.36         | 1.52            | 86.89         | 1.33       | 2.28       |                 |
| Standard Error                         | 0.08              | 0.27              | 0.03          | 1.90       | 0.02       | 0.05           | 0.07          | 0.22            | 0.03          | 1.68       | 0.02       | 0.04           |
| Min                                    | 19.00             | 41.00             | 16.80         | 1.00       | 0.10       | 1012.53        | 19.10         | 41.00           | 16.50         | 0.00       | 0.10       | 1012.80        |
| Max                                    | 36.70             | 95.00             | 26.10         | 358.00     | 11.80      | 1046.40        | 33.80         | 93.00           | 26.10         | 358.00     | 12.80      | 1038.80        |
| Standard Deviation                     | 5.62              | 15.84             | 4.77          | 131.00     | 0.40       | 1019.31        | 23.60         | 70.00           | 20.50         | 121.00     | 0.90       | 1019.30        |
| Standard Error                         | 0.05              | 0.14              | 0.04          | 1.18       | 0.00       | 0.04           | 0.05          | 0.13            | 0.04          | 1.20       | 0.01       | 0.04           |
| Min                                    | 1.00              | 27.00             | -5.27         | 0.00       | 0.10       | 1009.15        | 1.80          | 31.00           | -3.50         | 0.00       | 0.00       | 1009.15        |
| Max                                    | 34.27             | 96.00             | 24.27         | 359.00     | 19.00      | 1032.85        | 37.20         | 94.00           | 23.90         | 359.00     | 8.10       | 1029.47        |
| Size                                   | 2695              | 2695              | 2695          | 2695       | 2695       | 2695           | 2695          | 2695            | 2695          | 2695       | 2695       | 2695           |
| Missing                                | 0.00              | 0.00              | 0.00          | 0.00       | 1.00       | 0.00           | 0.00          | 0.00            | 0.00          | 0.00       | 0.00       | 0.00           |

| Dry Season: 2 November 2014 through 12 March 2015 | Vegetated Cell 12 | Open Water Cell 13 |
|---------------------------------------------------|-------------------|-------------------|
| **Descriptive Statistics**                         | **Air Temp.**     | **Relative Humid.** | **Dew Point** | **Wind Dir.** | **Wind Sp** | **Baro. Pressure** | **Air Temp.** | **Relative Humid.** | **Dew Point** | **Wind Dir.** | **Wind Sp** | **Baro. Pressure** |
| **Mean**                                            | 19.48             | 75.70             | 14.59         | 157.27     | 0.62       | 1022.22        | 19.92         | 74.68           | 14.89         | 164.36     | 1.52       | 1021.74        |
| **Median**                                          | 19.57             | 83.00             | 15.47         | 122.00     | 0.50       | 1022.69        | 20.20         | 79.00           | 15.60         | 140.00     | 1.20       | 1022.69        |
| **Standard Deviation**                              | 5.62              | 15.84             | 4.77          | 131.42     | 0.41       | 1019.31        | 23.60         | 70.00           | 20.50         | 121.00     | 0.90       | 1019.30        |
| **Standard Error**                                  | 0.05              | 0.14              | 0.04          | 1.18       | 0.00       | 0.04           | 0.05          | 0.13            | 0.04          | 1.20       | 0.01       | 0.04           |
| **Min**                                             | 1.00              | 27.00             | -5.27         | 0.00       | 0.10       | 1009.15        | 1.80          | 31.00           | -3.50         | 0.00       | 0.00       | 1009.15        |
| **Max**                                             | 34.27             | 96.00             | 24.27         | 359.00     | 19.00      | 1032.85        | 37.20         | 94.00           | 23.90         | 359.00     | 8.10       | 1029.47        |
| **Size**                                            | 12,483            | 12,483            | 12,483        | 12,483     | 12,483     | 12,483         | 12,483        | 12,483          | 12,483        | 12,483     | 12,483     | 12,483         |
| **Missing**                                         | 1.00              | 1.00              | 1.00          | 1.00       | 1.00       | 0.00           | 0.00          | 0.00            | 0.00          | 1.00       | 0.00       | 0.00           |

1—statistically significant difference at \( p < 0.01 \); 2—statistically significant difference at \( p < 0.001 \).
Wind speed exceedance probability analysis, based on the 15-min observations, indicated that zero occurrence of wind speed above 13 m s$^{-1}$ during the observation period, at both Cell 12 (EAV) and Cell 13 (open water) locations (Figure 3). In general, wind speed was higher in the open water compared to the vegetated site and two to three times higher at the standard height (ENR 308) compared to the vegetated site. Median wind speed was 1.5 m s$^{-1}$ and 2.0 m s$^{-1}$ in the open water cell and the ENR 308 location, respectively, and 0.6 m s$^{-1}$ in the vegetated cell (June–July 2014). Dry season median wind speed values were 0.5 and 1.2 m s$^{-1}$ from November 2014 through March 2015 for vegetated and open water sites, respectively. The difference in the median values between the two groups is statistically significant ($p < 0.001$, Table 2).

![Figure 3](image)

Figure 3. Exceedance probability curves for wind speed based on 15-min observations. Probability distributions for wind speed in vegetated (light gray solid line), un-vegetated (dark gray solid line) cells, and a ten-meter height weather station (ENR308 black solid line). Panel (a) Wet season (June to July 2014); and Panel (b) dry season (November 2014 through March 2015).

Wind speed also varied during “time-of-day” in both seasons (Figures 4 and 5). Wind speed was higher during daytime (i.e., between 800 through 1900), compared to night-time hours, and decreased during night- and early-day hours (i.e., between 1900 and 700) at both sites and during both seasons. The time-of-day trend was more pronounced during the wet, compared to the dry season (Figure 4 vs. Figure 5). The maximum speed for an entire day occurred between 1300 and 1800 depending on the season (Figures 4 and 5). Hour-of-day box and whisker plots also demonstrate how the low wind speed values varied in the vegetated, compared to the non-vegetated site. Wind speed values were at their lowest from 0 to 900 h and increased to their highest values starting at hour 900 and peaked around hour 1400–1600 every day (Figures 4 and 5).

The overall average wind direction (resultant vector) for the wet sampling seasons (June–July) were 273° and 205°, for vegetated and open water sites, respectively (Figure 6). Similarly, during the dry season, wind vectors were 14° and 20°, for vegetated and open water sites, respectively. During the dry season, wind direction was dominated by northerly wind, and westerly and south-westerly direction during the wet season (Figure 6).
3.2. Wind Stress and Wind Drag Coefficients

The differences in the means and the medians values of the wind-generated surface sheer stress, during wet season for Cell 12 and 13, respectively, are statistically significant ($p \leq 0.001$) along both N–S and E–W directions (Table 1). Similarly, wind stress means and medians during the dry season are statistically significant ($p \leq 0.001$) and their values along the N–S and E–W directions are an order of magnitude different for dry compared to wet season values (Table 1).

Calculated wind speed profiles (wind speed vs. elevation), using Equations 2 and 8, are different between dry and wet seasons. The range of wind speed is narrower during wet season than during dry season, using the standard height of wind speed measured at ENR 308, Cell 12, and Cell 13 (Figure 7). For both seasons, the increase in wind speed with height is more gradual at the vegetated site (Cell 12) compared to that at the open water site (Cell 13).

3.3. Air Temperature, Relative Humidity, Dew Point, and Barometric Pressure

Air temperature, relative humidity, and dew point values were unaffected by the presence of emergent vegetation in both wet and dry season, and the observed differences were not statistically significant (Table 2). Although the differences are not significant, they are consistently higher in the vegetated Cell (12), particularly during the wet season, compared to the dry season (Table 2). At the study site barometric pressure range varied between a minimum of 20 mb to a maximum of 33 mb at the vegetated and un-vegetated sites (Table 2). While, the range in barometric pressure at the ENR 308 station (about 2200 m away and standard ten-meter height) was approximately 35 mb over a five-year period.

Figure 4. Wind speed time of day (1 through 24 h) box and whisker plots during dry and wet seasons, respectively. All available hourly data were averaged over the entire period of time. Hour 24 = midnight and represents the average wind speed during that hour for the period of record. Panel (a) vegetated (Cell 12) and Panel (b) Open Water (Cell 13) depict wind speed during the dry season (November 2014 through March 2015), while Panel (c) vegetated (Cell 12) and Panel (d) Open Water (Cell 13) depicts wind speed during the wet season (June to July 2014).

Figure 5. Wind direction (0.0–360°) and wind speed (ms$^{-1}$) during dry (11 February 2014 to 3 December 2015) and wet season (12 June 2014 to 10 July 2014). Panel (a) depicts Vegetated conditions (Cell 12) during dry season; Panel (b) depicts Vegetated conditions (Cell 12) during wet season; Panel (c) depicts open water conditions (Cell 13) during wet season, and Panel (d) depicts open water conditions (Cell 13) during dry season. Each spoke is divided into different colors representing wind speed ranges. The length of each spoke indicates its relative percentage of time that wind blows from that direction.
Figure 6. Calculated wind speed profiles. Wind speeds are calculated via wind power law (gray solid line) and wind log profile law (black solid line). Panel (a) open water (Cell 13) dry season (11 February 2014 to 3 December 2015) and panel (b) open water (Cell 13) wet season (12 June 2014 to 10 July 2014); Panel (c) vegetated (Cell 12) dry season and Panel (d) vegetated Cell 12 wet season (12 June 2014 to 10 July 2014).

3.2. Wind Stress and Wind Drag Coefficients

The differences in the means and the medians values of the wind-generated surface shear stress, during wet season for Cell 12 and 13, respectively, are statistically significant \( (p \leq 0.001) \) along both N–S and E–W directions (Table 1). Similarly, wind stress means and medians during the dry season are statistically significant \( (p \leq 0.001) \) and their values along the N–S and E–W directions are an order of magnitude different for dry compared to wet season values (Table 1).

Calculated wind speed profiles (wind speed vs. elevation), using Equations (2) and (8), are different between dry and wet seasons. The range of wind speed is narrower during wet season than during dry season, using the standard height of wind speed measured at ENR 308, Cell 12, and Cell 13 (Figure 7). For both seasons, the increase in wind speed with height is more gradual at the vegetated site (Cell 12) compared to that at the open water site (Cell 13).
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The standard barometric pressure of 1013.25 mb (millibar) and the less than 2 mb per three hours (mb/hr) rate of change, are both within expected ranges associated with diurnal oscillation in temperate climates. The barometric pressure in the tropics simply does not change a lot from day to day and barometric pressure (corrected to sea level) varies from 1008.7 to 1018.9 mb. Barometric pressure at Miami, Florida, for example, might change from 1002.0 mbar to 1032.4 mb, a range about 30 mb. In higher latitudes, variation from 981.65 mb to 1049.4 mb, a 68 mb range, is not uncommon. The observed ranges are within the expected values for this region. We also found no major differences in results obtained for the aforementioned parameters (except wind speed and directions), due to presence or absence of emergent vegetation at the two wetland cells. Therefore, no further discussion regarding those parameters will continue due to lack of significant changes observed between data collected in the vegetated and the open water sites.

4. Discussion

4.1. Wind Speed and Direction

Wind speed and direction means in the vegetated wetland were half their counterparts in the non-vegetated site during wet and dry seasons (Table 2). The difference in both mean and median values between the vegetated and non-vegetated sites were statistically significantly different for both dry and wet seasons (Table 2 and Figure 2). Similar to vegetation resistance to water movement in the water column induced by the presence of aquatic vegetation [24,30], emergent vegetation in this experiment, induced resistance to air flow (which can be quantified by a drag coefficient) and consequently impacts the frequency of wind classes compared to open water site. The observed

![Figure 7. Calculated wind setup and percentage increase in outflow due to winds in the same direction](image)
reduction in wind speed, is attributed to the mere presence of an obstacle, emergent vegetation in this experiment.

The highest frequencies of wind classes ($0 \leq \text{wind speed} \leq 2.1 \text{ m s}^{-1}$) were 92% and 64%, while the second highest ($2.1 \leq \text{wind speed} \leq 4.1 \text{ m s}^{-1}$) were 29% and 5%, for vegetated and open water site, respectively, during the wet season sampling period (Figure 6). The main reason for the observed high frequency (92%) at the lowest wind class in the vegetated site is attributed to the presence of emergent vegetation. Vegetation resistance reduced wind speed and led to the observed highest frequency (92%) to occur at the lowest wind speed class ($0 \leq \text{wind speed} \leq 2.1 \text{ m s}^{-1}$). Similar to the wet season trend, the highest frequency of wind speed classes during the dry season was in the range of 0 to 2.1 m s$^{-1}$ with values of 99% and 75% for vegetated and open water site, respectively. However, the second highest frequency ($2.1 \leq \text{wind speed} \leq 4.1 \text{ m s}^{-1}$) was less than 1% for the vegetated site, and 22% for the open water site during the dry season.

Wind speed values were remarkably similar, for both vegetated and open-water sites, at the higher speed (i.e., wind speed > 6 ms$^{-1}$) compared to the low range, which may have greater implications. For example, during hurricanes, one would expect that both locations would be in close agreement due to higher wind speeds that damage existing emergent vegetation (larger impact on existing vegetation). On the other hand, during the current experiment, lower wind speed causes less “bending”, prompting higher vegetation resistance, and causing the highest wind speed frequency to occur at the low wind as evident from our results (highest wind speed class occurring at 92 and 99% for wet and dry seasons, respectively). Similar to observed results in this experiment, [31] showed deceleration of flow within the vegetation layer and a maximum Reynolds stress at the tops of the plants were similar to the observed vertical profiles for velocity and Reynolds stress. The higher wind speeds would have greater impacts on emergent vegetation to the point that measured wind speed are equal at top of vegetation and water surface.

Wind directions may have also been impacted by the emergent vegetation bending as a result of the prevailing wind at the study site. Wind direction vectors over the entire wet sampling season (June–July) were 273° and 205°, for vegetated and open water sites, respectively, while wind vectors were 14° and 20°, for vegetated and open water sites, respectively during the dry season, (Figure 6). The dominant wind direction at the study site is from the north, as indicated by the open water site, during the dry season, and this dominant wind direction change to south-westerly and westerly during the wet season. However, it is clear that the dominant wind direction is from the north in the open water site, while wind direction is a “scatter” around the true north during the dry season in the vegetated site. The observed scatter in wind directions was triggered by the emergent vegetation bending caused by the prevailing winds. We believe that the prevailing wind sways (or bends) the emergent vegetation and creates channel-like patterns in the vegetated site, which not only reduce wind speed but also alter wind direction.

4.2. Wind Stress and Drag Coefficients

Wind also induces stress at the water surface, causing the surface layer of the water column to move, in general, in the same direction as wind, due to the small fetch and negligible effects from Coriolis force [32]. Wind stress over surface water produces currents in the top layer aligned with the wind direction, which in turn lead to wind setup and water surface slope. Although wind stress from normal wind conditions may be exceedingly small, the small wind setup may still have an impact on HRT particularly for a shallow wetland.

To demonstrate the effect of wind setup on wetland hydrology, Equations (10) and (11) were used to estimate wind impact set up near the outlet of the open water cell (Figure 7). If the maximum wind speed of 19 m s$^{-1}$, observed during this study, were in the same direction as the flow, the wind setup could be as high as 0.6 cm over a depth of 80 cm at the wetland outlet and would increase outflow discharges by 3%. The effect over shallower water is more pronounced. For a water depth of 20 cm, the wind setup is 2.5 cm, and the flow increase by 61%. The same wind condition (i.e., wind speed
of 19 m s\(^{-1}\)) would lead to a wind setup of 1.3 cm over a water depth of 40 cm and increase outflow discharges by 13% (Figure 7).

In addition to the effect of wind set up and increasing water depth at the wetland outlet, wind drag may also increase surface water velocity, and if aligned in the same direction as the surface water flow, decrease HRT, and consequently reduces phosphorus treatment. Several researchers have concluded that decreasing HRT would lead to an overall decrease in TP uptake, while increasing contact time (HRT) with resident biota, leads to improve P performance in a wetland [9,33].

Constructed wetlands by design are deeper near the outlet and shallower near the inlet, which allow gravity to move water between inflow and outflow. Wind set up would increase water depth near the wetland outlet and may cause unnecessary consequences because water depth is a critical factor in determining the health of aquatic vegetation in wetlands. Aquatic vegetation is a major sink in reducing TP in large constructed wetlands, particularly in south Florida due to an extended vegetation growing season. The health of emergent macrophytes, such as cattail, in those large constructed wetlands depends on how deep and how long those water depths persist. Cattail floated island were observed in the Everglades Removal Project (ENRP) when water depth increased to more than four feet and lasted for extended period (>two weeks; [33]). In summary, wind drag increases water velocity and decreases HRT, while wind set up increases water depth near the wetland outlet, and the consequences of both will depend on how long and how fast the wind is blowing.

Wind drag coefficient depends on several factors including vegetation flexibility, leaf density (vegetation porosity or number of stems/plants per m\(^2\)), prevailing wind speed, and vegetation structure (stem size, height, frontal area, etc.). Drag coefficient is also a function of wind velocity and the vegetation angle of incidence and increases as wind speed increases and also increases as leaf width increases [34]. However, wind drag, in most wetland applications, is considered to be part of the variability of marsh friction and is several times as strong as submerged plant stem drags in open water areas [24].

Vegetation impact on prevailing wind velocity is illustrated and quantified using Equations (2) and (8) (Figure 7). During wet and dry seasons, the increase in wind speed with height is more gradual at the vegetated site (Cell 12) compared to that at the open water site (Cell 13), indicating wind attenuating effect of vegetated site due to higher surface roughness length (Figure 7). Narrow wind speed range vs. height is evident during both wet and dry seasons (Figure 7) and is more pronounced in the open water cell compared to the vegetated one. This narrow range is there because changes of surface roughness in the open cell area is only a function of height. On the other hand, in the vegetated site, changes in surface roughness is a function of both height and plant characteristics such as stem diameter, leaf index, and number of plants per m\(^2\).

Wind drag coefficients results (Table 3) from this study are similar to literature values [35,36]. Cattail drag coefficients using Equations (2) or (8) are almost in perfect agreement with values calculated for cropland, brush, and forest. Open water values from the current experiment are higher than the reported literature values for “smooth open water.” However, it was clear during this experiment that the water surface at the open water site was dominated by wind waves and ripples (personal observations), which may not be classified or described as smooth open water. Roughness lengths in wetlands were reported to have a higher value in summer months compared to winter months due to differences in growing seasons [37]. The pattern of growing seasons is different in south Florida. Our data indicates that the roughness length and drag coefficients are lower in the wet season than in the dry season, probably due to lower water levels, which lead to less smooth overall surface.
Table 3. Comparison of calculated roughness lengths and drag coefficients from wind observations and roughness classes reported in literature.

| Class | Name                  | Landscape Features                          | Roughness Length (m) | Drag Coefficient | Roughness Length (m) | Drag Coefficient |
|-------|-----------------------|---------------------------------------------|----------------------|-------------------|----------------------|------------------|
|       |                       |                                             |                      |                   |                      |                  |
| 1     | sea                   | open water, tidal flat                      | 0.0002               |                   |                      |                  |
| 2     | smooth                | featureless land with negligible vegetation | 0.005                | 0.002–0.003       |                      |                  |
| 3     | open                  | flat terrain with very low vegetation (grass) | 0.03                 | 0.003–0.006       | 0.0384 open water    | 0.005 open water |
| 4     | roughly open          | area with low crops or plant covers         | 0.1                  |                   |                      |                  |
| 5     | rough                 | area with high crops or plant covers of varying height | 0.25                 | 0.0075–0.02       | 0.1366 open water    | 0.009 open water |
| 6     | very rough            | landscape with bushes, young dense forest etc. | 0.5                  |                   | 0.3889 Cattail       | 0.012 Cattail    |
| 7     | closed                | mature forest, low-rise built-up area        | 1                    |                   |                      |                  |
| 8     | chaotic               | city center, large forest of irregular height | over 2.0             | 0.03–0.3          |                      |                  |
4.3. Winds Impact on Wetland Hydrology

Velocity measurements were taken during a flow discharge event of 14.16 m$^3$/s, which is the average discharge observed during previous field experiments. When wind blows across a water body, it pushes the surface water layer via shear stress. This downward transfer of momentum from the air to the water generates a deformed surface current (ripples/wind wave). Those generated waves become bigger as wind speed increases.

The water level responses to wind stress depend on the site location and the wind direction. In this experiment, wind direction is unlikely to change significantly across the full-size wetland (i.e., STA-2 Cell 3; STA2C3), due to the absence of cattail where velocity measurements were taken on 1 March 2014. At station near the inflow, and over the entire STA2C3, wind was blowing from the south, while inflow discharges were moving from north to south (Figure 8). Wind speed was measured at 0.53 m s$^{-1}$. The measured velocity profile at that station showed that surface wind-generated water flow, is aligned with wind direction from south to north, and opposite to inflow discharges (north to south; Figure 8).

![Figure 8](image_url)

**Figure 8.** An observed two-layer flow at Station near the inflow to Cell 3 of Stormwater Treatment Area 2 (STA-2). Surface layer exhibited water flow from north to south (caused by wind stress) coinciding with wind direction from south to north; measured wind speed is approximately (0.53 m s$^{-1}$). A mid-water column layer flowing between inflow and outflow structures from north to south (opposite to wind direction). A near-bottom layer appears to be flowing from north to south, likely due to backscatter from acoustic measurements.

The opposing wind-generated surface flow in the opposite direction of gravity flow may significantly impact HRT in a constructed wetland. For example, during a 14.16 m$^3$ s$^{-1}$ (34 cm day$^{-1}$ or 1.1 ft day$^{-1}$) flow discharge event in STA2C3, wind-generated flow was in the opposite direction to gravity flow. The wind-generated surface water flow (and opposite to inflow discharge direction), during this discharge event, is approximately 0.15-m-deep (Figure 8), and a width of approximately 2000 m. This indicates that up to 12% of the water volume, during this discharge event, could be moving in the opposite direction of gravity discharges (Figure 8). When discharges at the inflow site stop (G333), the wind does not. Instead, wind continues to generate flow in the northerly direction creating a 15-cm surface layer moving back towards the inflow site, while the sub-surface layer continues in a southerly direction due to its momentum, and eventually stops. Those opposing currents generate more velocity shear (~7 to 25 cm s$^{-1}$; Figure 8), which in turn creates more mixing/entrainment and re-cycling of water.
between the two layers, causing an increase in HRT and improvement of P performance. However, if wind and gravity discharges are aligned in the same direction, wind generated flow would decrease HRT and potentially reduce P performance.

Increasing water velocity between inflow and outflow is likely to decrease HRT, a key factor that impacts and determines P performance in a wetland [1–3]. For example, when prevailing wind is opposite to flow direction, wind generated current increases HRT (i.e., contact time) and is likely to increase P performance. In this experiment water moved between inflow and outflow in S–N direction. The calculated wind stress along the x-axis (S–N direction) in the non-vegetated wetland (during the dry seasons) is positive and aligned with the flow discharges in this cell (i.e., S–N). Mean wind stress in vegetated wetland (even smaller compared to non-vegetated wind stress) is also positive and aligned with flow discharges in the S–N direction for both seasons. However, for the open water during the dry season, wind stress components are negative (i.e., N–S) along the x-axis and opposite to inflow discharges from S–N. Alignment of wind stress with water flow is likely to decrease HRT, which decreases contact time, and consequently P performance in wetlands.

Phosphorus performance in wetlands is the result of too many factors, yet previous researchers pointed out that, in general increasing contact time (HRT) leads to improve P performance. For example, Ruel et al., [33] changed bottom topography by creating baffled wetlands with multiple vertical-scale topographic features to increase HRT, while Dierberg et al., [9] used different HRT in a comparative mesocosm study involving SAV. In both cases increasing HRT leads to improved P performance in those constructed wetlands. Many researchers also identified hydraulic factors that impact wetland treatment efficiency [8]. However, to our knowledge, none reported the effect of a single factor impact such as increasing or decreasing HRT, due to wind action, on nutrient transport and efficiency in large constructed wetland. Most studies focused on the collective effects of several factors combined with HRT (e.g., [3,9]), and literature reported discussions indicated that HRT is expected to impact and change P removal efficiency in a wetland, yet this relationship is complex.

Because no monitoring of P between inflow and outflow took place during this experiment, we were not able to determine how wind-generated flow may have impacted P removal efficiency. In addition, even if P monitoring took place at the inflow and outflow sites, the reduction in P concentrations at the wetland outlet, is the result of the combined effects of too many factors, not individually and solely, by HRT alone. In this case, P performance would be the result of the combined interaction of soil, vegetation, HRT, and wind at a minimum.

In most cases when designing and constructing a wetland for P treatment, little attention has been paid for wind action and its impact on HRT and P performance. Our study showed that wind effect would decrease HRT if wind and flow are in the same directions (Figure 8). In addition, wind speed and direction are natural phenomena that cannot be controlled. However, one could potentially use a combination of vegetation types in a wetland to change wind speed/direction and optimize HRT and hence P performance. For example, a combination of EAV and SAV strips would be a good choice to achieve this goal. The EAV and SAV in the same wetland would provide high and low vegetation resistance and wind drag coefficients, respectively. However, allowing only strips of SAV within EAV would ensure a small fetch for the wind, resulting in lower speed, and hence, lessen the impact on HRT and P performance.

5. Conclusions

Meteorological data from vegetated and un-vegetated wetlands during wet and dry seasons, were collected and analyzed to evaluate the role of wind and vegetation on wetland hydrology. Wind speed reductions and changes in wind direction were more pronounced during the wet season compared to the dry season. Vegetation induced resistance reduced wind speed and caused the lowest wind speed class to be the highest frequency class. Water flow, from inflow to outflow, is accelerated when wind direction is aligned with gravity flow and decreased when wind direction (wind-generated flow as a result of wind stress) opposes gravity flow from the wetland inlet.
We demonstrated how wind forces affect surface water flow, by measuring velocity profiles and wind speed/direction in a large constructed wetland. The water velocity profile showed that surface water flow was aligned in the same direction as the wind and was exactly opposite to inflow discharges. Those opposing currents generate more velocity shear, which in turns created more mixing/entrainment and re-cycling of water within the wetland, causing an increase in HRT and improvement of P performance. However, if wind and gravity discharges are aligned in the same direction, wind generated flow would decrease HRT and potentially reduce P performance.

We demonstrated how wind induced stress at the water surface enhanced flow velocity and described how wind stress impact was more pronounced at shallower water depth. We also disclosed how a wind speed of 19 m s$^{-1}$ resulted in a wind set up, near the wetland outflow, which increased water depth by more than 12% and increased surface flow by as much 61% in a shallow wetland (water depth $\leq$ 20 cm). However, the impact on a deeper water depth (40 cm) was less pronounced for the same wind speed.

We were also able to calculate roughness lengths and drag coefficients for both vegetated and un-vegetated sites based on field observations. Calculated drag coefficients changed between dry and wet season due to changes in vegetation porosity (space between individual plants and between stems or leaves), caused mainly by prevailing winds. Cattails and open water wind drag coefficients using the log wind profile, were 0.016 and 0.009 for dry season, and 0.012 and 0.005 for wet season, respectively. This study highlights the need to account for changing vegetation resistance (drag coefficients) over time in future model applications and to consider prevailing wind in the design phase of constructed wetlands.

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**References**

1. Kadlec, R.H.; Knight, R.L. *Treatment Wetlands*; CRC Press: Boca Raton, FL, USA, 1996.
2. Moustafa, M.Z. Nutrient retention dynamics of the Everglades Nutrient Removal Project. *Wetlands* **1999**, *19*, 689–704. [CrossRef]
3. Moustafa, M.Z. Analysis of phosphorus retention in free-water surface treatment wetlands. *Hydrobiologia* **1999**, *392*, 41–53. [CrossRef]
4. Moustafa, M.Z.; White, J.R.; Coghlan, C.C.; Reddy, K.R. Influence of hydropattern and vegetation type on phosphorus dynamics in flow-through wetland treatment systems. *Ecol. Eng.* **2011**, *37*, 1369–1378. [CrossRef]
5. Moustafa, M.Z.; White, J.R.; Coghlan, C.C.; Reddy, K.R. Influence of hydropattern and vegetation type on phosphorus reduction in a constructed wetland under high and low mass loading rates. *Ecol. Eng.* **2012**, *42*, 134–145. [CrossRef]
6. Gillies, J.A.; Nickling, W.G.; King, J. Drag coefficient and plant form response to wind speed in three plant species: Burning Bush (*Euonymus alatus*), Colorado Blue Spruce (*Picea pungens galauca*), and Fountain Grass (*Pennisetum setaceum*). *J. Geophys. Res.* **2002**, *107*, 4769. [CrossRef]
7. Lal, A.M.W.; Moustafa, M.Z.; Wilcox, W.M. The use of discharge perturbations to understand in situ vegetation resistance in wetlands. *Water Resour. Res.* **2015**, *51*, 2477–2497. [CrossRef]
8. Reed, S.; Crites, R.W.; Middlebrooks, E.J. *Natural Systems for Waste Management and Treatment*, 2nd ed.; McGraw-Hill, Inc.: New York, NY, USA, 1998.
9. Dierberg, F.E.; DeBusk, T.A.; Jackson, S.D.; Chimney, M.J.; Pietro, K. Submerged aquatic vegetation-based treatment wetland for removing phosphorus from agricultural runoff: Response to hydraulic and nutrient loading. *Water Res.* 2002, 36, 1409–1422. [CrossRef]

10. Conn, R.M.; Fiedler, F.R. Increasing Hydraulic Residence Time in Constructed Stormwater Treatment Wetlands with Designed Bottom Topography. *Water Environ. Res.* 2006, 78, 2514–2523. [CrossRef] [PubMed]

11. Poindexter, C.; Variano, E.A. Gas exchange in wetlands with emergent vegetation: The effects of wind and thermal convection at the air-water interface. *J. Geophys. Res. Biogosci.* 2013, 118, 1297–1306. [CrossRef]

12. Deng, Y.; Solo-Gabriele, H.M.; Lass, M.; Leonard, L.; Childers, D.L.; He, G.; Engel, V. Impacts of hurricanes on surface water flow within a wetland. *J. Hydrol.* 2010, 392, 164–173. [CrossRef]

13. Dieter, C.D. The importance of emergent vegetation in reducing sediment resuspension in wetlands. *J. Freshw. Ecol.* 1990, 5, 467–473. [CrossRef]

14. Grant, P.F.; Nicking, W.G. Direct field measurement of wind drags on vegetation for application to windbreak design and modeling. *Land Degrad. Dev.* 1998, 9, 57–66. [CrossRef]

15. Hammond, D.S.; Chapman, L.; Thrones, J.E. Roughness length estimation along road transects using airborne LIDAR data. *Meteorol. Appl.* 2012, 19, 420–426. [CrossRef]

16. Luers, J.K.; Macarthur, C.D.; Haines, P.A. The Roughness Lengths Associated with Regions of Heterogeneous Vegetation and Elevation; Contract DAAD07-80-D-0206; University of Dayton Research Institute: Dayton, OH, USA, 1981.

17. Lugo, A.E. Effects and outcomes of Caribbean hurricanes in a climate change scenario. *Sci. Total Environ.* 2000, 262, 243–251. [CrossRef]

18. Large, W.; Pond, S. Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Oceanogr.* 1981, 11, 324–336. [CrossRef]

19. Peterson, E.W.; Hennessey, J.P., Jr. On the use of power laws for estimates of wind power potential. *J. Appl. Meteorol.* 1978, 17, 390–394. [CrossRef]

20. Elliott, D.L.; Holladay, C.G.; Barchet, W.R.; Foote, H.P.; Sandusky, W.F. *Wind Energy Resource Atlas of the United States*; Pacific Northwest Laboratory: Richland, WA, USA, 1986.

21. Robeson, S.M.; Shein, K.A. Spatial coherence and decay of wind speed and power in the north-central United States. *Phys. Geogr.* 1997, 18, 479–495. [CrossRef]

22. Oke, T.R. *Fundamentals of Stack Gas Dispersion*, 4th ed.; McGraw-Hill: New York, NY, USA, 2005; ISBN 0-9644588-0-2.

23. Kadlec, R.H.; Wallace, S.D. *Treatment Wetlands*, 2nd ed.; Taylor and Francis Group: Boca Raton, FL, USA, 2009.

24. Baptist, M.J. A flume experiment on sediment transport with flexibles, submerged vegetation 2003. In *Proceedings of the International Workshop on Riparian Forest Vegetated Channels: Hydraulic, Morphological and Ecological Aspects*, Trento, Italy, 20–22 February 2003.

25. Holton, J.R. *An Introduction to Dynamic Meteorology*; Academic Press: Cambridge, MA, USA, 2004; p. 18. ISBN 0-12-354015-1.

26. SFWMD. *Chapter 6 of the Everglades Consolidated Report*; South Florida Water Management District: West Palm Beach, FL, USA, 2000.
34. Baldocchi, D. Canopy-atmosphere water vapor exchange: Can we scale from a leaf to a canopy? In *Estimation of Areal Evapotranspiration*, Proceedings of the XIXth General Assembly of the International Union of Geodesy and Geophysics, Vancouver, BC, Canada, 9–22 August 1987; IAHS Press, Institute of Hydrology: Wallingford, UK, 1989; Volume 177, pp. 21–41.

35. Wieringa, J.; Davenport, A.G.; Grimmond, C.S.B.; Oke, T.R. New Revision of Davenport Roughness Classification. In Proceedings of the 3rd European and African Conference on Wind Engineering, Eindhoven, The Netherlands, 2–6 July 2001; pp. 285–292.

36. Holmes, J.D. *Wind Loading of Structures*; Spon Press: New York, NY, USA, 2001.

37. Hansen, F.V. *Surface Roughness Lengths, ARL Technical*; Report (ARL-TR-61); U.S. Army Research Laboratory: Adelphi, MD, USA, August 1993.

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