HYDROLOGICAL EXCHANGE PROCESSES IN HUDSON RIVER TIDAL WETLANDS

A Final Report of the Tibor T. Polgar Fellowship Program

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Arrigoni, A.S., S. Findlay and K. Tockner. 2006. Hydrological exchange processes in Hudson River tidal wetlands. Section I: 27 pp. *In* W.C. Nieder & J.R. Waldman (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 2005. Hudson River Foundation.

ABSTRACT

The Hudson River between New York City and the federal dam in Troy contains over 200 tidal wetlands. In this study 10 wetlands were randomly selected and a GIS database was used to quantify 12 of their physical characteristics: the sum area, percent open water, a shape index, the percentages of seven vegetation classes, the number of tributaries, and the width of the exchange points with the river. The dissolved oxygen (DO) concentration of mainstem water exchanging with the wetlands was measured using YSI 6000 SONDE data recorders; these instruments collected data at the exchange points between the river and wetlands. In conjunction with the collection of DO data, the SONDEs recorded water depth at exchange points between the wetlands and river. Patterns in DO and rates of change in water depth for the 10 marshes were compared to the physical attributes. A strong correlation was found between the sum area and the shape of the wetlands and the ebb tide exchange flow. The DO concentrations were positively correlated with the percent of broadleaved vegetation and negatively correlated with the percent of graminoid vegetation in a wetland. However, no direct link between the hydrological data (i.e., rate of change in depth at the exchange points) and the average DO was found. There is, however, a link between the tidal elevations and where the different vegetation types occur in the wetlands. This vegetation in turn is what influences the dynamics of DO during wetland exchange.

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INTRODUCTION

In riverine wetlands (floodplains, tidal marshes) hydrology is the "master variable" that controls biogeochemical and ecological processes (Junk et al. 1989; Thorp and Delong 1994; Poff et al. 1997; Tockner et al. 1999b). However, Anderson *et al.* (1996) stated, "floodplain processes can be considered as a four-dimensional jigsaw (x-y-z through time) in which most of the pieces (data) are missing." A possible way to investigate functional river-wetland interactions is to measure the balance between hydrological transport and biological transformation processes (e.g., Tockner et al. 1999b; Valett et al. 2005). In estuarine systems, the tidal exchange between the river and its adjacent wetlands moves sediments, nutrients, organic matter, and organisms in and out of the wetlands (Kiviat et al. 2005). Differences of in- and output fluxes reflect the efficiency of the wetland to retain, transform, or release material. The efficiency potentially depends on hydrological (e.g., hydraulic retention capacity), morphological (shape, extent) and biological (vegetation cover, organic content of sediments) properties of the wetland and on the quality of the incoming water (e.g., nutrient concentration) (Templer et al. 1989; Wigand et al. 2003; Kiviat et al. 2005).

To begin to understand the exchange of matter between the river and its wetlands it is important to understand the hydrological connectivity of sub-units within the wetland during the tidal cycles. The river-wetland and within-wetland hydrological connections should be useful predictors of the capacity of tidal wetlands to affect whole-ecosystem material budgets.

This study was conducted in a set of Hudson River tidal freshwater wetlands. The Hudson River was ideal for this study in part because it is complementary to many other floodplain/wetland systems, as well as having a very predictable pulsing water level, limited groundwater influence, diverse vegetation cover that changes seasonally, and limited geomorphic reworking. Specifically, we analysed the hydrographs at the exchange points between the river and wetlands to obtain an estimate of the hydrological connectivity and retention, if any, between the mainstem and marsh. Measurements of dissolved oxygen (DO) over multiple tidal exchanges were taken to assess the influence of wetland exchange on oxygen balance. Tidal wetlands play a significant role in the reduction of oxygen levels in the tidal water, therefore DO was measured at the exchange points between the river and wetlands. The profiles were compared to the hydrology and vegetation cover types to determine if there was any correlation between the different vegetation compositions of the wetlands and the DO levels.

The goals for this project were: (i) to produce a simple characteristic classification table using different physical attributes for the wetlands along the tidal Hudson, (ii) to gain an understanding of the hydrological exchange between the river and wetlands, and within the wetlands, (iii) to measure the amount of DO in the ebb tide water at the exchange point between the river and wetlands, and to compare patterns in DO with the different physical attributes of the marshes.

METHODS

Site Description: Hudson River and Tidal Wetlands

The length of the Hudson River from New York City to the federal dam in Troy (total river area 25000 ha; Kiviat *et al.* 2005) contains approximately 200 tidal wetlands that fringe the river over a distance of 250km. The tidal wetlands are vegetated sections along the fringe of the river that are inundated daily by tidal surges. The range in tidal elevation varies from ~1.0 to 1.8m. The ten wetlands used in this study were located along the Hudson River from just north of Peekskill (river kilometer 73) to just south of Albany (river kilometer 220) (Figure 1). Except for the downstream most wetland (Manitou, Figure 1), which was slightly brackish, all of the wetlands were freshwater tidal marshes. Consequently they have similar vegetation composition dominated by broad-leaf vegetation (BV) such as *Nuphar sp., Pontederia cordata,* and *Peltandra virginica,* and graminoid vegetation (GV) such as *Typha angustifolia*, and *Scirpus spp.* Some wetlands also contained areas of swamp shrub (SS) composed of *Alnusspp., Cepahalanus occidentalis, Andromeda glaucophylia, Comus spp.*, and *Chamaedaphne calyculata*, swamp tree (ST) areas composed of *Acer rubrum, Salix spp., and Fraxinus*

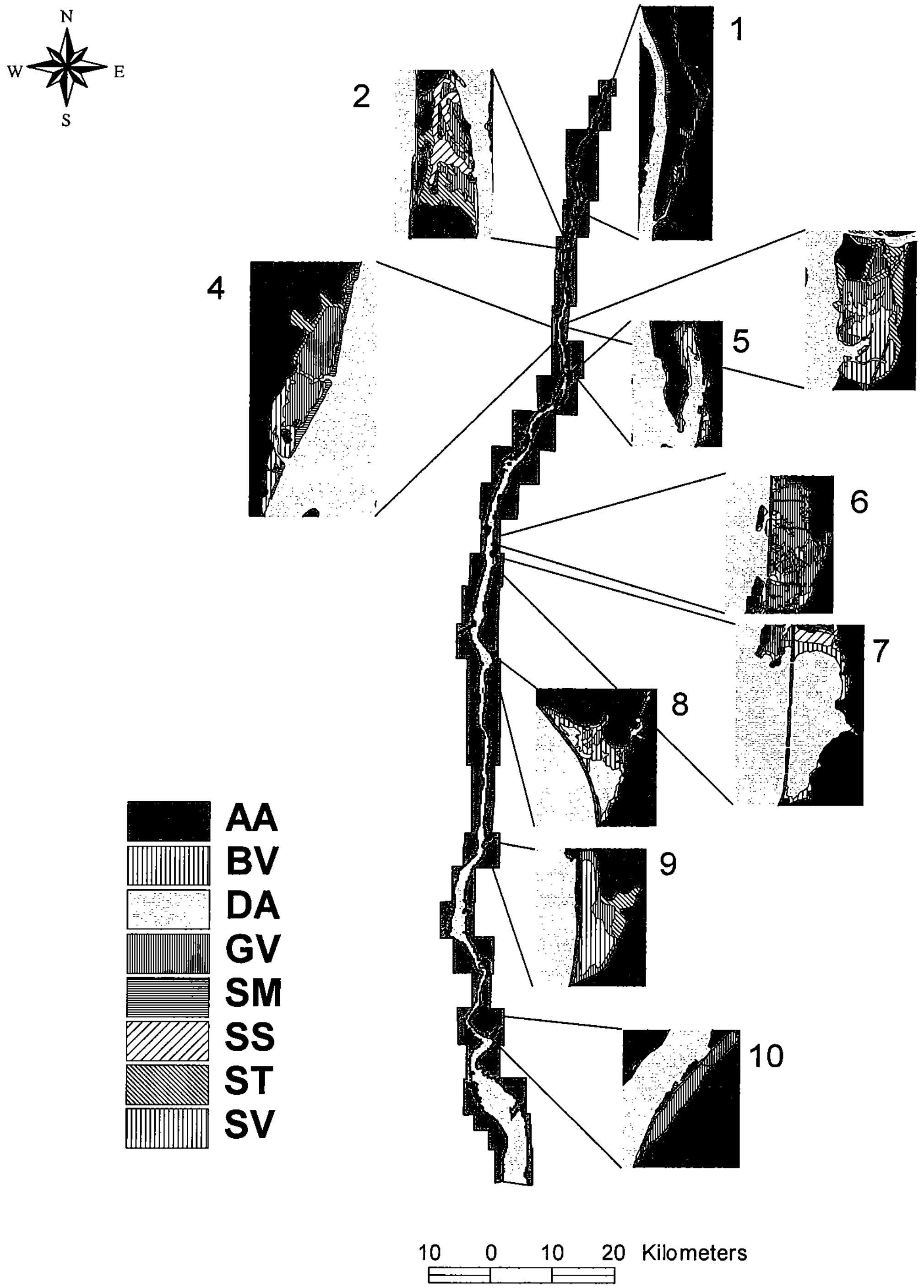

Figure 1. Site Map. Site map of the Hudson River between New York City and the federal dam with the locations of the 10 wetlands in this study. The different vegetation classes are indicated by the varying striped lines. Wetland names: 1-Papscanee, 2-Houghtaling, 3-Stockport Flats, 4-West Flats, 5-Gays Point, 6-Tivoli North Bay, 7-Tivoli South Bay, 8-Vanderburgh Cove, 9-Quarry, and 10-Manitou.

nigra, and submerged aquatic vegetation (SAV) composed of *Trapa natans and Vallisneria americana.* Each of the wetlands analyzed in this study had distinct exchange points with the river ranging in width from 4m to 440m.

Analysis of Wetlands

In this project, we selected and performed field analyses on ten wetlands along the Hudson River that differed in size/volume, area of vegetation cover types, morphology, and shape. The choice of the ten wetlands used in this study depended on the outcome of extensive pre-analyses of map variables and available hydrological data. Temperature loggers and depth recorders were deployed in the wetlands and at the exchange points to estimate the pattern of hydrological exchange throughout the inundated area and the exchange rate and flow pattern during a tidal cycle. These data were used in a comparison with the pattern of DO concentration for each wetland during a tidal cycle to determine the potential influence of different wetland characteristics on the DO concentration.

GIS Attributes of Hudson River Wetlands

Using the Hudson River vegetation GIS database that categorized and classified the different vegetation types within the Hudson River wetlands, a spreadsheet was created with 12 attribute categories for the 50 largest wetlands. The spreadsheet contained the number of vegetation covers in each wetland, the sum area, the percent open water, the percent area of each vegetation class within the wetland (these included: broad leaf vegetation (BV), graminoid vegetation (GV), coastal shoals, bars and mudflats (SM), swamp shrub (SS), swamp tree (ST), vegetated coastal shoals, bars and mudflats (SV), and the percentage of submerged aquatic vegetation (SAV) inside the wetland), a shape index (1 = circle, larger values are more irregular, calculated by Fragstats statistics software), and the combined widths of all the exchange points in each wetland, and the number of tributaries.

Each of the attributes in the classification scheme was used as a variable to perform a PCA analysis on the wetlands. The first two factors of the PCA analysis, "sum area" and "# vegetation covers" explained 45% of the variation, and were used to arrange the wetlands in order of ascending factor score value. From this list every fourth wetland was selected; out of these eleven wetlands, ten were selected for field monitoring based on access ability and hydrogeomorphic class. Only those classified as enclosed or sheltered (Findlay et al. 2002) , meaning they had reasonably distinct exchange points suitable for sampling water quality, could be used for the analysis of the hydrological exchange.

Temperature Logger Deployment

Pre-Study Monitoring:

To begin to understand the hydrological exchange throughout the wetlands we first deployed YSI 6000 SONDEs (Findlay et al., in press) at three locations in May, throughout Tivoli North Bay. These instruments recorded the water temperature, pH, conductivity, turbidity, dissolved oxygen and water depth. In conjunction with the SONDE deployment, VEMCO temperature loggers (10 cm length by 2 cm diameter, and a range of -5 to 35 °C, with a 0.2 °C resolution+/- 0.3 °C accuracy) and iButton temperature loggers (1 cm x 0.5 cm, with a range of -5 °C to 26 °C, with a resolution of 0.125 °C and an accuracy of +/- 1.0 °C) were placed at known locations and elevations throughout the wetland.

Using cable ties the temperature loggers were attached to a PVC pipe that was pushed into the wetland sediment so that the temperature loggers lay flush against the wetland surface. Due to the limited number and availability of the SONDEs another method for tracking when different areas of the wetlands were inundated by incoming tidal water was needed for the summer months. The temperature loggers were deployed to determine if they could be used to track when different areas were inundated by the tidal surge.

The VEMCO and iButton loggers were calibrated together in the lab by placing them in a water bath in a single layer for ½ hour, recording data in one-minute intervals. The data were then downloaded and any necessary adjustment factor for each logger was calculated by subtracting the recorded temperature from the known temperature of the controlled water bath.

Temperature Logger Deployment:

To determine if the tidal surge influenced an entire wetland equally with little to no lag time, and to determine if similar vegetation types are located at similar elevations above the low water line in different wetlands, temperature loggers were placed throughout a wetland at the transition points between different vegetation cover types, specifically, broad leaf vegetation and graminoid vegetation. Three wetlands were initially included in this study, a southern site at Vanderburgh Cove, a middle site at Tivoli North Bay, and a northern site at Houghtaling Island (Figure 1). The study was done during the weeks of June 13 – 17 and June 20 – 24. VEMCO temperature loggers were placed within PVC casings that were open on both ends with one end attached using cable ties to a PVC stake. The stakes were then placed in the wetland sediment so that the loggers lay flush with the wetland surface along the transition line. A depth recorder and a PVC stake with seven temperature loggers, placed every 20 cm with the bottom logger laying flush against he wetland surface, were deployed within the permanent wet channel to record the timing of inundation (abrupt change in temperature) during a tidal cycle. Three different vegetation transects were used in each wetland, one near the exchange point, one in the middle of the wetland, and one located at the back of the wetland.

Dye Test

Rhodamine dye was deployed in Tivoli North Bay at the northern exchange point to document the pattern of tidal water exchange between the river and wetland, i.e., whether it was mixing completely with the wetland water throughout the total area or remaining in one large concentrated plume near the exchange point. The dye test was simultaneously used to measure the amount of water retained in the wetland for a given tidal cycle.

For this analysis six gallons of rhodamine dye were injected into the water at the northern railroad bridge exchange point (Figure 1) on July 5, 2005 at 9:20 am during the first five minutes of the rising tide. Once the dye had been deployed it was left to mix and distribute for three hours before taking the first water samples within the wetland. Multiple water samples were taken approximately every 90 m throughout the wetland, using a canoe and GPS, to measure where and how the dye had been distributed during the rising tide. During the ebb tide water samples were taken every 10 minutes at both the north exchange point as well as the southern exchange point, to determine if any dye had migrated that far south in the wetland. The samples were taken with a bucket that was dragged across the exchange point to get a mix of water. Each of the samples was labeled with the time it was taken and location for later analysis in the lab. These samples were taken throughout the ebb tide until 20:00 when an auto-sampler was set up at the northern exchange point with 24 bottles to take a sample every 20 minutes beginning at the start of the next ebb tide, at 2:00 am the following morning. The auto-sampler and current meter were collected on July 6, 2005 at 10:30 am.

At the lab the rhodamine water samples were placed in a Perkin Elmer LS-50 to calculate the amount of fluorescence in each sample, and using a predetermined rhodamine calibration curve, the amount of dye in each sample was then calculated.

SONDE Deployment

YSI 6000 SONDEs (Findlay et al., in press) were used to measure the water depth, temperature, turbidity, conductivity, pH, and dissolved oxygen. The focus of this study was on the dissolved oxygen (DO) and use of the water depth data for analyzing the hydrographs of each wetland. The SONDE deployments were broken up into two one-week deployments the first beginning July 11 – 15 for the three southern most sites, Vanderburgh Cove, Quarry, and Manitou and July 25-29 for the five northern most sites, Papscanee, Houghtaling, Stockport Flats, West Flats, and Gays Point. Both Tivoli North and South Bay have SONDEs deployed regularly by HRNERR staff and data were acquired from them for the week of July 4 – 8 during the dye deployment. The SONDEs were calibrated and programmed to take readings every 15 minutes throughout the week. They were placed in a rack on the ceiling of wire cages filled with brick. The cages were placed on the bed surface in the middle of the exchange points, the SONDEs sat about 40 cm above the bed surface. A depth measure and time was taken when the instruments were deployed.

The DO data from the SONDEs were sorted in Microsoft Excel; for examining effects of wetlands (and their shape, vegetation characteristics) we used only ebb-tide data as the dependent variable. The average ebb tide DO value for each wetland was compared to the different wetland attributes calculated from the GIS dataset and the hydrograph data.

The depth data from the SONDEs were used to create hydrographs for each wetland during the period of deployment. To compare the pattern of flow out of the wetlands (ebb tide) the change in depth (delta Z) between 15 minute sampling increments was calculated. Descriptive statistics were calculated on the dataset for each wetland, these included the mean delta Z value for each wetland, the 95% confidence intervals, the sum of delta Z values, the minimum and maximum, the range, variance, standard deviation, standard error, and skewness.

The information from these hydrographs was then used for analysis with the different physical attributes of the wetlands to determine which of the attributes has the highest potential (as determined by the correlation r-value) to influence the pattern of ebb tide flow from the wetlands. In conjunction with this analysis, the hydrograph data were compared to the average ebb tide dissolved oxygen data to determine what if any relationship exists between the hydrological patterns and the effect of wetland exchange on dissolved oxygen concentrations.

RESULTS

Analysis of Wetlands

GIS Attributes of Selected Hudson River Wetlands

The values for the first 12 attributes (number of vegetation covers through the number of tributaries) in Table 1 were calculated from the Hudson River vegetation GIS database and show that the ten wetlands varied widely in their size, shape, and vegetation composition. For example, the sizes of the ten wetlands ranged from 91,395 m^2 (Quarry) to 1,544,445 m^2 (Tivoli North Bay), and the shape indices ranged from 1.68 (Quarry) to 8.71 (Papscanee), 1.0 being an indication of a very circular shape, and 10.0 being an indication of a very elongated shape. The wetlands also varied in their percent composition of vegetation types and the amount of open water.

Wetland #	Name	PCA Factor 1 Scores	# Veg Covers	Sum Area (m^2)	% Open Water	%BV	%GV	%SM	%SS	%ST	%SV	% SAV Inside Wetland	Shape Index (SI)	Widths of Exchange Points (m)	T
1	Papscanee	-1.40	26	561847	6.5	5.96	47.00	6.85	6.56	10.78	0.00	19.62	8.71	140	
2	Houghtaling	-0.70	30	904344	8.9	13.35	31.38	2.18	19.49	22.83	1.83	0.00	6.46	15	
3	Stockport flats	-1.10	33	1390471	5.3	34.19	30.59	0.22	0.00	18.24	0.00	12.89	5.65	215	
4	West flats	-1.09	11	686997	2.9	24.20	47.09	12.27	0.00	10.42	0.00	3.20	3.26	50	
5	Gays point	1.31	3	530591	61.6	19.37	17.14	0.00	0.00	0.00	0.00	59.75	2.90	440	
6	Tivoli North bay	-1.10	44	1569021	1.5	25.60	65.35	0.00	1.41	0.37	3.51	2.28	2.97	30	
7	Tivoli South bay	0.89	5	1207579	46.1	5.59	1.42	0.00	4.35	0.00	0.00	74.02	3.03	40	
8	Vanderburgh cove	0.83	12	451673	27.0	26.47	10.49	0.83	4.47	0.57	0.00	43.24	4.64	30	
9	Quarry	1.03	3	91395	0.0	46.67	25.98	0.00	0.00	15.66	0.00	13.23	1.68	4	
10	Manitou	0.12	3	283099	0.0	0.00	93.18	0.00	0.00	0.00	4.30	2.58	3.23	8	

Table 1. Wetland Physical Attribute Characteristics. Using a GIS database of Hudson River vegetation classifications, different physical attributes of 10 wetlands along the length of the river, from Manhattan up to the Troy Dam in Albany, were measured. These measures were used to compare different physical attributes of the wetlands to their ebb tide hydrographs and the ebb tide DO values (**Figures 5 and 6**).

Temperature Logger Deployment

The initial study using the temperature loggers to determine if similar vegetation types are located at similar elevations above the low water line at Vanderburgh Cove, Tivoli North Bay, and Houghtaling, was not successful. During the months of July and August the temperature of the water and air were indistinguishable in the wetlands. This resulted in unclear records of time at which the temperature loggers became inundated. Therefore it was necessary to repeat the study in September when the nightly air temperature was dropping sufficiently to distinguish between the air and water temperatures. However, due to time constraints in September this study was only carried out at two of the wetlands, Tivoli North Bay (a southern site), and West Flats a northern site (Figure 2).

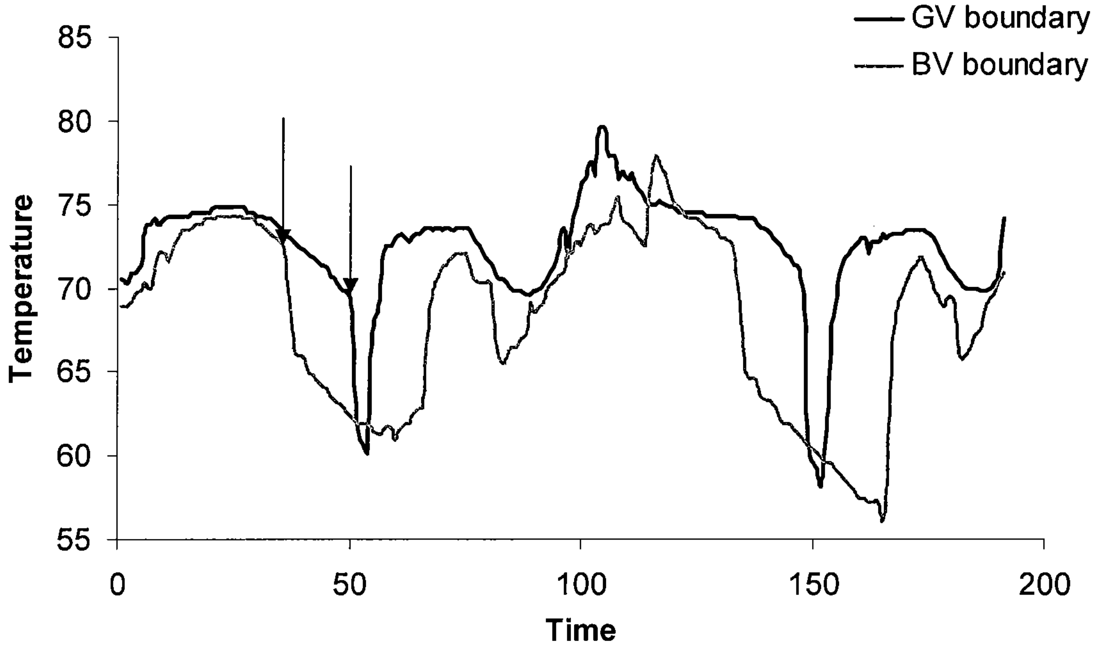

Figure 2. Vegetation Transect. Temperature profiles of the two loggers at the boundaries of the broadleaved vegetation (BV) and the graminoid vegetation (GV). The sharp drops in temperature indicated by the two arrows are the times at which each of the loggers was inundated by the incoming tidal water. The actual depths of inundation are determined by comparing times of temperature change to a nearby tidal creek deployment of temperature loggers (every 20 cm vertically).

The vegetation transects at TNB had very similar inundation times for each of the vegetation classes, BV and GV. There was a slight delay between each transect as they moved progressively away from the exchange points (transect 1 being the nearest to the exchange point and transect 3 being the farthest) (Table 2). West Flats had a similar pattern of inundation times within each transect and between transects, again with slight delays between the transect closest to the exchange point compared to the transect farthest away (Table 2). Within each of these two wetlands the tidal elevations at which the BV and GV are inundated are very similar, and the difference between the BV and the GV boundaries for each transect are very similar (Table 2).

Site: Tivoli North Bay Date: 9-12-2005

Transect #	Time of BV Inundation	Tidal Elevation at Time of Inundation (cm)	Time of GV inundation	Tidal Elevation at Time of Inundation (cm)
1	09/13/2005 5:46	30.5	09/13/2005 8:31	94.5
2	09/13/2005 5:56	30.5	09/13/2005 9:00	100.6
3	09/13/2005 6:01	36.6	09/13/2005 9:01	100.6

Site: West Flats Date: 9-19-2005

Transect #	Time of BV Inundation	Tidal Elevation at Time of Inundation (cm)	Time of GV inundation	Tidal Elevation at Time of Inundation (cm)
1	09/21/2005 1:15	18.3	09/21/2005 03:00	79.2
2	09/21/2005 1:30	18.3	09/21/2005 03:45	97.5
3	09/21/2005 1:45	30.5	09/21/2005 03:45	97.5

Table 2. Wetland Vegetation Class Inundation Times. Three vegetation transects were set up at West Flats and Tivoli North Bay to measure the inundation times of the broadleaf (BV) and graminoid (GV) vegetation classes. This was used to determine if the different vegetation classes were located at similar tidal water elevations in the different wetlands.

Dye Test

During peak high tide the highest concentration of dye in Tivoli North Bay was located in the areas with the longest travel distance from the exchange point. Dye was found in low concentrations in the channels flowing between the exchange point and the areas located with the highest dye concentration (Figure 3).

The concentration of dye at the exchange point during the ebb tide was measured and appeared as a relatively tight “cloud” exiting the marsh (Figure 4). The highest intensity of dye occurring between 18:30 and 20:00, the end of the ebb tide, supporting the above findings of dye concentrations at the highest intensity in the farthest reaches of the marsh (Figure 3).

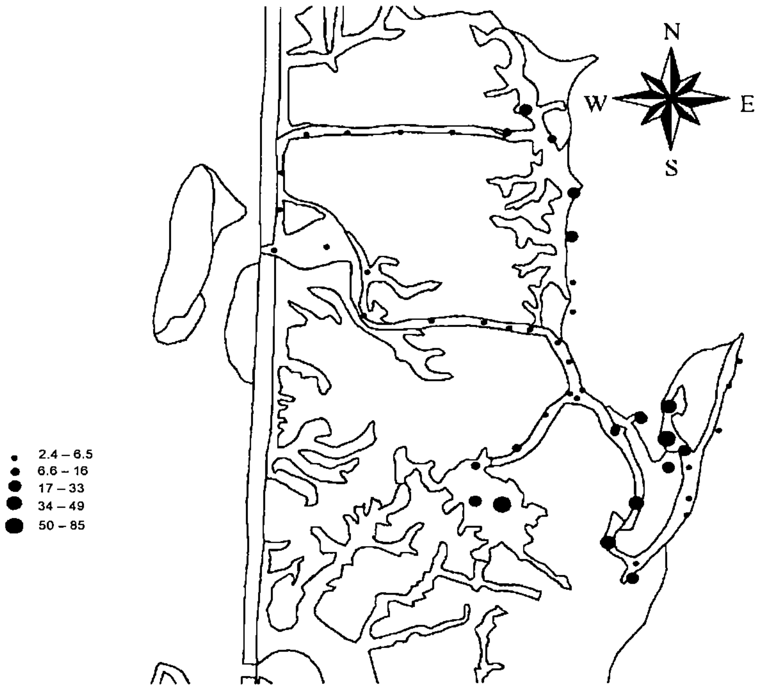

Figure 3. Map of Dye Concentrations. The varying concentrations of rhodamine dye throughout Tivoli North Bay during the first peak high tide after the dye had been injected into the wetland at the northern exchange point.

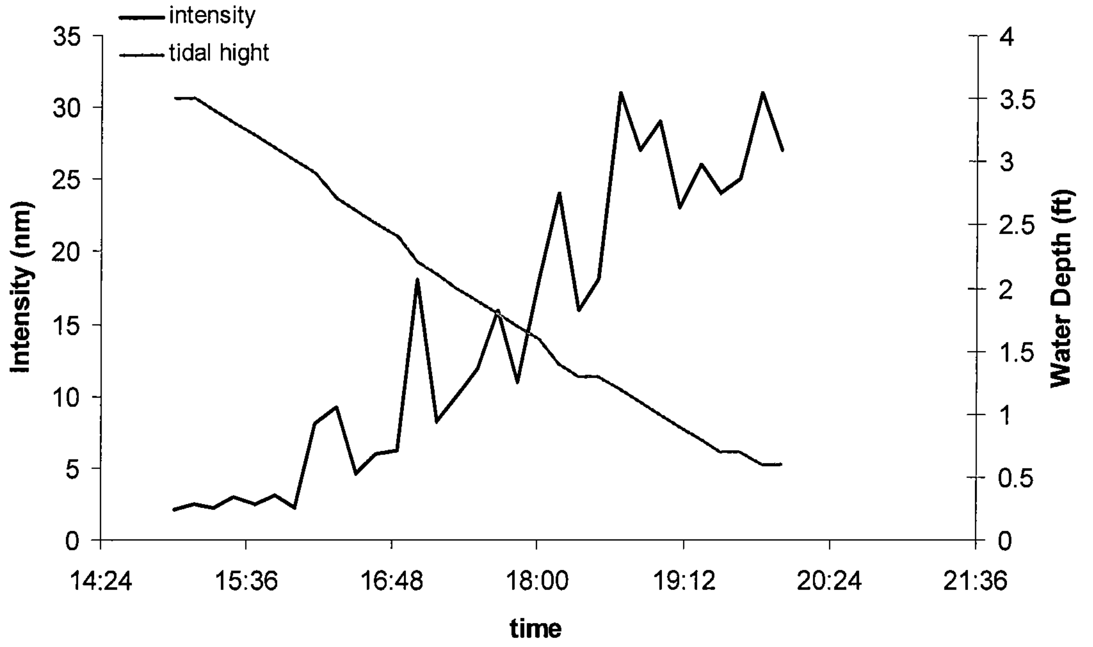

Figure 4. Intensity Curve. This is a graph of the dye intensity (nM) at the northern exchange point of Tivoli North Bay and the corresponding tidal water depths. The large slope in dye intensity as the ebb tide progresses is an indication of the dye exiting the marsh in a concentrated "cloud".

Wetland #	Average Ebb Tide DO mg/L
1	7.18
2	7.24
3	8.36
4	9.16
5	8.32
6	7.51
7	7.48
8	9.34
9	8.02
10	6.21

Table 3. Average Ebb Tide Dissolved Oxygen Concentrations. The DO values recorded by the SONDEs at each wetland during 4 ebb tides were average, and used to compare the oxygen values in each wetland to the different physical attributes in **Table 1** and **Figure 3**.

SONDE Deployment

The average ebb tide dissolved oxygen (DO) concentrations for each of the 10 wetlands (Table 3) was calculated from DO data collected and recorded every 15 minutes for a one week period by the SONDE instruments, Figure 5 is an example of this data from Gays Point. The profile shows the relatively high DO value of the river water as it flows into the wetland and the moderately low DO values in the ebb tide for each tidal cycle. The average for each marsh was compared to different attributes in Table 1. The strongest correlations were found between DO and two of the "percent" vegetation classes, BV and GV. The highest positive r value of 0.62 was calculated between the average ebb tide DO and the percent BV (Figure 6A). The relationship was negative, r value of -0.56, when comparing to the percent GV inside the wetlands (Figure 6B). There were no correlations found between the average ebb tide DO and any of the other 11 characteristic attributes from Table 1.

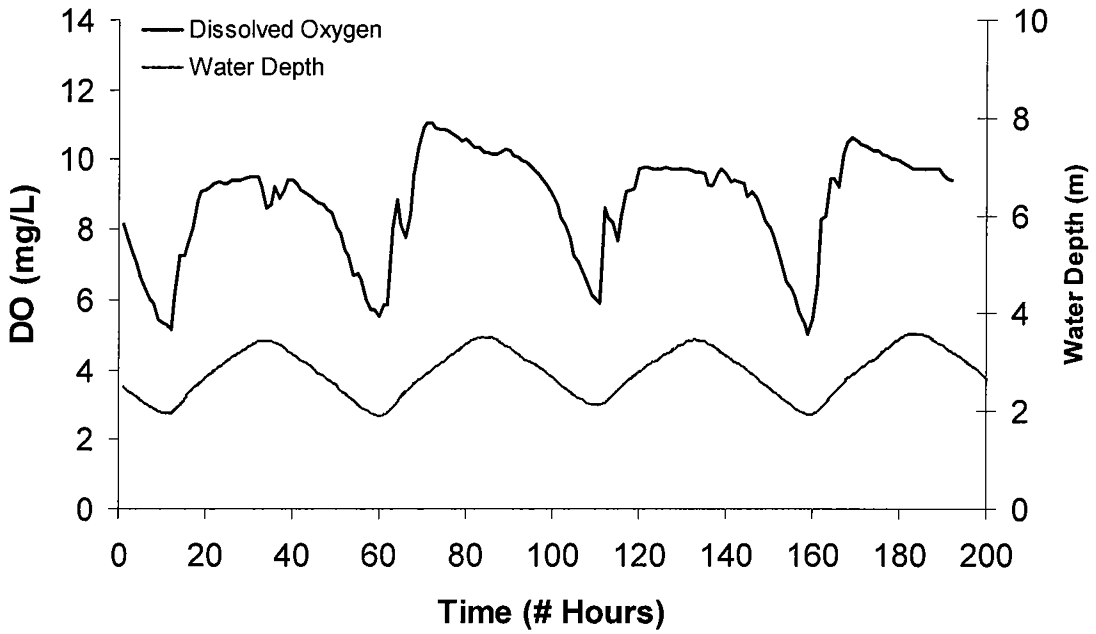

Figure 5. Dissolved Oxygen and Depth Data. An example of the recorded SONDE data for both dissolved oxygen and water depth at an exchange point between the river and Gays Point wetland. These are the raw data for a one week period.

Descriptive statistics were calculated for the depth/hydrograph data (Figure 5) collected by the SONDEs concurrently with the DO data for each wetland (Table 4). The statistical values were compared to the different attributes in Table 1. Only one combination of attributes and statistics was found to have a significant correlation value. The standard deviation of the delta Z values for each wetland compared to the sum area

Wetland #	Mean	Confidence 95.000%	Sum	Min	Max	Range	Variance	Std.Dev.	Standard Error	Skewness
1	0.061	0.071	1.757	0.001	0.092	0.091	0.0007	0.026	0.005	-0.695
2	0.055	0.064	1.491	0.008	0.083	0.075	0.0005	0.023	0.004	-0.806
3	0.043	0.051	1.242	0.001	0.066	0.065	0.0005	0.022	0.004	-0.573
4	0.046	0.054	1.236	0.001	0.066	0.065	0.0004	0.020	0.004	-0.809
5	0.059	0.067	1.541	0.009	0.083	0.074	0.0004	0.019	0.004	-1.252
6	0.095	0.112	1.430	0.020	0.130	0.110	0.0009	0.031	0.008	-1.271
7	0.080	0.096	0.880	0.030	0.110	0.080	0.0006	0.024	0.007	-0.683
8	0.034	0.041	0.814	0.003	0.059	0.056	0.0003	0.016	0.003	-0.331
9	0.031	0.037	0.702	0.002	0.055	0.053	0.0003	0.016	0.003	-0.123
10	0.032	0.038	0.882	0.005	0.059	0.054	0.0003	0.016	0.003	0.185

Table 4. Ebb Tide Delta Z Description Statistics. Basic description statistics were performed on the average ebb tide delta Z values for each wetland. This data was then compared to the different physical attributes in **Table 1** and **Figure 6**, and to the average ebb tide DO values for each wetland.

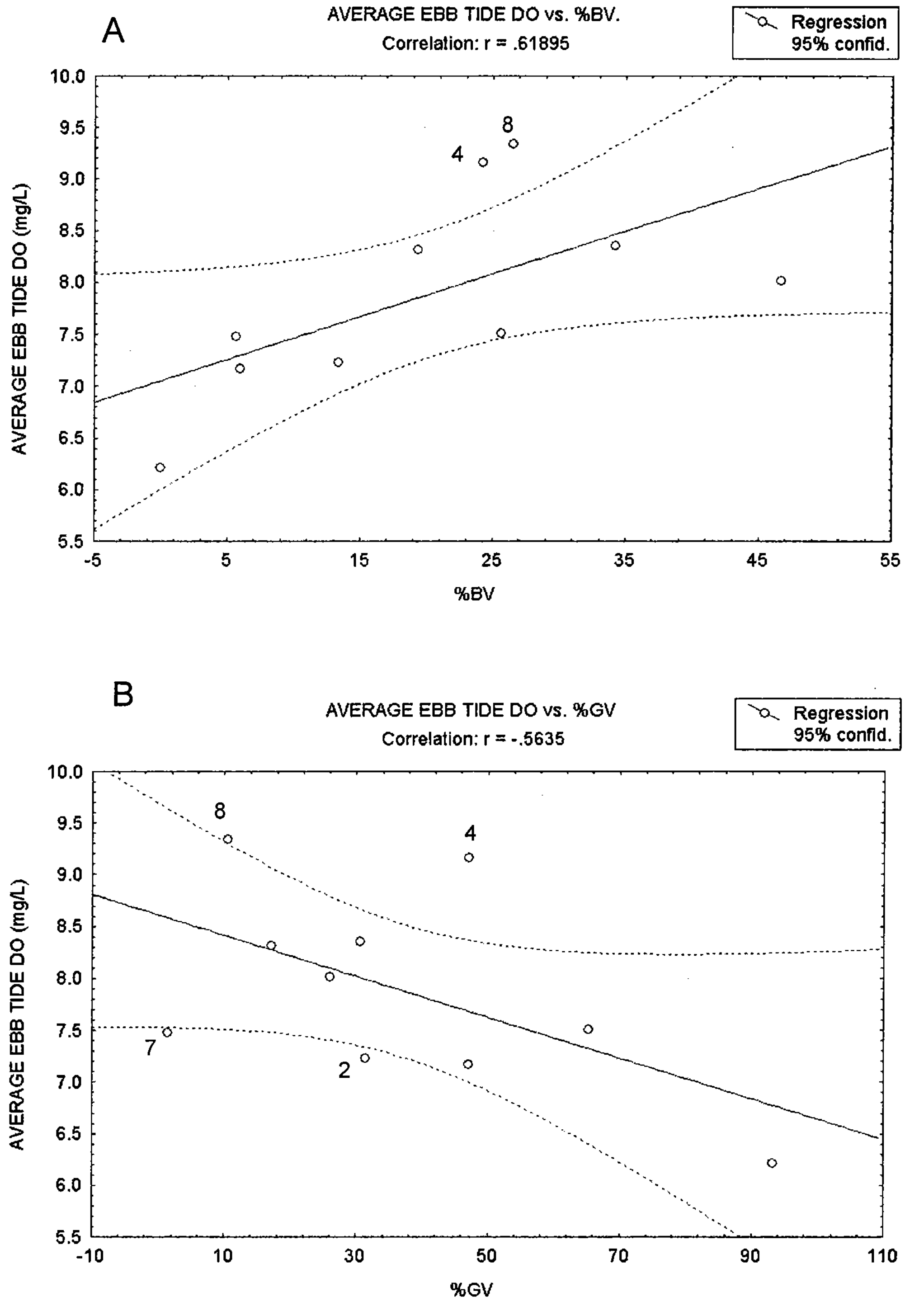

Figure 6. Dissolved Oxygen vs. Broadleaf and Graminoid Vegetation. The average ebb tide DO was compared to all of the different attributes in **Table 1**, but was found to only be positively correlated with the %BV and negatively correlated with the %GV. The numbers for each outlier correspond to the number of a wetland from **Figure 1**.

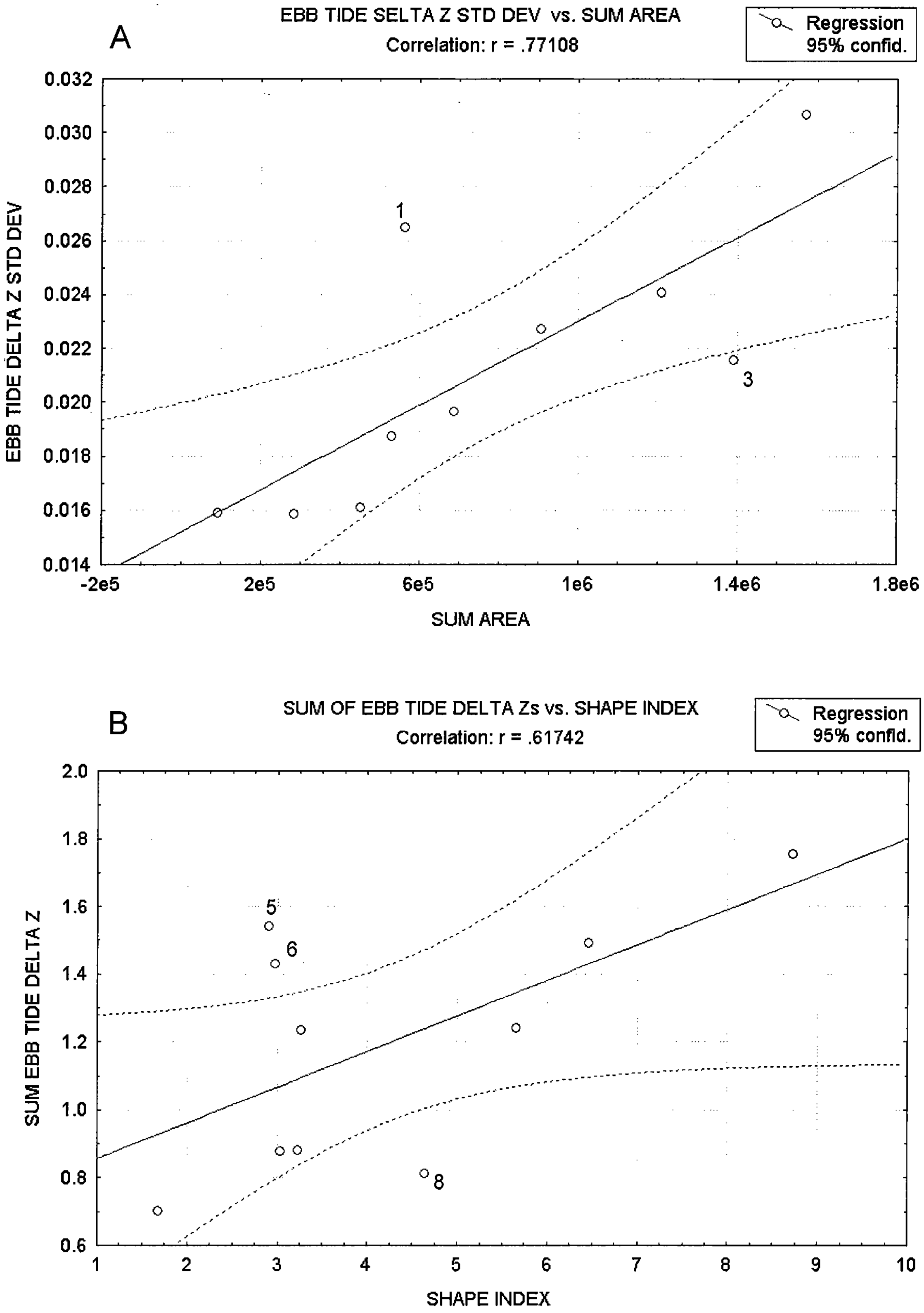

Figure 7. Ebb Tide Delta Z Values vs. Sum Area and Shape Index. The different description statistics in **Table 4** were used to compare the ebb tide hydrographs to the different physical attribute characteristics in **Table 1**.

of the wetland, which resulted in an r-value equal to 0.77 (Figure 7A). The second comparison with a significant correlation was between the sum of the delta Z-values for one ebb tidal cycle and the shape index with an r-value of 0.62 (Figure 7B).

DISCUSSION

The 10 wetlands used in this study, selected at random from the 50 largest wetlands in the Hudson River, varied greatly in terms of their physical attributes such as shape, size, quantity of open water, exchange point width, and percent of vegetation cover types (Figure 1 and Table 1). The variation within these attributes allowed for a comparison of the hydrographs and DO profiles to a variety of physical characteristics of the wetlands, such as comparing the relative elevations of different vegetation classes to the ebb tide water line (Figure 2). This analysis used temperature as an indicator of when the tidal water inundated the different vegetation boundaries. As shown in Figure 2, when the temperature loggers were inundated during the day there was a sharp drop in temperature values, first at the broadleaf vegetation boundary and then at the graminoid vegetation boundary, indicating the higher elevation of the graminoid vegetation. This pattern was observed at all of the wetlands except Manitou because of its more brackish water, and was measured at two of the wetlands (Table 2), as well as agreeing with findings by Kiviat and Beecher (1991). This pattern suggests the possible use of vegetation elevations as indicators of water retention and inundation patterns in the wetlands.

The hydrological connection between the river and wetlands was analyzed first using rhodamine dye to assess the lateral distribution of tidal water within Tivoli North Bay. The dye release data did show that the tidal water laterally mixes through the entire inundated wetland area (Figure 3), indicating that a percent of the incoming river water mixes fully with the "residual" marsh water during each tidal cycle at Tivoli North Bay. The timing of tidal inundation at the vegetation transects deployed at West Flats and Tivoli North Bay in September, did show that there is a slight lag time between the exchange point and the back of the wetlands (Table 2).

The hydrographs corresponding to the ebb tide were analyzed and found to have individual patterns of flow in each wetland as indicated by the delta Z properties calculated for each hydrograph (Table 4). Therefore each wetland has differing rates and duration of water flow per ebb tide. The physical attributes of the wetlands which exert the most influence on the differing hydrological patterns, are the sum area of the wetland and the shape of the wetland (Figure 7A). As the sum area of a wetland increases the standard deviation of the delta Z values increase. The larger the standard deviation the more variation in the rate of flow out of the wetlands, indicating there are periods of very high flow where there is a large reduction in depth for one of the 15 minute increments, as well as periods of very slow flow with only a small reduction in depth (Figure 7A, and Table 4). A possible explanation for this trend is that larger wetlands have, in general, a more complex internal channel network compared to the smaller wetlands (Figure 1). As each individual channel drains during the ebb tide there is a surge of water through the exchange point, as that channel empties the rate of flow through the exchange point slows until the next channel surge.

The two outliers in graph 7A are, Papscanee and Stockport Flats (Figure 7). Papscanee has a high range but only a midsized sum area; however, it has a very elongated and complex internal channel system, which could increase the potential for the surges in flow during the ebb tide, as well as a relatively large (compared to the other wetlands) tributary entering the wetland at the top most section (Figure 1). This tributary could be exerting significant influence on the hydrological as well as chemical characteristics of this wetland. The second outlier, Stockport Flats, has a low range in delta Z values but a large sum area; however, Stockport Flats has a very wide natural exchange point that could dampen the overall influence of internal channels draining during an ebb tide.

The shape of a wetland, as determined by the shape index (SI), influences the total change in water depth during a single ebb tide (Figure 7B), as SI increases the value of the sum of delta Zs increases. Therefore, the more elongated a wetland the greater the total amount of change in water depth at the exchange point. An explanation for this is that elongated wetlands have comparatively narrow areas surrounding their exchange points in the interior of the wetlands, and a larger quantity of water traveling a longer distance to reach all areas of the wetland (Figure 1 and Table 1). Consequently a larger quantity of tidal water is retained near the exchange point for a longer duration, increasing the depth at that location as compared to a rounded wetland where water exchange throughout the entire wetland may occur with comparative ease.

The three outliers on Figure 7B are Gays Point, Tivoli North Bay, and Vanderburgh Cove (Figure 1). Gays Point has a lower SI value, meaning it is more rounded, but has a high delta Z sum value (Figure 7B). However, in actuality it is an elongated wetland compared with the other wetlands with similar SI values (Figure 1 and Table 1). This discrepancy is due to Gays Point having very simple, clean boundary lines inducing the statistical software to view it as more rounded than it is. Similarly, Tivoli North Bay has a low SI value and a high delta Z sum value. Unlike Gays Point, Tivoli North Bay is rounded in shape; however, it has a very complex internal channel network (Figure 1). This complex network in conjuncture with two very narrow (15 m) exchange points for the total size of the wetland (1,569,021 m^2) has the potential to create an ebb tide flow pattern similar to an elongated wetland but without the shape (Figure 7B). Conversely Vanderburgh has a high SI value but a low delta Z sum value. Although Vanderburgh has a comparatively rounded shape, it also contains a long thin channel that flows off of its eastern boundary, creating a statistical illusion that it is an elongated wetland (Figure 1).

Similarly to the analysis of the hydrograph data, the average DO values (Table 3) for all of the ebb tides at each wetland were compared to the physical characteristics of the wetlands in Table 1. The attributes with the highest correlation to the DO values were the percentages of BV and GV in each wetland (Figure 6A, and B). However, the correlations were opposite, BV was positive and GV was negative. As the overall percentage of BV increases in a wetland the DO increases, where as when the overall percentage of GV increases the DO decreases (Figure 6A and B). Despite a positive correlation with BV, the average DO values for all the wetlands except two, West Flats and Vanderburgh, were lower than the average DO value of the inflowing river water (8.8 mg/L). West Flats and Vanderburgh are the two outliers in Figure 6A, as well as being two of the four outliers in Figure 5B. Both of these wetlands have high amounts of DO compared to their percent composition of BV and GV (Figure 6B).

There is no consistent evidence for why these two wetlands are outliers, while Vanderburgh has double the amount of BV compared to GV; it is not high enough to explain the DO value and when taking into consideration the composition of its SAV, it is dominated by *Trapa* which is known to decrease the DO values in the water (Caraco and Cole 2002). West Flats actually has a higher percentage of GV than BV, yet it has an abnormally high DO value as well (Figure 6A and B, Table 1); however, its SAV composition is solely *Vallisinaria*, which is known to increase the amount of DO in the water (Caraco and Cole 2002). Nor is there any consistent relationship between DO and the other wetland attributes in Table 1 to explain these outliers. However, one potential explanation for this is that in the wetlands the BV and GV consistently inhabit the wetlands at distinct elevations above the low water line (Table 2, and in accordance with findings by Kiviat and Beecher 1991), with the BV niche lower than the GV, thus the BV is in contact with the tidal water longer than the GV increasing the potential influence on the water chemistry. In fact the GV is at most partially inundated and so would not release O2 to the water column. Additionally, the litter layer is much thicker in the GV zone and microbes on litter may be contributing to lower DO levels.

The two other outliers in Figure 6B are Houghtaling and Tivoli South Bay; both wetlands have lower DO values than can be explained by their percent GV composition. A potential explanation for this is that Houghtaling has high percentages of the other vegetation classes in its composition, all of which could be overall oxygen reducers; and Tivoli South Bay has very low percentages of both BV and GV but a very high percentage of *Trapa*, which has a negative effect on DO values (Caraco and Cole 2002) (Table 1). However, there is again no consistent correlation between the other vegetation classes and the amount of DO in the ebb tide water.

Although there is no direct correlation between the hydrological indicators (Table 4) most heavily influenced by the sum area and shape of the wetland (Figure 7A, and 7B), and the DO values, there is a relationship between the tidal water elevation and the area of a wetland occupied by both BV and GV (Table 2 and Kiviat and Beecher 1991). Both of these vegetation classes have a significant influence on the DO concentration of the ebb tide water (Figure 6A and 6B). This elevational distinction could have a significant role in the connection between the hydrological exchanges, both the river wetland exchange and exchange within the wetland, and the dissolved oxygen content of the water.

To further this analysis it would be advisable in the future to first measure the discharge at the exchange points for all of the wetlands and to measure the tidal lag and height difference between the exchange points and the farthest reaches of the wetlands. In addition it would be valuable to collect vegetation transects at additional wetlands for a better comparison between tidal elevation and vegetation classes, as well as the length of time of inundation for each vegetation class. In conjuncture with this, measure the DO values within the different vegetation patches for a better understanding of the oxygen patterns in different locations throughout the wetlands.

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