HYDRODYNAMICS OF A COASTAL WETLAND ECOSYSTEM

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by
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Descriptions of wetland hydrology have historically used a water budget approach or ignored below ground hydrodynamics. In so doing, they lose the ability to relate hydrologic properties to ecological processes. My approach is to develop ecologically significant parameters from hydrographs that allow inferences about wetland processes to be made. Data were analyzed from sites in mainland and back barrier tidal salt marshes on the Eastern Shore of Virginia over a period of 6 years. The nature of water level fluctuations and the source of those fluctuations were used to characterize tidal marsh sites which ranged from a tidal, semi-diurnal flooded creekbank edge to a precipitation driven high marsh that received tidal inputs only with wind-driven storm surges. Hydrodynamics were highly variable among sites and the high marsh alternated between flooding above ground surface during winter and water levels as low as 1m below ground surface in summer. The island high marsh site was also largely precipitation driven, but also received inputs from a regional groundwater source. Unlike the mainland sites, flooding above ground surface was not maintained during any season. Differences in these hydrologic parameters were useful for quantitatively estimating the capacity for ecological processes, such as tidal exchanges of material with the estuary and maintenance of aquatic habitat.

Acknowledgments

The research for this thesis has been a challenging and rewarding experience that I have greatly enjoyed. This is due largely to the fact that I was lucky enough to have worked with excellent people throughout the process. Most of all, I owe thanks to Mark Brinson who provided me the opportunity to work on a project which was perfectly suited to my interests. Furthermore, he always provided insightful and experienced advice, from which I have learned a great deal. It was a pleasure, both professionally and personally, to work with him. Bob Christian, Michael Slattery, and Terry West were truly good committee members by providing alternate points of view and helpful manuscript reviews.

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Introduction

On a large scale, ecosystems are structured by the physical factors of the environment in which they exist. These forcing functions include such factors as temperature, solar radiation, wind, precipitation, tides, and groundwater. Collectively these factors both promote and impose “ecological constraints” on ecosystem processes and, in doing so, drive the structure and function of the system (Odum 1971). In wetlands, the physical dominance of hydrologic factors has a strong modifying influence, and separates wetlands from other ecosystems across all climatic zones. Consequently, it makes sense to classify wetland types based on differences in hydrology and other associated factors. A modified Piper diagram illustrates the typical association between wetland type and dominant hydrologic sources (Brinson 1993) (Figure 1). For example, a fringe wetland, on the edge of a lake or coast, would be expected to have predominantly lateral overland flows from the lake or tidal source, while a depressional wetland would be expected to receive inputs predominantly from precipitation and groundwater sources. While this holds true on a large scale, factors affecting the timing, amount, and frequency of hydrologic inputs can vary across climatic zones, regionally within a climatic zone, and even at a small scale within an individual wetland. Variation in source and hydrodynamics are both ecologically significant, as they translate into wetland structure and function.

Although a number of studies have qualitatively associated hydrology with wetland processes, very little has been done that quantitatively links the two. A few studies have established a quantitative link between hydrodynamic aspects and a single

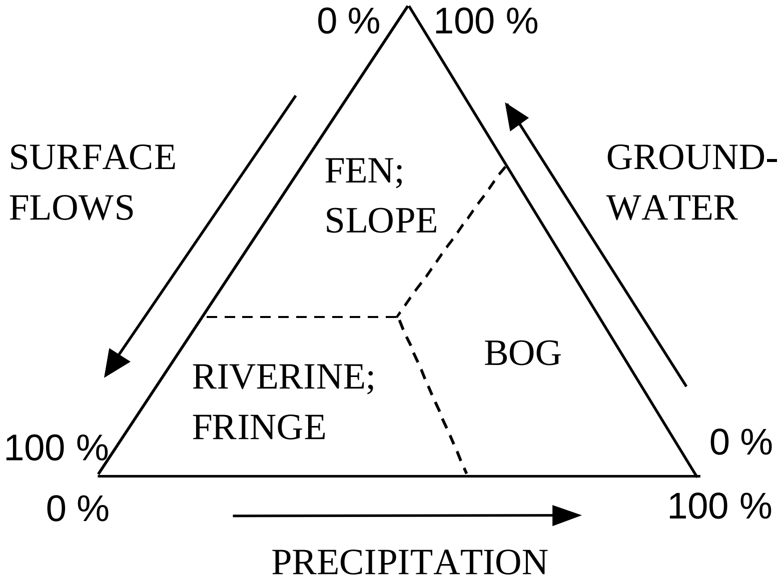


Figure 1. Association between wetland types and hydrologic sources, from Brinson 1993. Each apex of the diagram represents dominance of an input from the corresponding source. Wetland types are indicated based on relative dominance of inputs from the three sources.

process. For example, Hook (1988) used the metric of cumulative water table drawdown as an indicator of aeration potential, which was associated with vegetation dynamics. Similarly, Day et al. (1989) correlated the rate of root decomposition with continuous verses periodic soil saturation in forested freshwater swamps. Even though few studies have correlated hydrologic parameters with specific processes, there is no lack of hydrologic studies in wetlands. Most studies have taken a water budget approach in which inputs and outputs are measured, calculated, and balanced such that inputs equal outputs over sufficient time periods. While this is useful information in a strictly hydrologic sense, it provides little information of ecological significance. In addition, many studies focus on above ground flooding and largely ignore water table dynamics (Carter 1986). Even a currently accepted definition of hydroperiod ("the depth, duration, frequency, and seasonality of flooding", Mitsch and Gosselink 1993) excludes below ground dynamics. Lack of information on below ground hydrology loses the ability to relate the data to processes dependent on saturation and moisture status of the soil. Variation in water source has not been well documented, and such variations may help to explain differences in functions.

A comprehensive approach to examining the relationship of wetland functions and hydrology, with emphasis on ecological significance, could vastly improve the usefulness of hydrologic data. To address some of the shortcomings mentioned above, a separation between above ground and below ground dynamics should be made. This is based on the premise that major wetland functions can be generally grouped into those highly dependent on saturation/desaturation cycles and those highly dependent on above ground flooding (Figure 2). The logic follows that hydrologic inputs drive water table fluctuations, and these in turn control saturation/desaturation cycles that influence wetland functions, such as decomposition. In contrast, maintenance of aquatic habitat and exchange of dissolved and particulate matter are highly dependent on above ground flooding (Figure 2). Separation of data by season may also be useful as wetland functions could differ among seasons. For example, hydrologic variations affecting sedimentation rates, such as large flows originating from storm surges, maybe separated using a seasonal time scale. Likewise, the maintenance of habitat for aquatic organisms or waterfowl would most likely vary seasonally, as depth of floodwater varies.

I will use salt marshes and adjacent ecosystems to develop a quantitative description of wetland hydrology that will help to reveal hydrologic differences among wetlands along a continuum of water sources and flooding frequency. The range of conditions falls between a creekbank environment that consistently floods and drains twice daily to a shrub zone landward of a marsh community that floods only during extreme events. With these combinations of sources and hydrodynamics, differences in ecological significance should be revealed. Specifically, I will (1) quantify parameters typically associated with hydrodynamics (depth, duration, and seasonally of flooding) with a separation between above and below ground dynamics, (2) quantify the relative contribution of inputs from various hydrologic sources for above and below ground separately, and (3) quantify absolute values for the timing, frequency, and amplitude of inputs from hydrologic sources for above and below ground surface separately. The

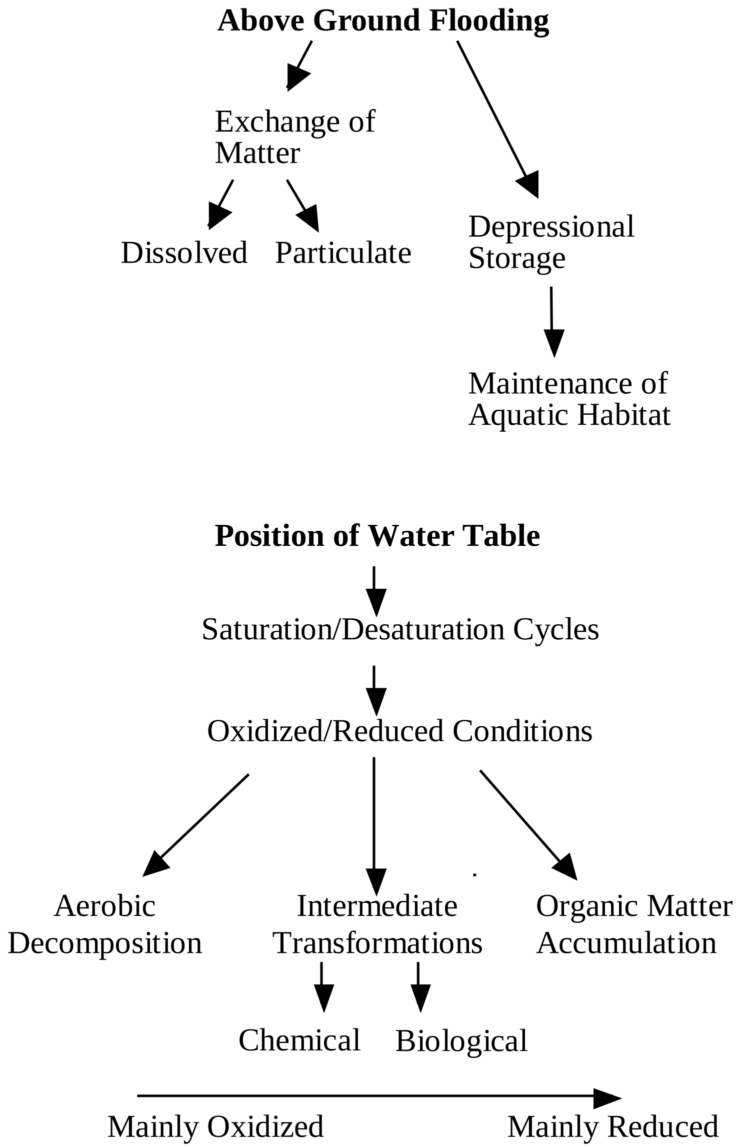


Figure 2. Hierarchy of wetland processes as influenced by hydrology. Several wetland processes are presented based on their dependence on above ground flooding or saturation condition of the soil.

ability of these parameters to identify possible differences in ecological processes among sites is discussed.

Description of Sites

Regional Description

The study sites were located at the Virginia Coast Reserve (VCR) Long Term Ecological Research Site (LTER). The VCR/LTER encompasses the seaside coastal land of the southern Delmarva Peninsula, at approximately 37° 27’ latitude and 75° 50’ W to 75° 40’ W longitude. Mean annual temperature is 15° C, with a mean annual low of -11° C and a mean annual high of 36° C. Average yearly precipitation is around 100 cm/year, with precipitation well distributed throughout the year (USDA Soil Conservation Service 1989).

Within the VCR/LTER, mainland fringe marshes, lagoonal marshes, backbarrier marshes, and wetlands in freshwater swales are found. To work with sites that varied hydrologically, several sites in a mainland fringe marsh and several sites on a barrier island were identified (Figure 3).

Mainland Marsh Sites

The mainland marsh is located at the upper reaches of a semidiurnal tidal creek with a tidal range of approximately 1.45 m and salinities of 22 parts per thousand (ppt). During the Pleistocene, the area was a stream valley at times of low sea level stands and was covered with estuarine water during periods of high sea level stands that resulted in deposits of silty estuarine sediments. The resulting soils are very poorly drained and poorly drained, silty and loamy soils, with 10 to 35% clay content and are classified as the Chincoteague-Magotha series (USDA Soil Conservation Service 1989). Current marsh was established during the Holocene transgression and, due to an antecedent

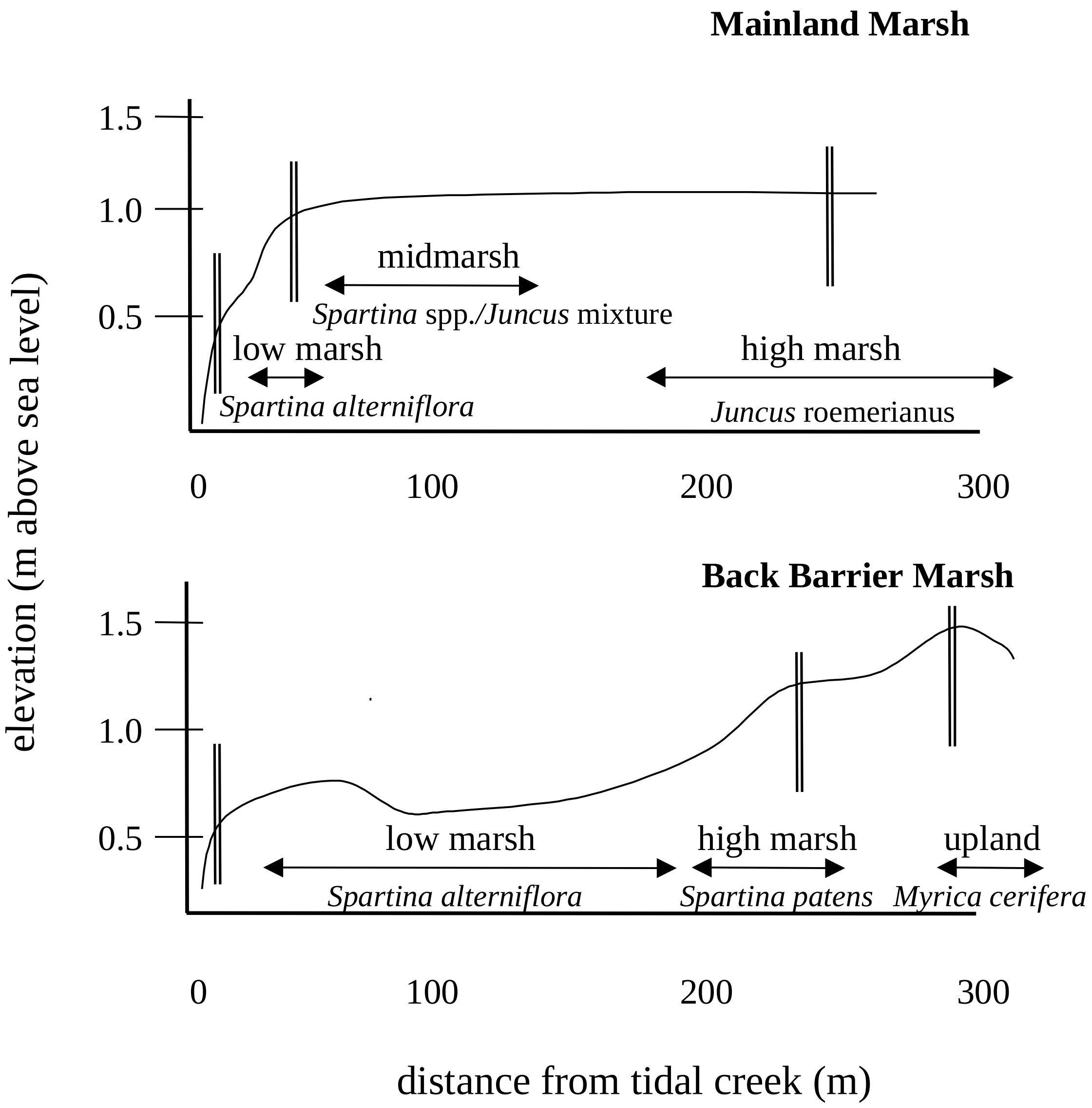


Figure 3. Cross section of study sites at mainland and back barrier locations. Cross sections of the marshes show the approximate position and elevation of water level recorder sites, indicated by vertical lines. Dominant plant species at each site are also indicated.

floodplain geomorphology, now covers a wide, flat area (Oertel et al. 1992). The distance from creekbank to upland is approximately 450 m with an average slope of 0.81 x 10^{-3} (Hmieleski 1993). Given its width and slope, this marsh offers a continuum of hydroperiods between sites with regular semi diurnal flooding and those that only rarely flood with estuarine water.

Along this gradient, three sites were chosen for monitoring: a creekbank site (0.4 m above sea level (SL) and on the creekbank edge), a middle marsh (midmarsh) site (1.0 m above SL and 25 m inland from the creek), and a high marsh site (1.05 m above SL and 400 m from the creek). Medium-form *Spartina alterniflora* covers the creekbank site. Mixtures of *S. alterniflora, Spartina patens, Distichilis spicata*, and *Juncus roemerianus* colonize the middle marsh. Large patches of *J. roemerianus*, *S. patens*, and *D. spicata* dominate the high marsh.

Island Sites

The barrier island sites are located along the northern tip of Hog Island (Figure 3). Sites were chosen to represent a variety of hydrodynamic patterns and hydrologic sources. Within the back-barrier marsh, two sites were established: a creekbank site and high marsh site. The creekbank site (0.4 m SL and on the creekbank edge) was similar in vegetation, soil, and tidal range to the mainland creekbank site. The high marsh site was located at the upper edge of the marsh, about 100 m inland from the creek and adjacent to a dune and swale system. *Spartina patens* is dominant in this area. Soils are of the Camocca series, consisting of fine sand with 5-12% clay (USDA Soil Conservation Service 1989). The salinity of surficial groundwater at this site has been monitored and was found to be 20 ppt lower than the mainland high marsh during dry summers when ET was high (unpublished, LTER database). A third site is located in the 125-year old dune/swale system adjacent to the high marsh site. Surficial groundwater at this site is consistently fresh (<2 ppt) throughout the year (unpublished, LTER database) and *Myrica cerifera* dominates the area. Soils are classified as Fisherman soils, which are moderately drained fine sands with a permeability of greater than 20 inches/hr (USDA 1989). This site may not be jurisdictional wetland, but is the dominant community on the island adjacent to the salt marsh continuum.

Data Collection and Analysis

As part of the LTER ecological databases, a 7-year database of water levels was collected with Stevens type F and type A continuous water level recorders. All but the two creekbank recorders captured fluctuations from approximately 1.5 m below ground surface to 0.5 m above ground surface. The creekbank water level recorders captured fluctuations from 0.5 m below ground surface to 1.5 m above ground surface. Essentially continuous data from 1991 through 1996 were available for development of the hydrologic descriptions, and were digitized using Java video capture software.

Depth-duration graphs were used to define the position of water levels for each site by season: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November). Duration was defined as the percentage of total time that water levels remained within 5 cm depth-increments (from 1cm of flooding up to and including 5 cm above ground surface, for example). The depth-duration graphs represent an average seasonal position of water levels, as years 1991 through 1996 were combined. For the island high marsh site, years 1992 through 1995 were used. The creekbank sites exhibited such little variability across months and years that only 6 months from 1993 of the mainland creekbank were randomly chosen and used to represent all months. The total numbers of hours of water levels used for data analysis are listed in Table 1.

Three possible hydrologic sources were identified: precipitation, tidal, and groundwater. When quantified as centimeters of rise in the water table or water surface, they are called inputs and are attributed to one of the three sources. To quantify the

Table 1. Total hours of water levels used for depth-duration graphs.

SITE	YEARS	WINTER	SPRING	SUMMER	FALL
creekbank	1993	------	--2661--	------	------
mainland midmarsh	1991-1996	4709	3686	4805	6666
mainland high marsh	1991-1996	4634	4745	4283	5211
island high marsh	1992-1995	2688	5869	3870	1945
island myrica	1991-1996	7631	7415	5027	8448

contribution of inputs from each source, all inputs on a hydrograph had to be attributed to one of the hydrologic sources. As hydrographs do not directly indicate the source of inputs, a protocol for identifying and separating the sources was developed.

Hydrographs and precipitation records were compared to identify inputs resulting from precipitation. Meterologic stations located at the mainland marsh and on the island provided daily total rainfall (mm) for 1991-1996 (Krovetz and Porter 1996). At all the sites, except the two creekbank sites, a precipitation event always produced a rise in either above ground flooding or a rise of the water table. The rise consistently occurred on the same day as the precipitation event. No lag greater than a day was ever seen between daily precipitation and the hydrograph response as illustrated for the mainland midmarsh hydrograph (Figure 4).

Water source at the creekbanks was considered to originate from tidal sources except for small precipitation contributions assumed from the rainfall records. Creekbank data were also used to identify, by time and elevation relative to sea level, tidal inputs to other sites further inland. Tidal inputs produce sharp response peaks and most rise tens of centimeters above ground surface, thus distinguishing this source from precipitation. Precipitation peaks have more muted response peaks and do not typically produce flooding past the maximum of depressional storage (Figure 4). For inland sites a given tidal elevation, 112 cm above ground surface (gs) at the mainland midmarsh and 130 cm (gs) at the mainland high marsh, was necessary to introduce tidal inputs to the sites. For both of the creekbank sites, groundwater inputs were never detectable from the hydrographs, and thus assumed to be negligible. The remaining

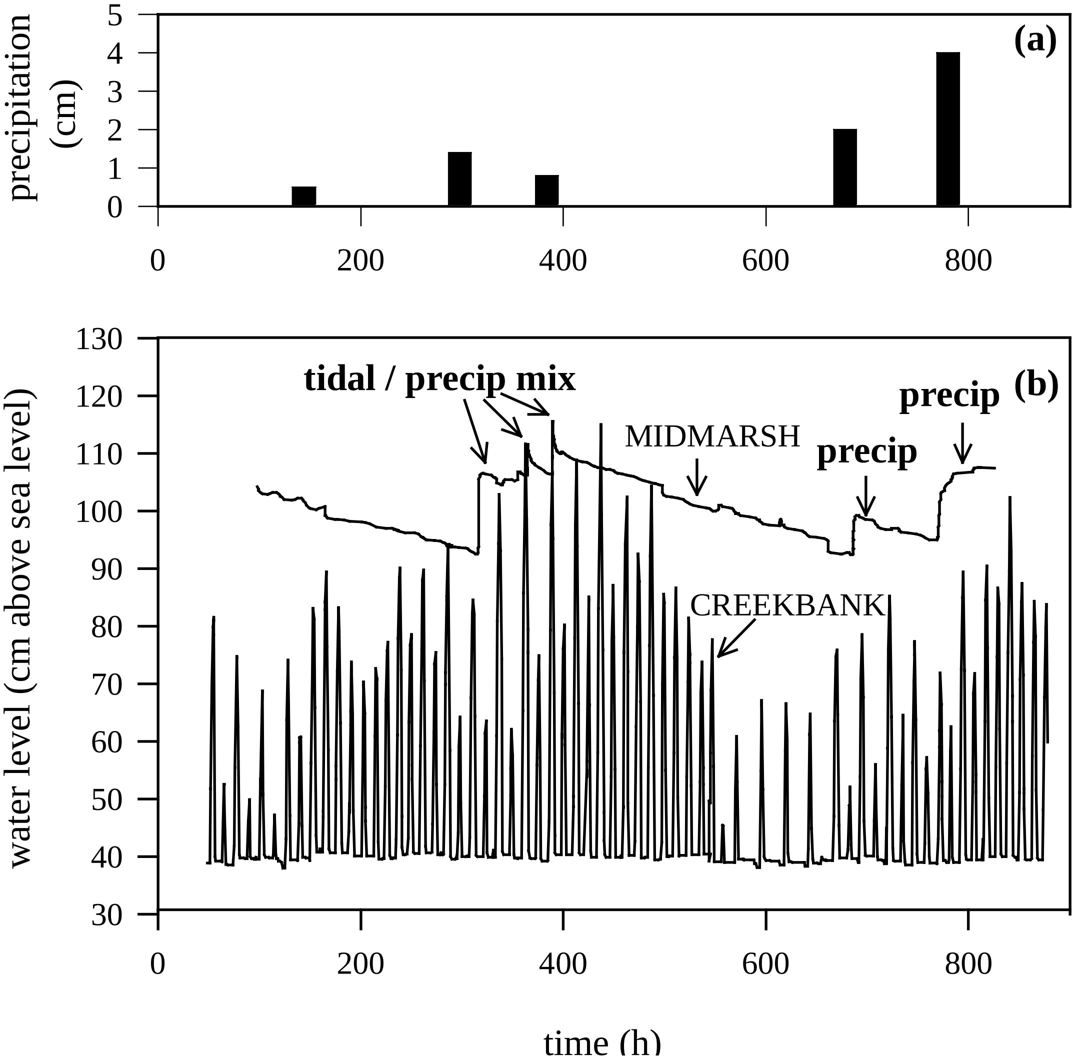


Figure 4. Identification of tidal and precipitation inputs. (a) Precipitation (precip) events and amounts. (b) Mainland creekbank and midmarsh hydrographs. Tidal and precipitation inputs were identified by comparing hydrographs, tidal magnitudes recorded at the creekbank site, and precipitation records. The source of each rise on the midmarsh hydrograph is indicated.

mainland sites were not expected to have any groundwater discharge due to the high clay content of the soil. This was supported by the fact that no mainland hydrograph from 1991 through 1996 showed a rebound in the water table (WT) following a decrease due to evapotranspiration (ET) or a rise that did not correspond to a tidal or precipitation input. In contrast, the island high marsh and *Myrica* hydrographs showed late evening and early morning WT rebounds during periods of drawdown. Differences in regional heads created by evapotranspiration, together with sandy soils, are thought to cause groundwater discharge at these sites. Groundwater inputs are defined as rebounds of the water table following ET which are presumed to originate from the lateral or upward movement of ground water (Figure 5). It is noted that a stable water table may not respond to flowthrough and, as a result, the hydrographs do not detect such flows.

When two sources simultaneously contributed to an input, a protocol was developed for separating them. For above ground flooding, a 1:1 ratio of precipitation to rise in flooding was assumed. Because displacement by vegetative biomass and overland flow can affect this ratio, its accuracy was validated by calculating the actual ratio of precipitation amount to rise in flooding. At all sites where above ground flooding occurred regularly, there was a very close 1:1 relationship between precipitation amount and rise in flooding (Figure 6a). The threshold of depressional storage was defined as the depth at which the ratio began to increase above 1 (Figure 6b). For below ground inputs, a ratio of precipitation amount to WT rise was determined from the hydrograph database. For every below ground rise that was attributed to precipitation alone, a ratio of precipitation amount to water table rise was calculated. No distinct patterns in water

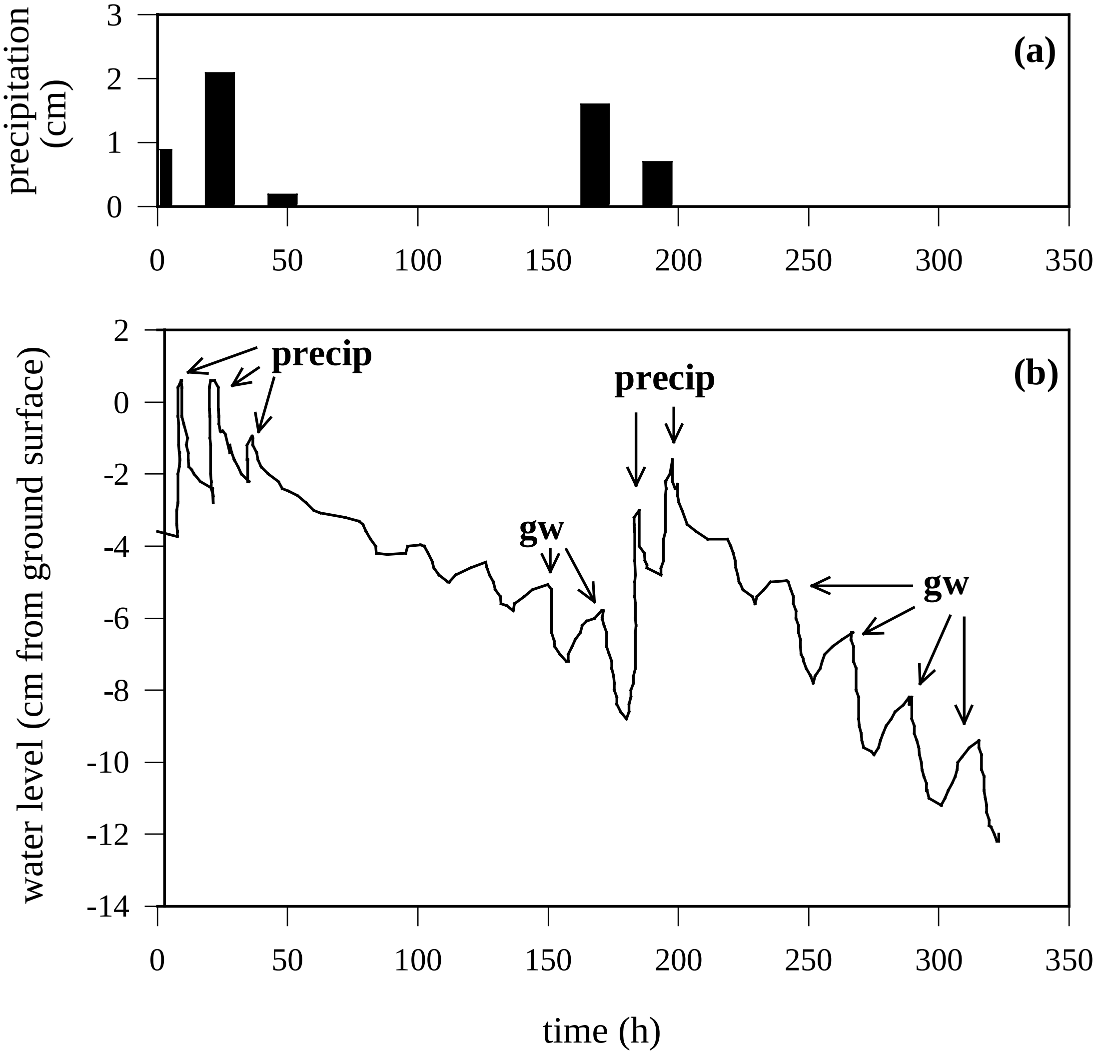


Figure 5. Identification of groundwater and precipitation inputs for the island high marsh. (a) Precipitation inputs clearly corresponded to precipitation records. (b) The daily pattern of water table rises occurred once a day in the late evening and early morning hours. These rebounds could be detected in the absence of any precipitation or tidal events, and were attributed to a groundwater source.

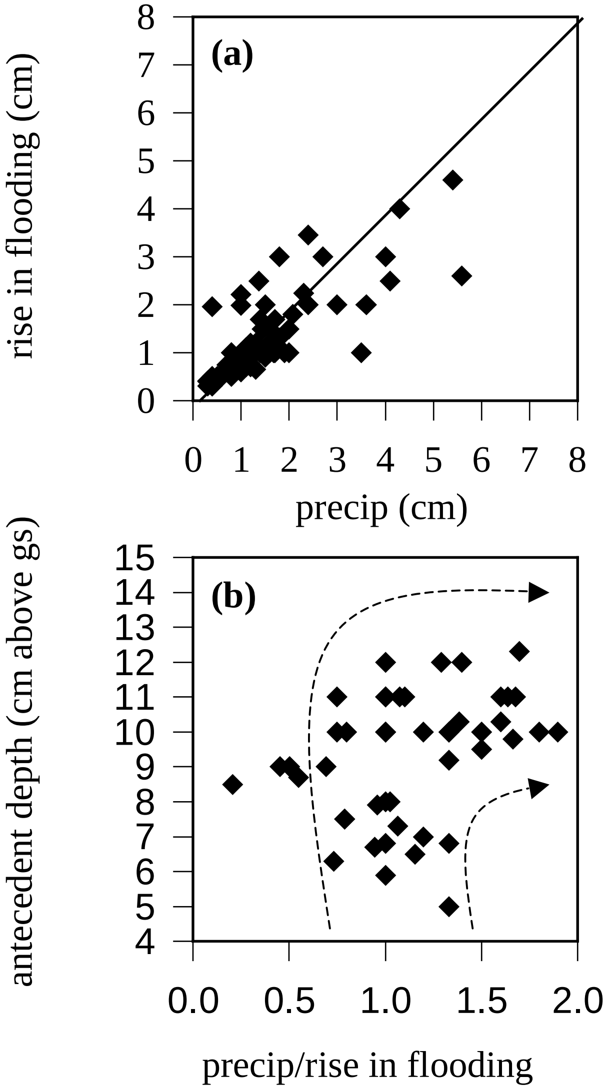


Figure 6. Validation of the 1:1 ratio. (a) Above ground rises at the mainland midmarsh site, attributed to precipitation alone, corresponded closely to a 1:1 ratio of precipitation to flood rise, especially for rainfall events < 3 cm. Larger deviations where the ratio is <1 were attributed to run-off. (b) Deviations of the ratio above 1.0 increased as the depth of flooding, prior to the rain event, increased. From this, the threshold of storage appears to be exceeded above + 9 cm, at which point overland flow prevents further storage.

table response were seen with depth, so an average was used for each site. Water table responses of 0.22 and 0.18 were assumed for the mainland midmarsh and high marsh sites (Figure 7). Water table responses were highly variable at the island sites and an average of 0.4 was assumed.

In order to compare sites with different magnitudes of hydrologic inputs, the relative percentage of inputs from each source was determined for each site. Cumulative rise in the water table, below ground, and cumulative rise in flooding, above ground, were used as a common metric for estimating inputs. Rises were measured as the difference between the maximum height of the input peak and the "baseline" level prior to the input. Rises from groundwater were measured as the water table rebound from the trough to the height of the rebound. Above ground and below ground rises were separated by source as described above and totaled by season. Relative percentages were then calculated by dividing the cumulative rises from each source by the total seasonal rises. The same seasonal division was used for the relative percentages that was used for the depth-duration curves, and hydrographs from the time periods indicated in Table 1 were used.

Relative contributions of inputs from the hydrologic sources were graphically represented with modified Piper, trilinear diagrams. Relative percentages from each source were plotted on axes ranging from 0 to 100%, with each apex of the triangle representing 100% input from the corresponding source. The center of the triangle represents equal inputs (33, 33, and 33%) from all three sources. An upward facing

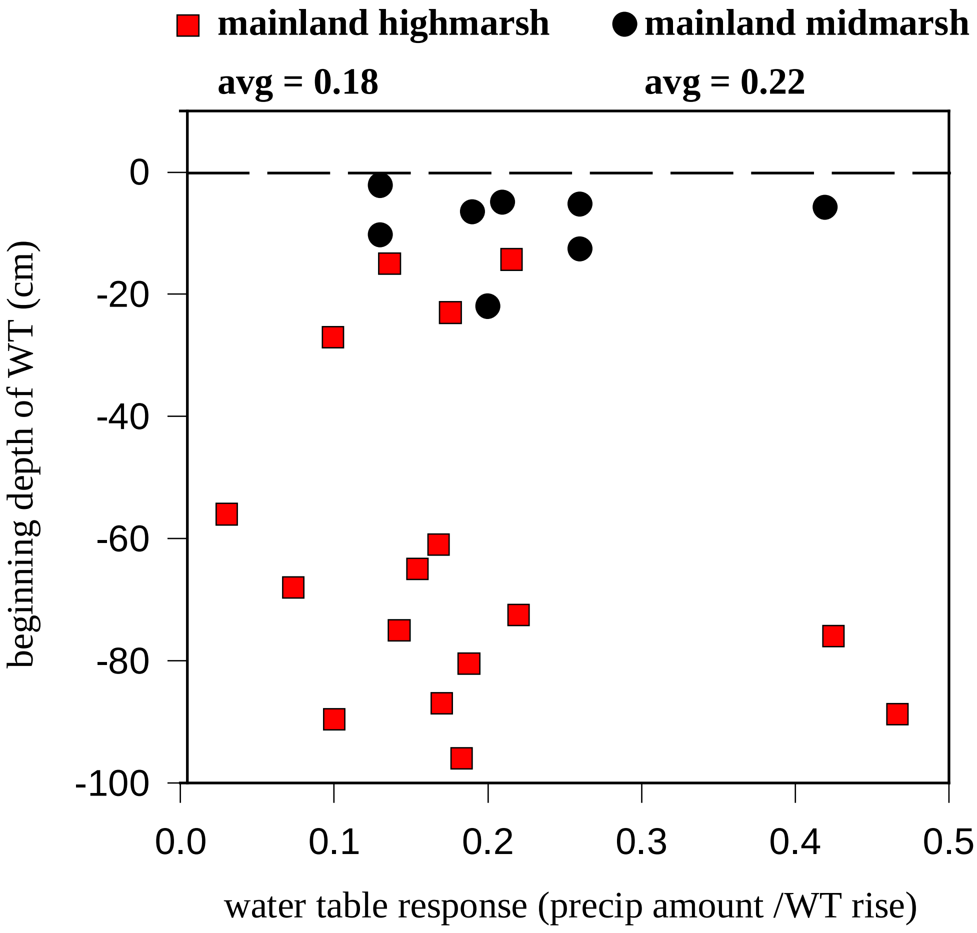


Figure 7. Water table responses for the mainland midmarsh and high marsh sites. Water table responses were determined by dividing known amounts of precipitation by the following water table rises. No trends in water table responses were seen with depth, and an average water table response value was used.

diagram represents above ground inputs and a lower facing diagram represents below ground inputs.

The frequency, average, and maximum amplitudes of precipitation, tidal, and groundwater inputs were represented in frequency-amplitude graphs. Separate graphs were created for above and below ground rises, and individual months were grouped together using the seasonal time scale previously defined.

Results

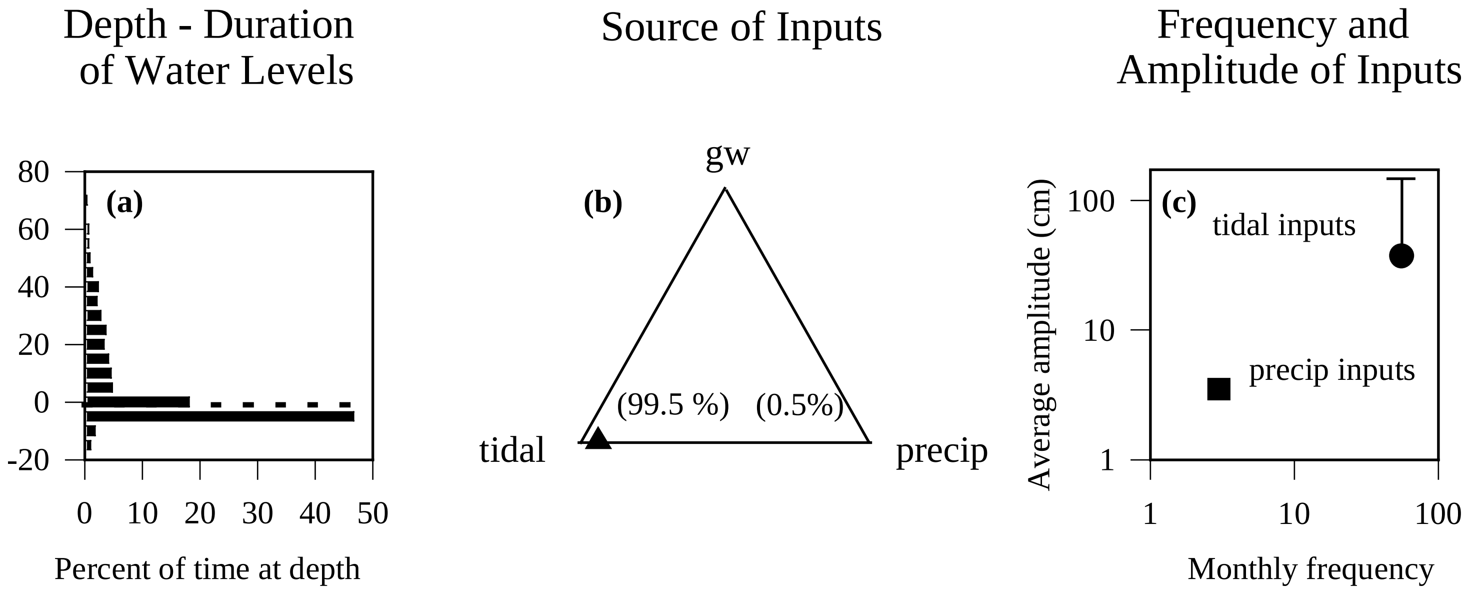
Creekbank Sites

The mainland and island creekbank sites exhibited typical semi-diurnal flooding with a consistent pattern in neap and spring tides. Water levels ranged between -15 cm below ground surface) and +80 cm (above ground surface), with the mean depth at +4 cm (Figure 8a). Water levels remained at -5 cm for the longest duration, 45 to 50% of the total time (Figure 8a). Storm and wind tides greater than +90 cm and +110 cm, up to a maximum of +140 cm, were recorded at a frequency of about three times a year. These events are so infrequent that flooding to these depths (< 1% of total time) was not reflected in the depth-duration graph.

As water levels at -5 cm represent a small region of the marsh, all hydrologic inputs were considered to be above ground surface. For the months in the database, tides contributed 99.5% of the total hydrologic inputs, and precipitation events contributed the remaining inputs (Figure 8b). Both the number and amplitude of tidal inputs were an order of magnitude greater than precipitation inputs (Figure 8c). In an average month, there were approximately 60 tidal inputs with an average amplitude of 36 cm. Only two precipitation inputs with average amplitudes of 3 cm occurred during the same month.

Mainland Midmarsh Site

Flood depths at the mainland midmarsh site had a tight range from -15 cm to +25 cm, with water levels between ground surface and +10 cm 84% of the time (Figure 9). Water levels in the winter and spring never dropped below ground surface. In winter, water levels were at +5 and +10 cm, respectively, 35% and 50% of the time. During



Depth - Duration of Water Levels

Source of Inputs

Frequency and Amplitude of Inputs

Figure 8. Hydrologic data from the mainland creekbank site. (a) Duration of flooding over depth intervals relative to ground surface, (b) the relative percentage of contributions from each hydrologic source, and (c) the monthly average number and amplitude of precipitation inputs and the monthly average number, monthly average amplitude, and monthly maximum amplitude of tidal inputs.

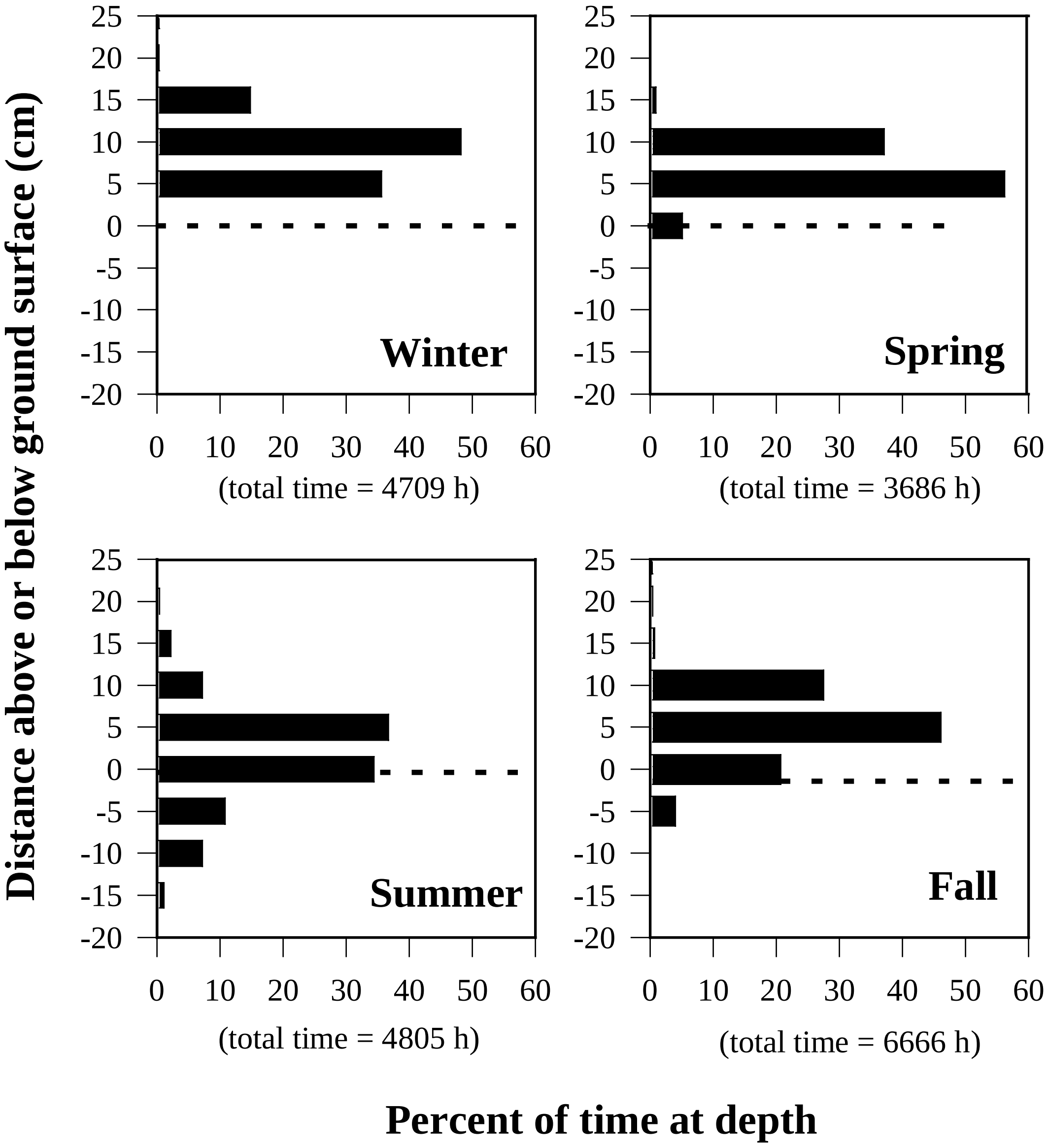


Figure 9. Seasonality of depth-duration distributions at the mainland midmarsh, 1991 to 1996. The duration of water levels at depths above and below ground surface are represented as percentages of the total time. Hours of total record are indicated.

spring months the distribution shifted down only slightly, with water levels at +5 cm and +10 cm, respectively, 55% and 40% of the time. Summer distribution of water levels expanded downward to -15 cm. Despite the loss of water by ET, water levels were below ground surface only 22% of the total time, and were at the yearly minimum (-15 cm) only 2% of the total time. The majority of time, water levels remained between zero and +5 cm. Water levels remained within this same range 75% of the fall. Only the occasional late drawdown in September resulted in water levels below ground surface, and then, constituted less than 5% of the time. The tidal source contributed 86% of total inputs and had little seasonal variation (Figure 10). The remaining inputs resulted from precipitation. Across all seasons, tidal inputs occurred at a frequency of 1 to 10 per month and precipitation inputs occurred at a frequency of 2 to 6 per month (Figure 11). The average magnitude of tidal inputs always exceeded those of precipitation events. Monthly average tidal rises were as high as 35 cm in the fall, whereas average precipitation rises were between 1 and 5 cm for all seasons. The frequency of extreme tidal inputs was greatest in the fall, with a maximum tidal input of 50 cm above ground surface (Figure 11). Despite the fact that tidal inputs may exceed depressional storage capacity and partially run-off, tidal inputs are significant in that they have the lasting effect of maintaining water levels at or above ground surface even during periods of ET.

Summer and fall were the only seasons when water levels were below ground surface (22% and 5%, respectively) (Figure 9). Precipitation was the dominant hydrologic source of the below ground inputs (Figure 12). In summer, 84% of below ground inputs were precipitation, and all below ground inputs in the fall were from

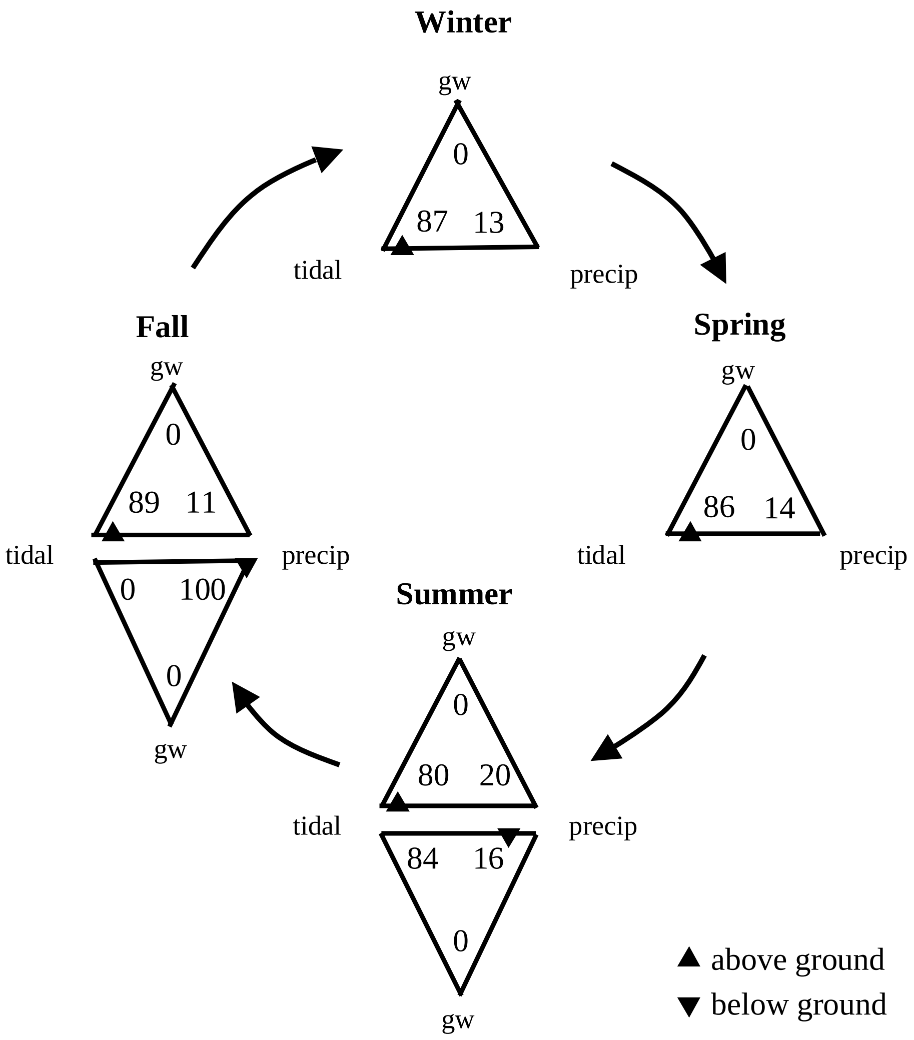


Figure 10. Relative percentage of hydrologic sources, mainland midmarsh. Relative percentages of inputs from groundwater, precipitation, and tidal sources are shown by season. Winter, spring, summer, and fall percentages are indicated in separate trilinear diagrams, moving from the top clockwise. For each season, an upward facing triangle represents above ground inputs and a downward facing diagram represents below ground inputs. Each corner of a triangle represents dominance of inputs from the corresponding source, and the center of the triangle represents equal inputs from all three sources.

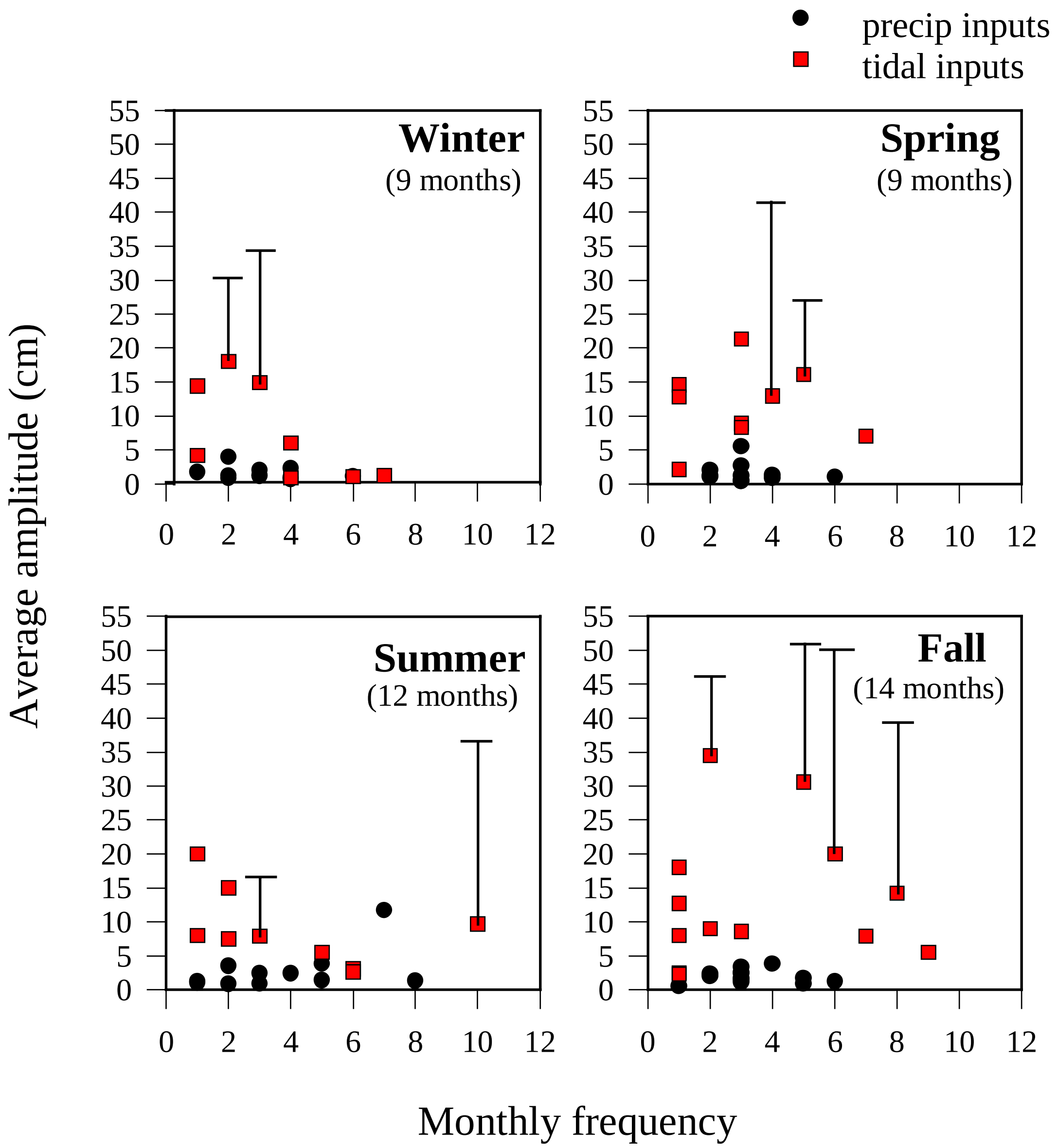


Figure 11. Frequency, average, and extreme amplitudes of above ground inputs, mainland midmarsh. Each point represents the monthly frequency and average amplitude of inputs from each source. When the difference between monthly average and extreme amplitude values is greater than 5 cm, the extreme amplitude is represented by vertical bars and connected to the average value with a line. The total number of months used for each seasonal graph is indicated.

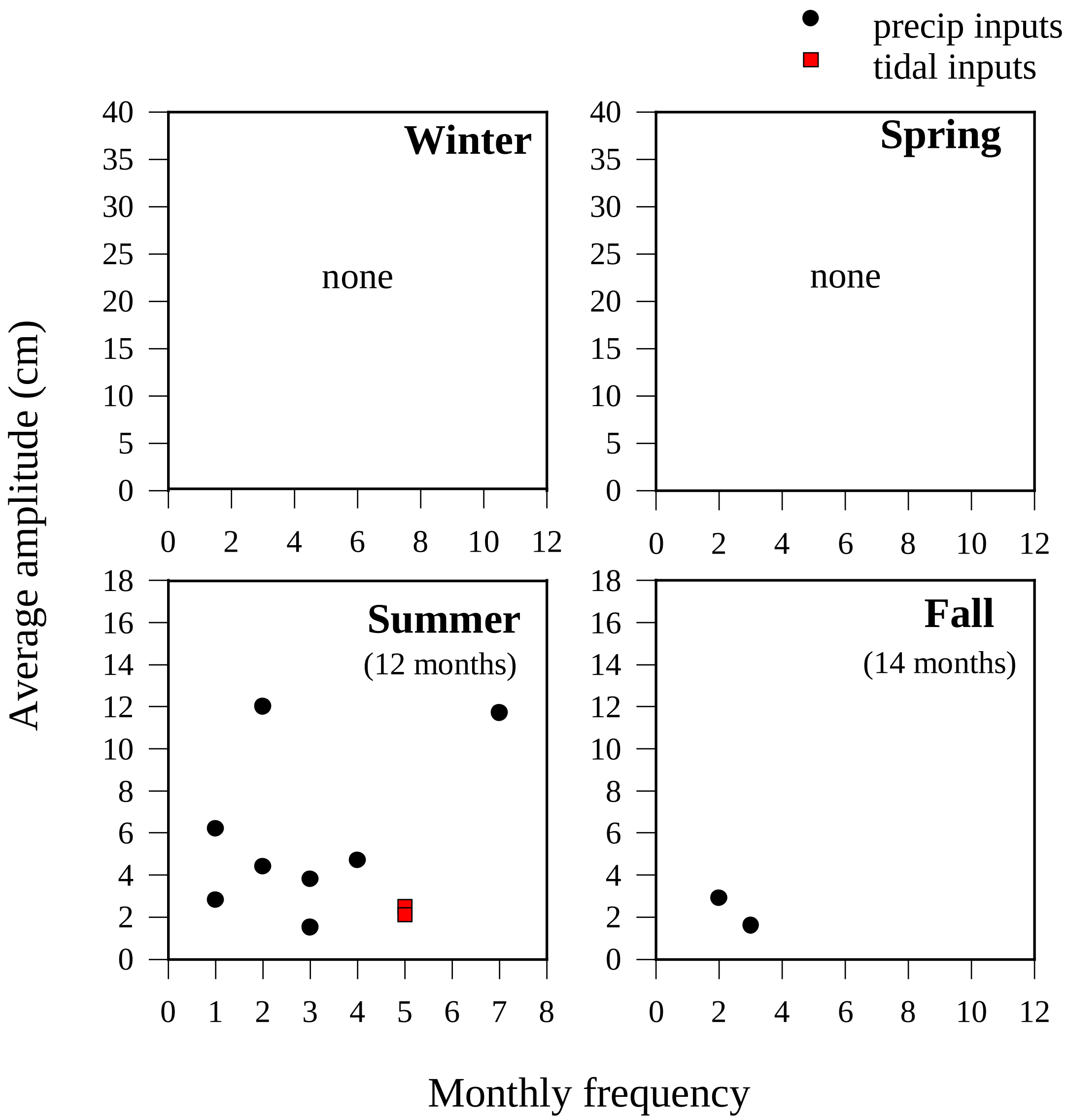


Figure 12. Frequency and average amplitude of below ground inputs, mainland midmarsh. Frequency, and average amplitude of inputs are shown by season. Each data point on a graph represents the monthly frequency and average amplitude of inputs from each source. The total number of months used for each seasonal graph is indicated.

precipitation. The dominance of contributions by precipitation events to below ground rises is explained by the lack of tidal inputs during periods of high ET. Tidal inputs occur at this site with nearly every spring tidal cycle. In summer and early fall, ET can potentially draw down water levels between spring tidal cycles or in the absence of spring tides. The number of below ground precipitation inputs in the summer ranged from 1 to 7 inputs per month, indicating that drawdown occurred at least once a month during the summer. Of all fall months, there were only two months in which water levels were below ground surface. The occurrence of any inputs below ground in the fall should be recognized as an unusual event.

Mainland High Marsh Site

The mainland high marsh was flooded at or above ground surface during all of winter and spring.   Flood levels ranged from ground surface to +25 cm, and duration of flooding was distributed across the +5 cm, +10 cm , and +15 cm depths increments and remained between +5 and +15 cm 93% of the winter months and 90% of the spring months (Figure 13). Water level fluctuations during summer months ranged from +15 cm to -100 cm. Water tables remained below surface 58% of the summer, and the mean depth of flooding was approximately -40 cm. Drawdown distinguishes this season and also distinguishes the site from the other mainland sites. In fall months, water tables remained below ground surface only 20% of the time. Water levels ranged from +25 cm above to -20 cm, with water levels at +5 cm 71% of the time. Although winter and spring depth-duration distributions at the high marsh and midmarsh site were very similar, hydrologic sources were different. During winter, when the site was always flooded,

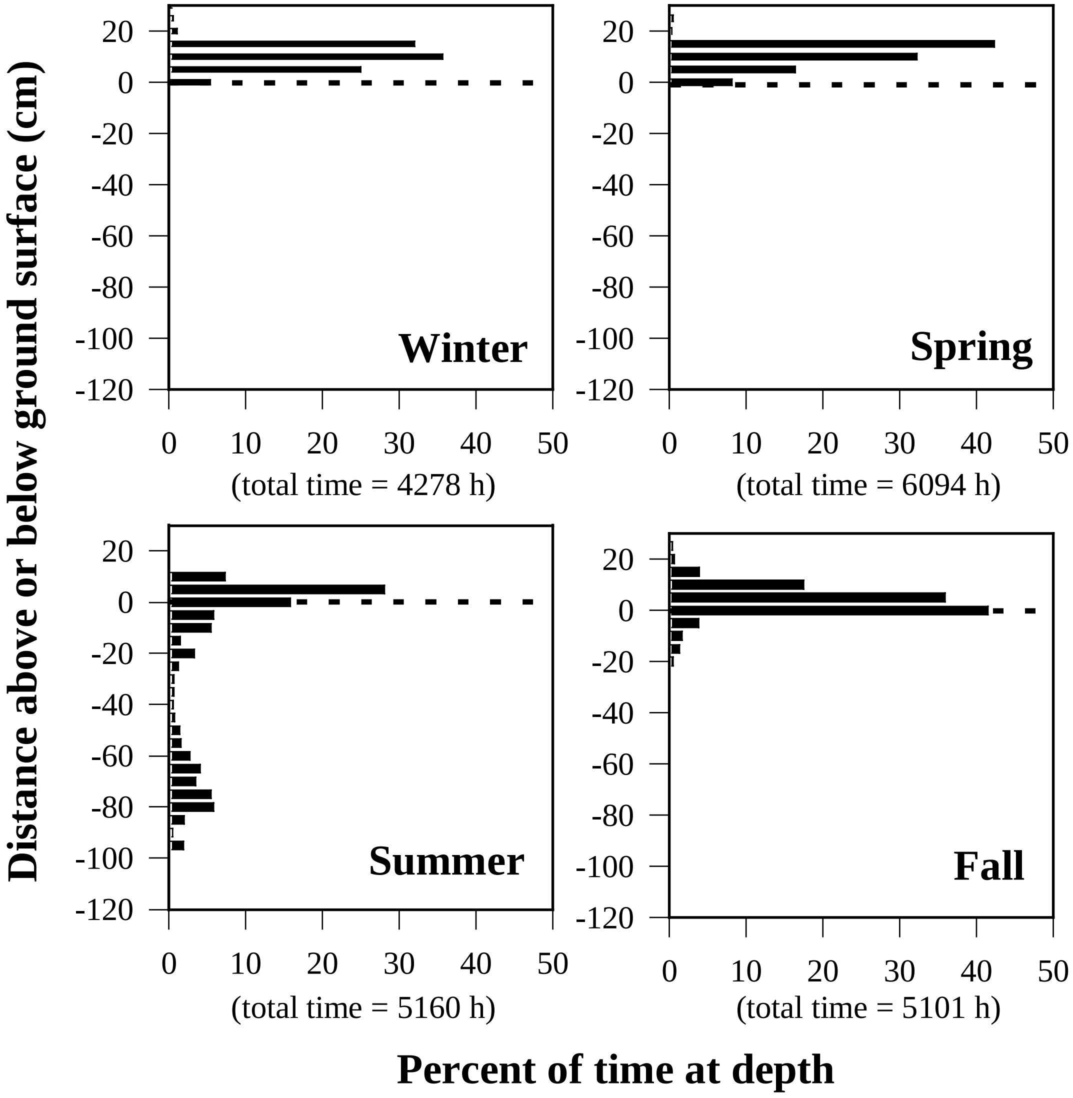


Figure 13. Seasonality of depth-duration distributions at the mainland high marsh, 1991 to 1996. See Figure 9 for explanation.

81% of the hydrologic inputs resulted from precipitation (Figure 14). The remaining 19% of inputs were tidal. In fact, there was only one tidal input during winter over the 6-year study period (Figure 15). Because, the amplitude of that rise (11 cm rise) was so large compared to the average amplitude of the precipitation rises (2 cm), the single tidal input contributed 19% of the relative percentage of inputs (Figure 15). Although tidal inputs during the winter appear to be discrete and infrequent, the magnitude of a tidal input can have a dominant effect on the relative percentage of inputs.

In spring months, tidal inputs comprised 48% of the above ground rises and precipitation contributed the remaining rises (Figure 14). Again, tidal inputs were discrete and infrequent. Only 3 of 10 spring months, spanning 1992-1996, had tidal inputs (Figure 15). These three months had either 1 or 2 tidal inputs, but the high magnitudes of these inputs (13 and 15 cm) resulted in the 48% value.

Nearly all inputs during summer, above and below ground, originated from precipitation (Figure 14). With ET high, losses exceeded the precipitation inputs, and drawdown occurred. The lack of tidal inputs at this site allowed the water table to drop as much as 85 cm lower than water levels at the midmarsh site where tides contributed 80% of the inputs during the same time period.

The fall depth-duration distribution was very similar to winter and spring months, with the site saturated 80% of the time. Unlike winter and spring months, the source of above ground flooding was dominantly tidal. Fifty nine percent of above ground rises resulted from tides, and the remaining 41% resulted from precipitation (Figure 14). The frequency and magnitude graphs confirmed the highest frequency and amplitude of tidal

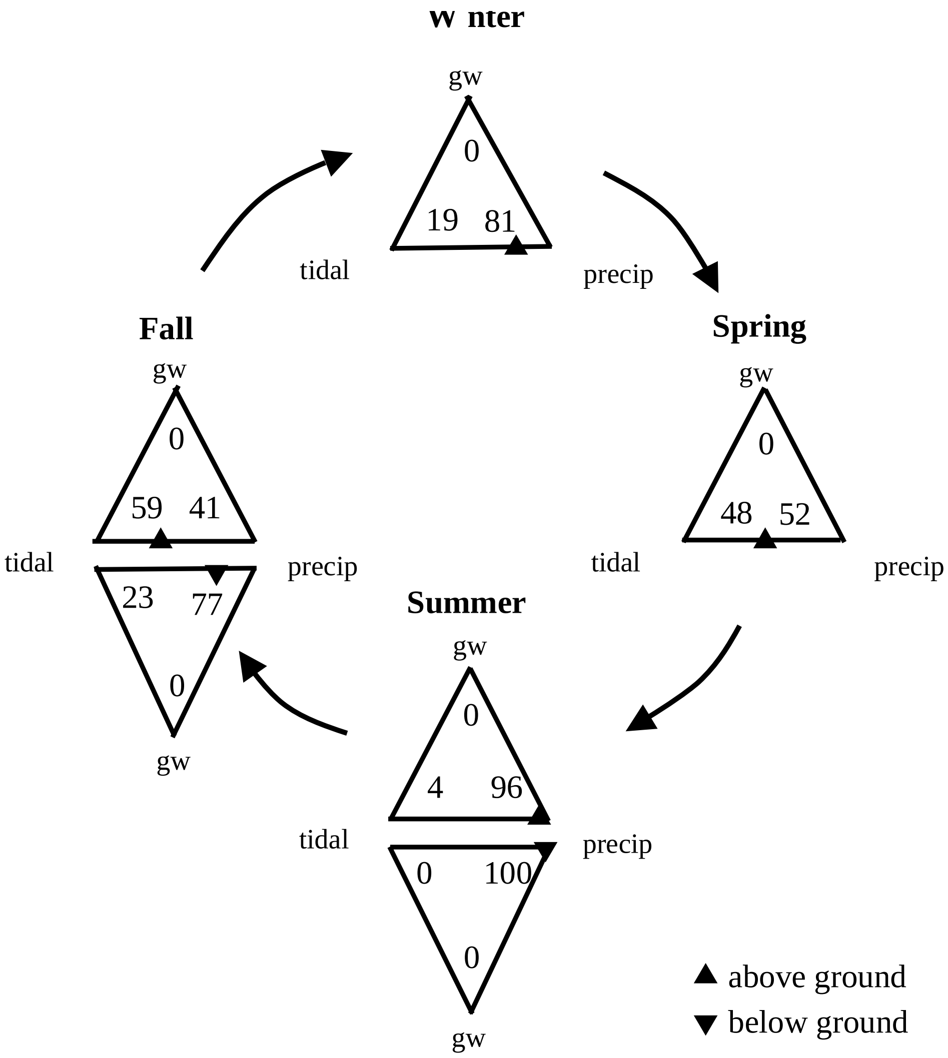


Figure 14. Relative percentage of hydrologic sources, mainland high marsh. See Figure 10 for explanation.

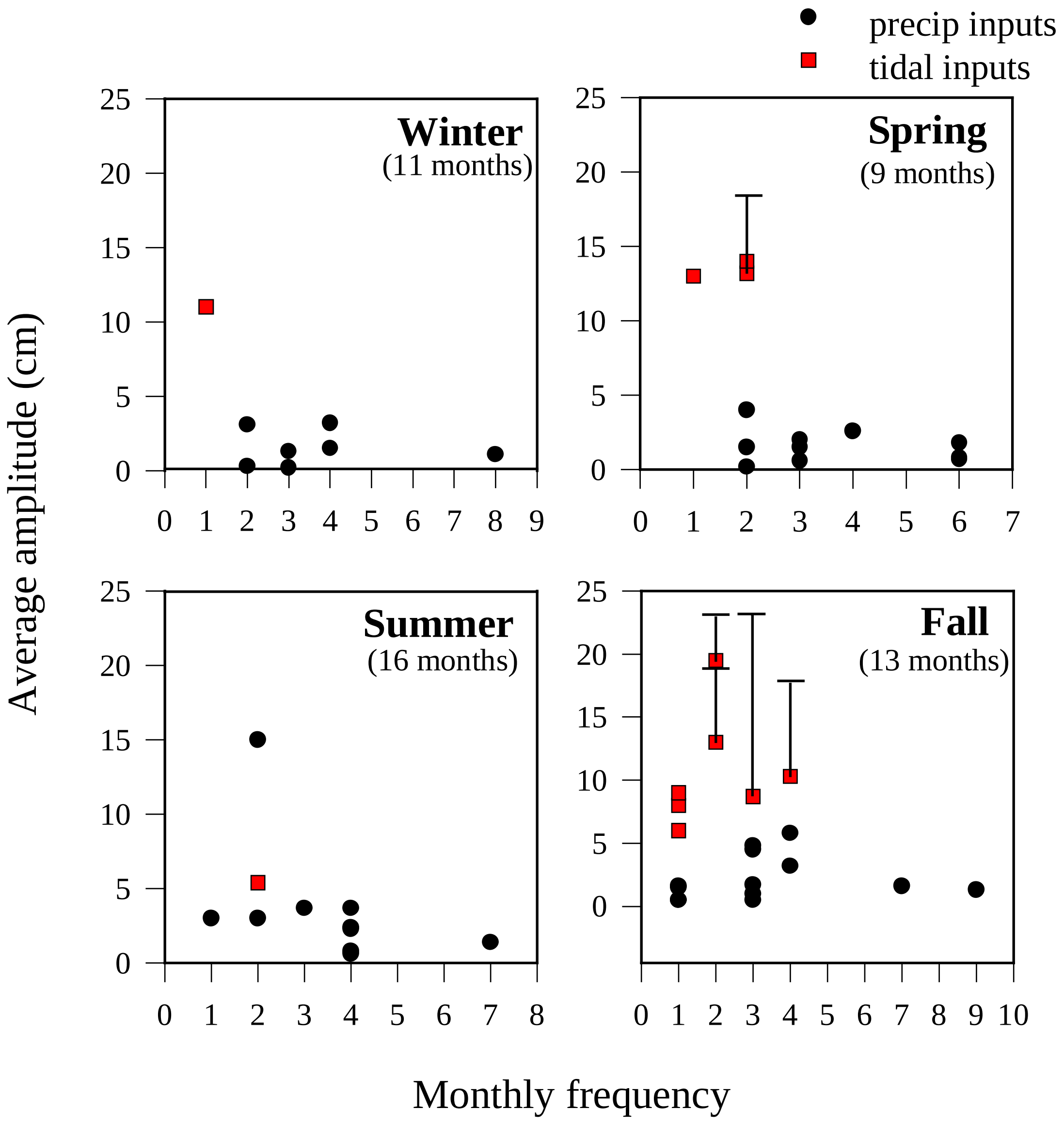


Figure 15. Frequency, average and extreme amplitudes of above ground inputs, mainland high marsh. See Figure 11 for explanation.

inputs in fall, when roughly half of fall months received between 1 and 4 tidal inputs (Figure 15). The average magnitude of these inputs ranged from 6 cm to 20 cm, with extreme amplitudes up to 25 cm.

The dominant hydrologic source below ground surface during fall months was precipitation. Seventy-seven percent of the rises resulted from precipitation and 23% of the rises resulted from tides (Figure 14). The dominance of precipitation inputs below ground, at the same time when tidal inputs were dominant above ground surface, is better understood by looking at the frequency of these inputs. Of all fall months, 1991-1996, only 3 inputs contributed to below ground rises (Figure 16). Two of the inputs were precipitation inputs with amplitudes of 2 and 18 cm. The third input was tidal, with an amplitude of 11 cm. The conditions which allowed these inputs were rare. An extremely dry summer had resulted in water table drawdown into October 1991. At the end of October, an unusually large extratropical storm, termed "The Storm of the Century", introduced tidal inputs to the site (Davis and Dolan 1993). It is evident that inputs, especially tidal inputs, below ground in the fall are rare and occurred no more than once out of the 6 years studied.

Island High Marsh Site

Unlike any of the mainland marsh sites, water tables at the island high marsh remained almost entirely below ground surface, and water levels were above the surface for less than 1% of year (Figure 17). However, there was a large seasonal variability in the position of the water table. In winter months, the water table was extremely stable and remained at the -5 cm and -10 cm depth-increments 96% of the time. Although the

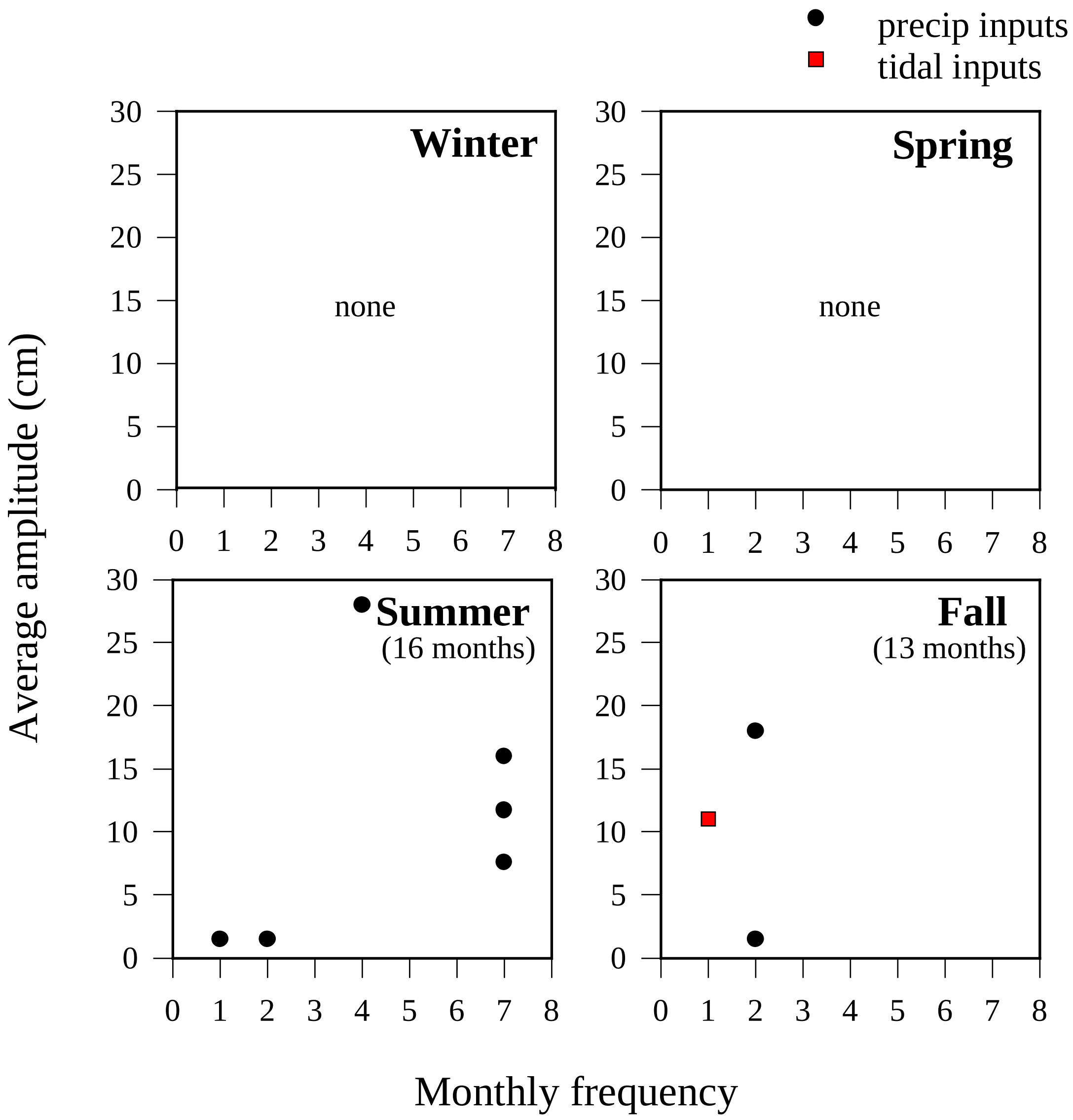


Figure 16. Frequency and average amplitude of below ground inputs, mainland high marsh. See Figure 12 for explanation.

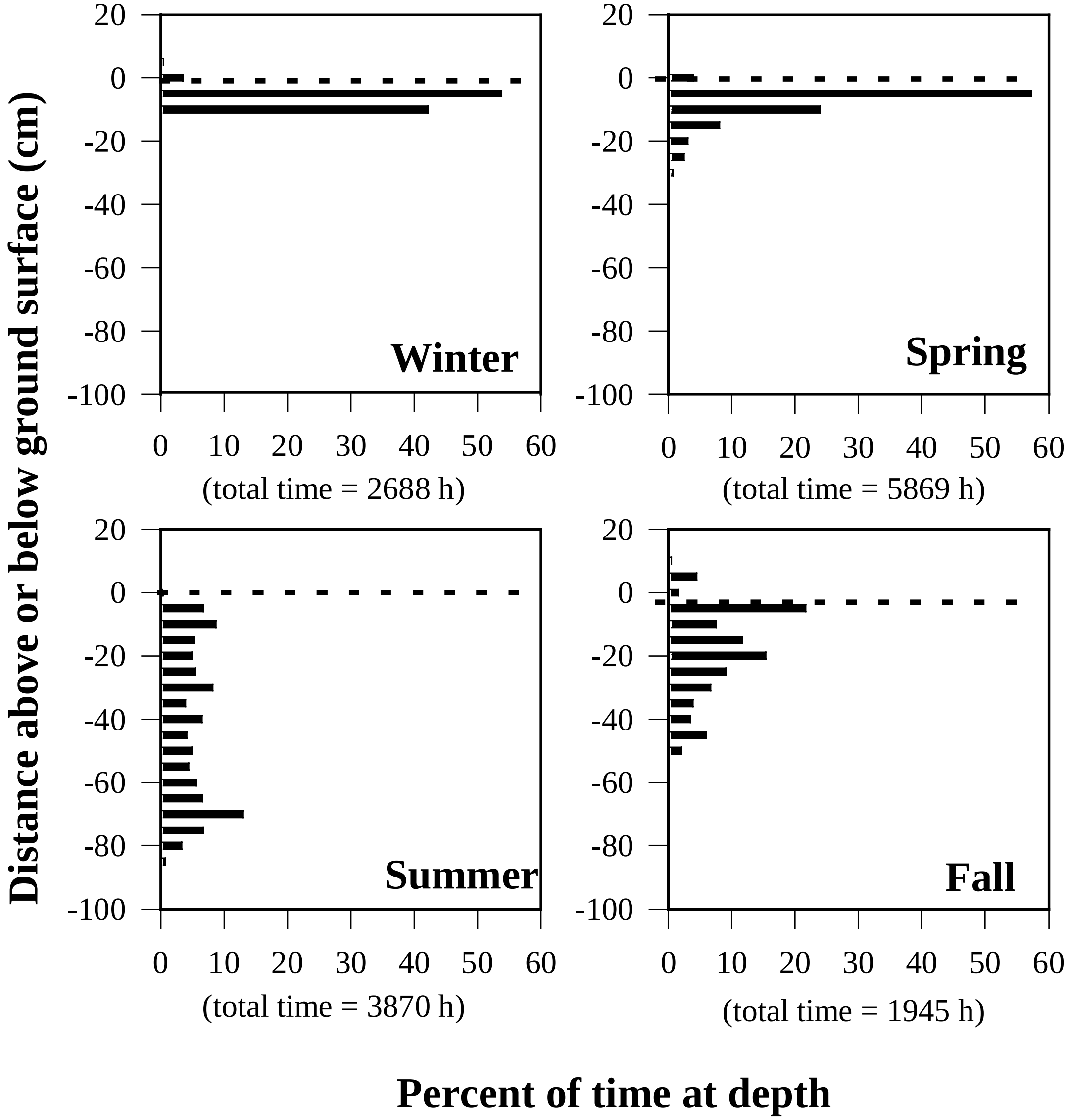


Figure 17. Seasonality of depth-duration distributions at the island high marsh, 1992 to 1995. See Figure 9 for explanation.

site was not flooded above the surface, it was saturated to just below ground surface in winter months. During spring, the range of water tables expanded downward to -30 cm, but remained between ground surface and -10 cm for 91% of time (Figure 17). With ET at its peak, summer water tables were evenly distributed from ground surface to a maximum drawdown of -90 cm. The water table position with the greatest duration was -70 cm, where the water table remained 13% of the time. The range of water levels in fall months was defined as -50 cm to a yearly maximum of +10 cm. This was the only season when water levels were above ground surface for more than 1% of the time, and the site was flooded 6.5% of total time.

Eighty percent of rises of the water table in winter resulted from precipitation (Figure 18). A single tidal input constituted the remaining 20%, and during all other winter months, below ground rises were due entirely to precipitation (Figure 19). Above ground rises resulted from of equal parts (50% and 50%) of precipitation inputs and tidal inputs (Figure 18). Because these inputs maintained flooding above ground surface less than 1% of the total time, they are not shown on the depth-duration graphs. In spring, the water table received inputs from all three sources. Precipitation remained the dominant source, contributing 54% of the below ground rises (Figure 18). Every spring month received precipitation inputs at an average frequency of 2 to 9 inputs per month (Figure 20). Tides contributed 30% of the below ground rises, and tidal inputs occurred in half of the spring months. Groundwater contributed 16% of the below ground rises, also occurring in half the months, with 2 to 12 inputs per month. Above ground inputs were 62% tidal and 38% precipitation (Figure 18). As with other seasons, above ground inputs

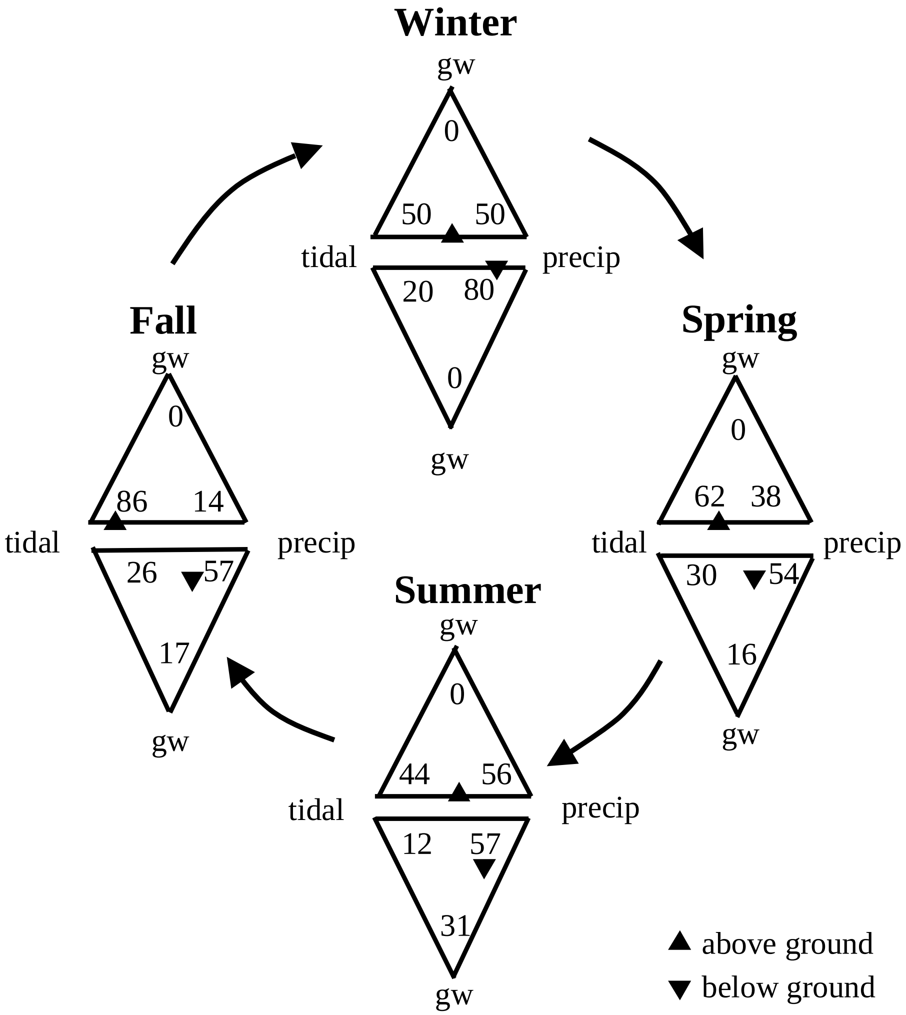


Figure 18. Relative percentage of hydrologic sources, island high marsh. See Figure 10 for explanation.

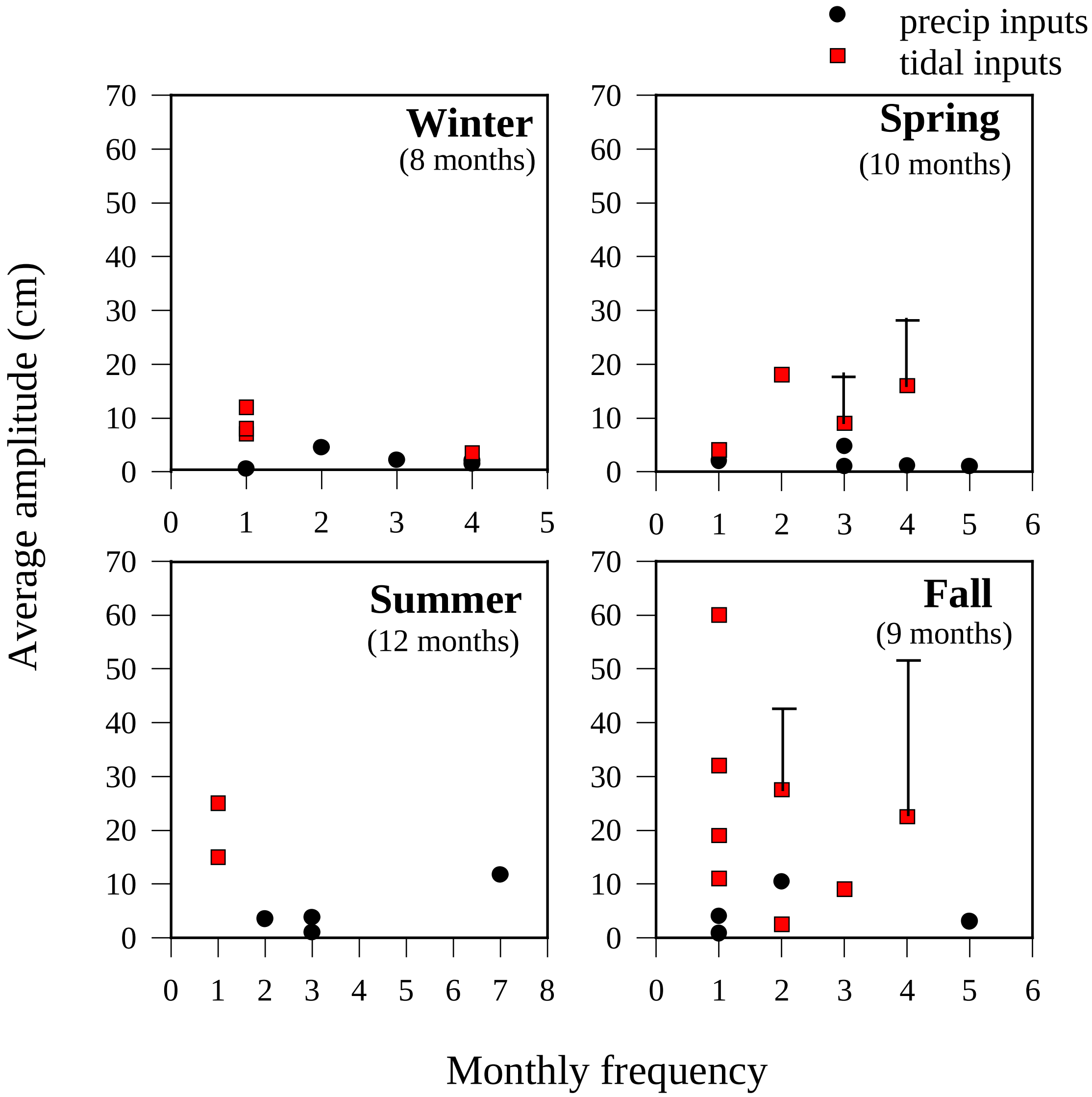


Figure 19. Frequency, average and extreme amplitudes of above ground inputs, island high marsh. See Figure 11 for explanation.

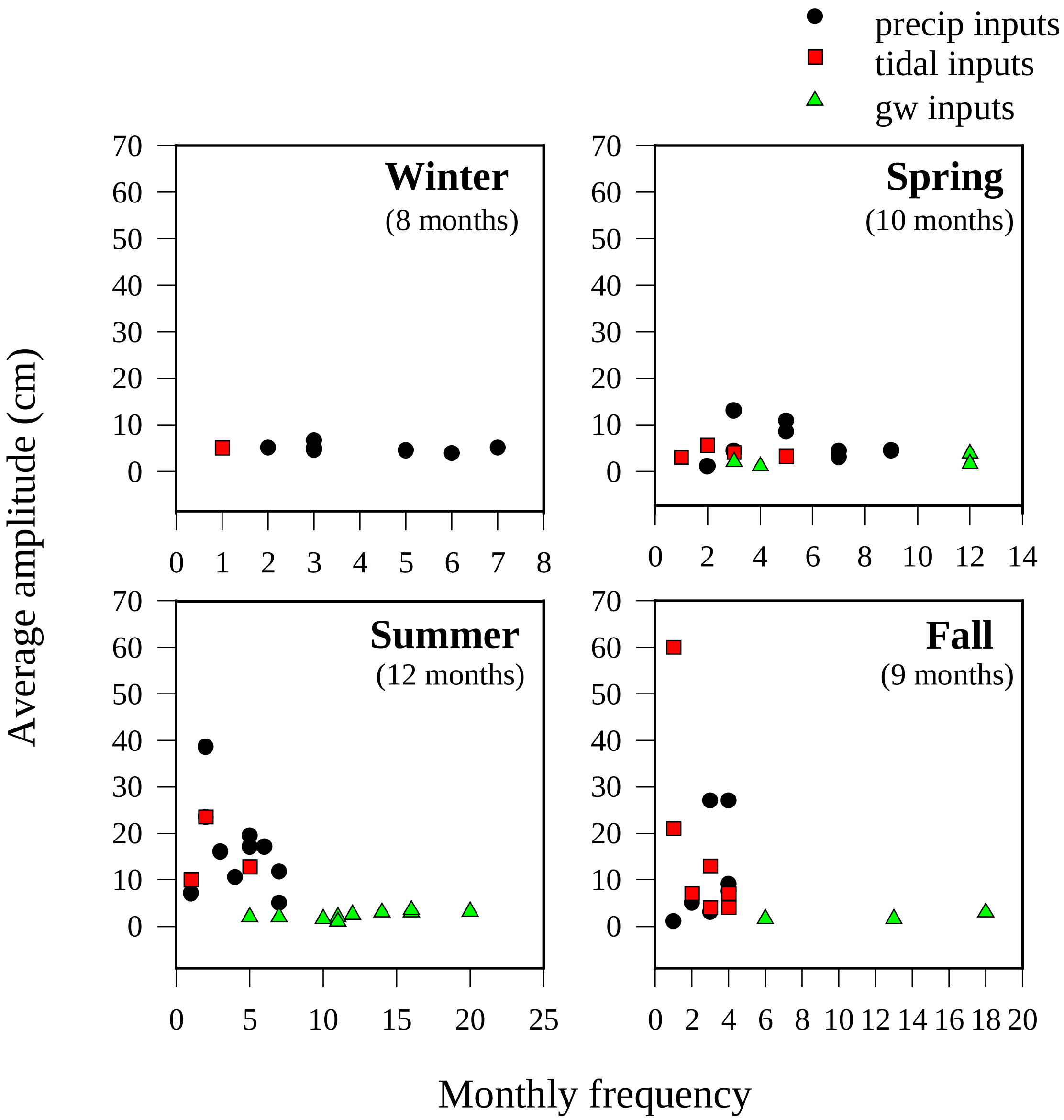


Figure 20. Frequency and average amplitude of below ground inputs, island high marsh. See Figure 12 for explanation.

maintained flooding above ground surface less than 1% of the spring. Both tidal and precipitation inputs above ground occurred in approximately half the months (Figure 19). The magnitude of the tidal inputs averaged 4 to 18 cm and the magnitude of precipitation inputs averaged 1 to 5 cm. However, inputs drained or ran-off quickly.

In summer, 57% of below ground inputs were precipitation (Figure 18). Most significantly, groundwater inputs increased in this season and 31% of total below ground rises were rebounds of the water table. This was the largest percentage of groundwater inputs for any season and any site. Tides contributed only 12% of the below ground inputs. A significant increase in the height and duration of flooding was seen in the fall, about 6% of the season at 5 cm. In concurrence with that increase, the relative percentage of tidal inputs above ground increased to 86%. Eight of twelve months received 1 to 4 tidal inputs a month, with average monthly amplitudes between 5 and 60 cm (Figure 19). Below ground, the majority of inputs, 57%, still resulted from precipitation. The relative percentage of groundwater inputs in the fall decreased from summer to 17%, and tidal inputs represented 26% of the relative inputs.

Island *Myrica* Site

The *Myrica* site was never flooded above ground surface, and water tables extended further below ground surface throughout the year than any other site (Figure 21). In winter, the water table fluctuated between ground surface and -60 cm. The longest water table duration was -35 cm where it remained 27% of the time. This is very different from the island high marsh site where the water table was stable between surface and -10 cm during the same time period. In spring, water levels ranged from - 70

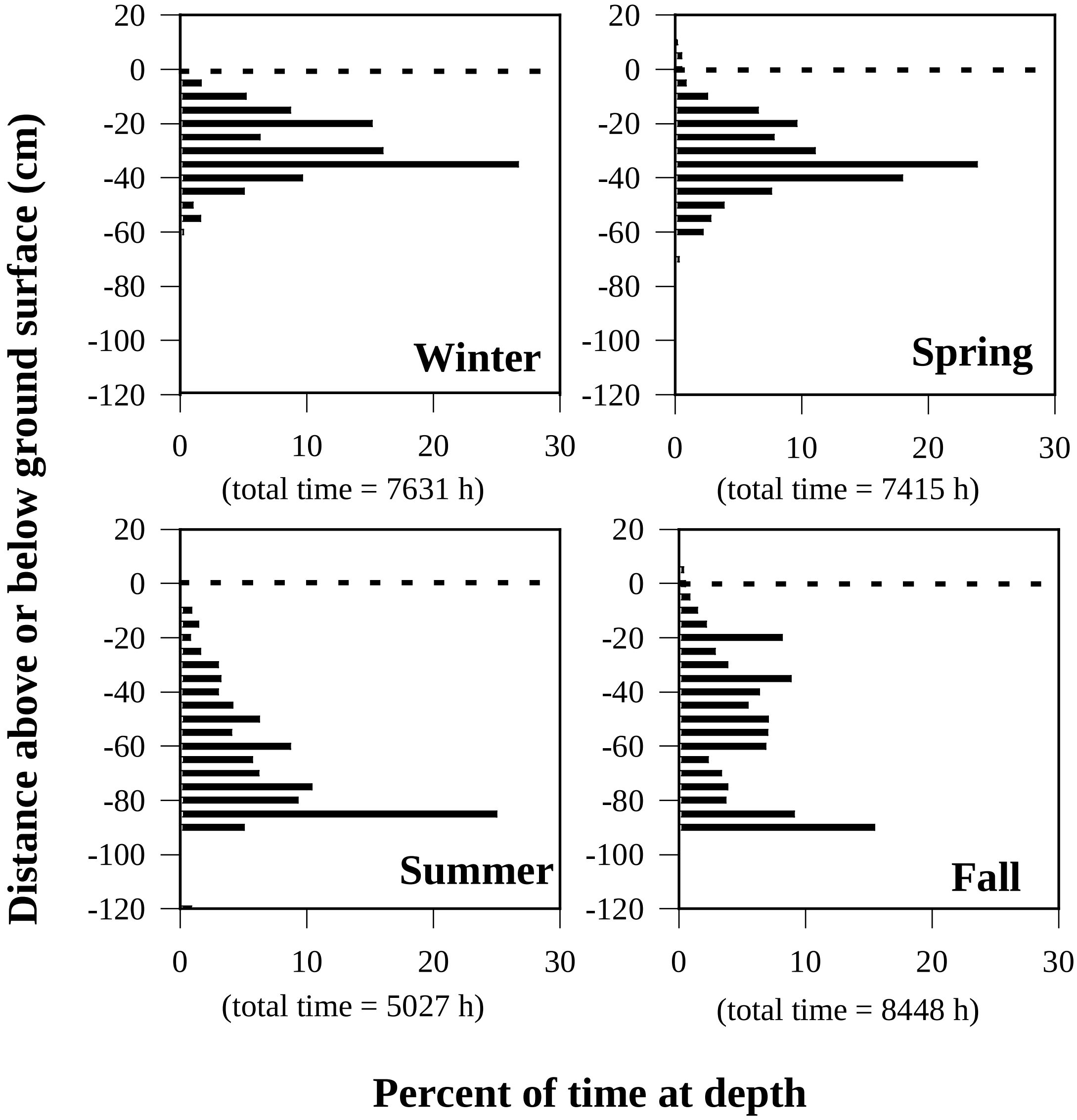


Figure 21. Seasonality of depth-duration distributions at the island *Myrica*, 1991 to 1996. See Figure 9 for explanation.

cm to +10 cm. Again, represented water tables did not remain at any given depth-increment longer than 23% of the time but did remain between -30 and -40 cm 53% of the time. Water tables in summer months ranged from a yearly low of -90 cm to -10 cm. Increasing durations at the lower depths skewed the depth-duration distribution towards the -80 cm and -90 cm depths, and the water table remained at the -85 cm depth-increment 25% of the time. In fall, water tables ranged from ground surface to -90 cm, where they remained 15% of the time, the longest duration at any water table depth. This duration is most likely an artifact of the depth of the stilling well, as the well went dry several summers and could not detect water tables below -90 cm. Water tables below this depth, with distributions similar to those seen at the -40 to -60 cm depths, are likely to have occurred.

All winter inputs resulted from precipitation events, and 99% of spring inputs were precipitation (Figure 22). The remaining 1% represented groundwater inputs which were detected in a single month with early drawdown (Figure 23). Along with the decrease in water tables in summer months, there was an increase in the percentage of groundwater inputs when they contributed 24% of the total inputs (Figure 22). All other inputs were from precipitation. Four to fifteen groundwater inputs occurred per month, with average rises of 3 cm each (Figure 23). By the fall, groundwater inputs occurred only 3 of 13 months and comprised 9% of below ground inputs. Above ground inputs contributed rises only 1% of the time and were entirely tidal, resulting from 2 discrete and rare events. The inputs occurred with the storm surge of an extratropical storm on October 31, 1991. It is most likely, over many years, that the frequency of above ground

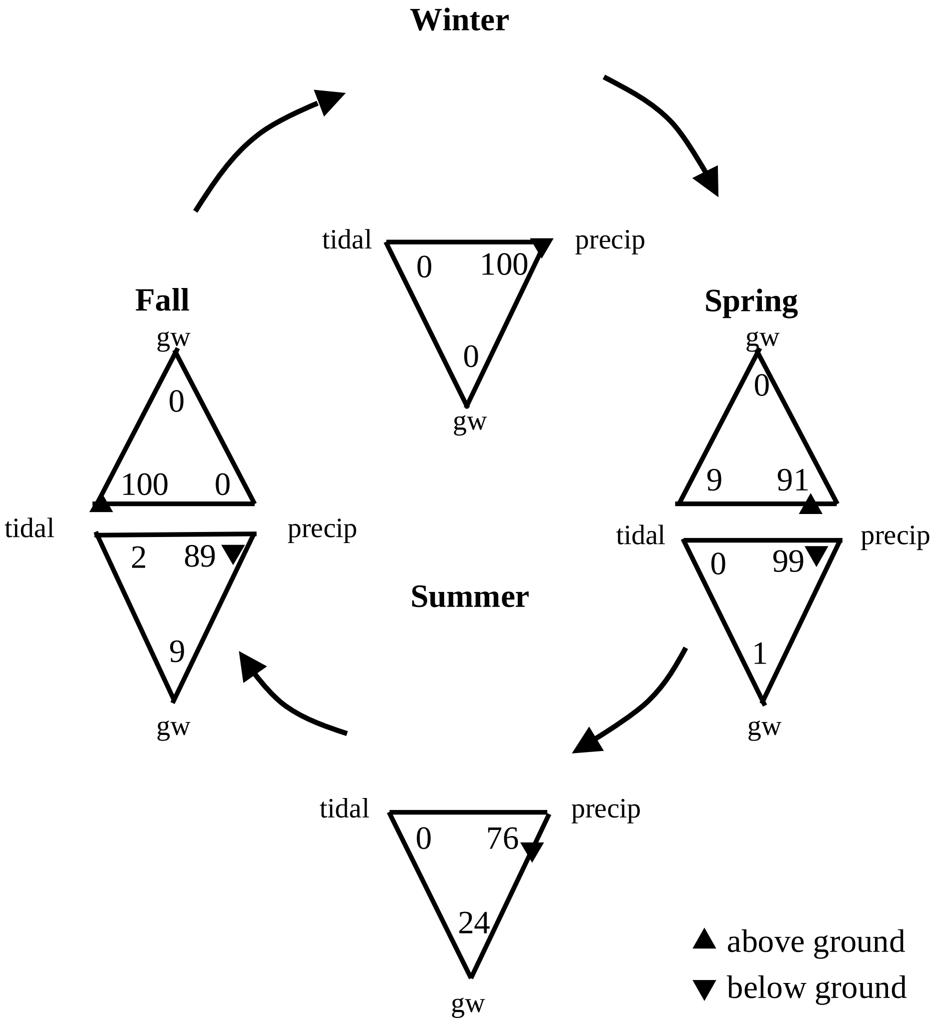


Figure 22. Relative percentage of hydrologic sources, island *Myrica*. See Figure 10 for explanation.

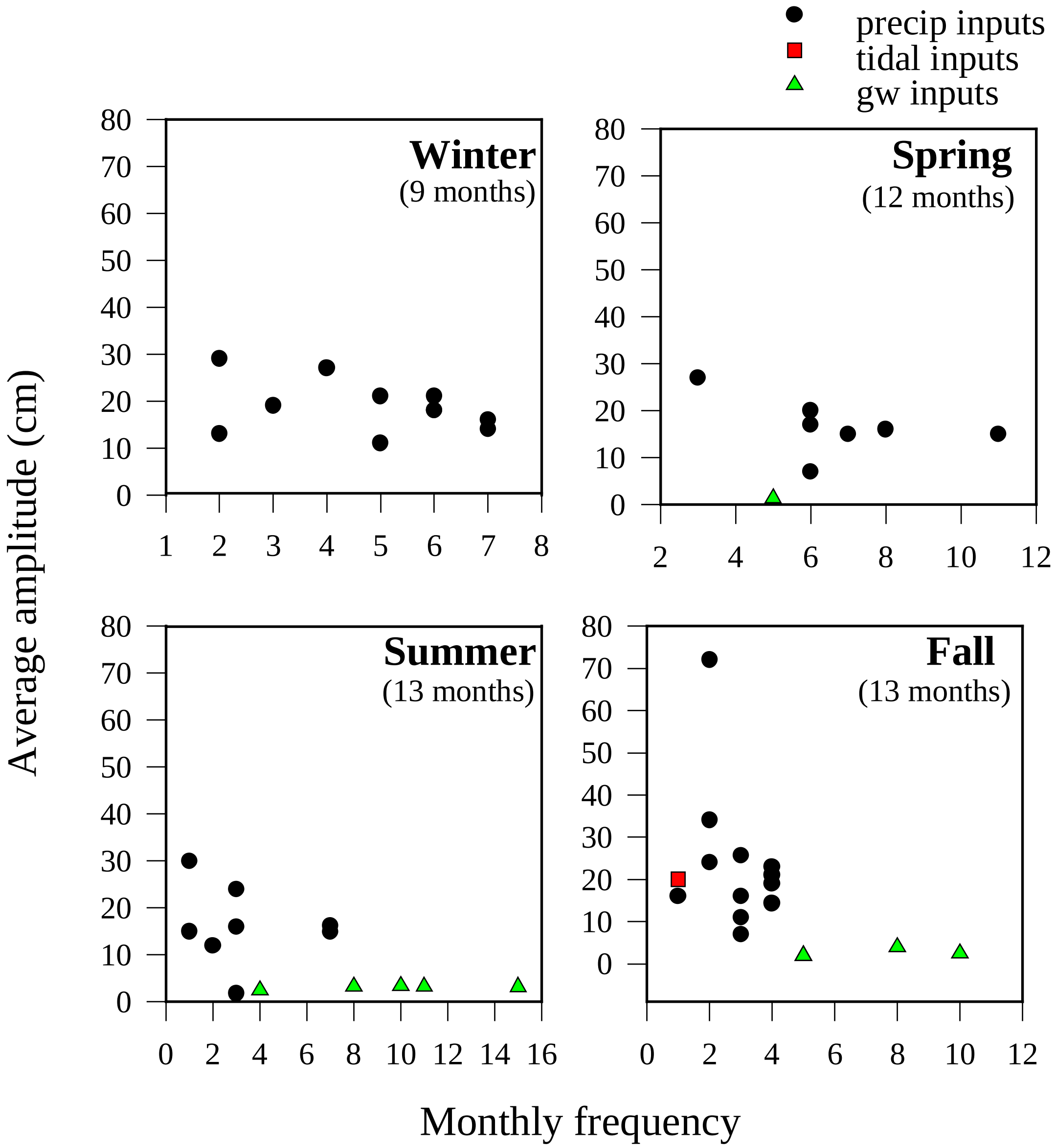


Figure 23. Frequency and average amplitude of below ground inputs, island *Myrica*. See Figure 12 for explanation.

flooding at this site is even less than the frequency seen in this database, as the storm which produced the surge is estimated to have a recurrence interval of greater than 100 years (Davis and Dolan 1992).

Discussion

The purpose of this study was to develop an improved description of wetland hydrology that would have ecological importance to overall wetland processes. This was done by expanding upon commonly used hydroperiod parameters, adding a separation between above and below ground dynamics, and identifying hydrologic sources. When the typically used parameters of depth, duration, and seasonality of flooding were considered alone, the mainland midmarsh and high marsh sites grouped together, the island high marsh and *Myrica* sites grouped together, and the creekbank sites separated from all other sites (Table 2). The mainland midmarsh and mainland high marsh sites were both continuously flooded the majority of the year, with the high marsh site showing some seasonal variation. The mean depth of flooding for these two sites was virtually identical year-round. The two island sites grouped together because of the small percentage of time the sites are flooded. It would be assumed, based on this information, that the two mainland sites are hydrologically equivalent and that the two island sites are hydrologically equivalent. Information about hydrologic sources and below ground dynamics (Table 3) showed differences between sites that had been grouped together based on depth and duration of flooding alone. The mainland midmarsh and high marsh sites separated strongly based on water source and seasonality of mean water table depth, even though both were flooded the majority of the year. Flooding at the mainland midmarsh site was found to be maintained by tidal inputs (88%). As a result, neither the source nor the position of the water table fluctuated seasonally as indicated by a lack of long-term drawdown. Flooding at the mainland high marsh, however, was maintained by

Table 2. Commonly used parameters of hydroperiod (depth and duration of flooding) for each site. The mean depth of flooding and the duration of flooding are seasonally separated by dashes: w (winter), sp (spring), s (summer), and f (fall).

Typical Hydroperiod Parameters	**Creekbank**	**Mainland Midmarsh**	**Mainland High Marsh**	**Island High Marsh**	**Island Myrica**
	w-sp-s-f	w-sp-s-f	w-sp-s-f	w-sp-s-f	w-sp-s-f
Mean depth of flooding (cm)	4-4-4-4	10-8-6-8	10-7-5-7	1-2-0-2	7-5-0-7
Duration of flooding (%)	30-30-30-30	100-100-85-97	100-100-51-91	4-4-0-20	3-1-0-1

Table 3. Summary of hydrologic sources and dynamics as they vary across sites. Sources are abbreviated as T (tidal), P (precipitation), and G (groundwater). Seasons are abbreviated by w (winter), sp (spring), s (summer), and f (fall).
* indicates value highly variable across seasons.

Additional Parameters	**Creekbank**	**Mainland Midmarsh**	**Mainland High Marsh**	**Island High Marsh**
Source (% above ground surface)	99.5 T, 0.5 P	88 T, 12 P	33 T, 67 P *	27 T, 73 P
Source (% below ground surface)	n/a	14 T, 86 P	10 T, 90 P	20 T, 58 P, 22G
Range of water levels (cm)	-15 to +80	-15 to +15	-90 to +20*	gs to -90*
Seasons with drawdown	w, sp, s, f	s,f	s,f	w, sp, s, f
Mean depth (cm)	-3 for all	-5, -1	-45, -7	-5, -6, -41, -22
Avg # tidal inputs above gs per month	60	3	0.6 *	1.0 *
Avg monthly amplitude of above ground tidal inputs	35 cm	10 cm *	10 cm *	15 cm *

precipitation events, with tidal inputs being highly variable across season. In contrast to the mainland midmarsh site where the mean water table depth was -5 cm during summer, the mean water table depth at the mainland high marsh was -45 cm. The source and mean water table information also indicated that the creekbank and mainland midmarsh sites may be more similar than is suggested by flood duration data, since both received an overwhelming majority of inputs from the tidal source. However, differences between the two sites can be detected as both the number and amplitude of tidal inputs were an order of magnitude higher at the creekbank site than at the midmarsh site (Table 3). The maintenance of a water table very close to ground surface (except summer) distinguished the island high marsh from the *Myrica* site, a separation that was not possible with flood data alone (Table 2). The source of inputs at the island high marsh site indicated that it received a greater percentage of tidal inputs below ground than the mainland high marsh, but also received groundwater inputs. These data, along with flood durations, indicate that the mainland high marsh and island high marsh sites are not hydrologically equivalent using any parameter. The mainland midmarsh, mainland high marsh, and island high marsh sites, normally grouped together as the high marsh zone of tidal saltwater wetlands, were found to be hydrologically un-equivalent. This indicates that landward portions of coastal wetlands are largely non-tidal and precipitation driven, while low marsh zones are mainly driven by tides. Considering these types of hydrologic differences may be important for understanding ecological processes as a whole. While the source and hydrodynamic descriptions can be used to better define hydrologic variation among wetland sites, the salient question is "can the parameters be associated with ecological processes and facilitate our ability to identify probable differences in function among sites?" To address this question, four major wetland processes were identified: two dependent on above ground dynamics and two dependent on below ground dynamics. The ecological usefulness of the hydrologic parameters and their ability to elucidate differences between sites are discussed.

Tidal Exchanges of Material with the Estuary

The exchange of particulate and dissolved matter between wetlands and adjacent systems is important in many wetlands, and above ground hydrologic connectors are critical for such exchanges. For the sites in this study, tidal exchanges between the marsh and estuary can be ecologically significant in several ways. A few examples are the deposition of sediment on the marsh surface, the import of dissolved and particulate matter into the marsh, and the import or export of organic material. Deposition of sediment is ecologically significant in that it provides the ability to maintain marsh elevation during sea level rise (Stumpf 1983). Although sediment deposition is dependent on tidal inputs, few studies have clearly linked rates with specific hydrodynamic parameters. Cahoon et al. (1995) linked storm tides to sediment deposition on a Louisiana marsh and found that storm tides increased deposition rates 1-3 orders of magnitude from the year before or after the storm, with a single event depositing 2-6 cm of material. A high frequency and amplitude of non-storm tidal inputs would also promote sedimentation rates, and low marsh areas typically accumulate more sediment than high marsh areas (e.g. Bricker-Urso et al. 1989). Deposition of dissolved and particulate matter, such as nitrogen import or phosphorus adsorbed on sediment particles, can have a significant impact on nutrient cycling. Several studies in mangroves have investigated nitrogen cycling across a continuum of tidal frequency and depth. The results suggest that infrequent, small amplitude tidal inputs result in closed systems with tight, internal cycling (Twilley 1985, Rivera-Monroy 1995). Conversely, a system with frequent and large tidal exchanges results in open nutrient cycles. A net accumulation or deposition of organic matter is also dependent on tidal exchange and can be ecologically significant in terms of disturbance in the marsh or productivity of the estuary. In tidal marsh at Sapelo Island, GA, Chalmers et al. (1985) found that almost all tidal exchanges deposited carbon on the marsh surface. Conversely, tidal amplitude and organic carbon export have been found to have a direct relationship in mangrove systems (Boto 1981, Heald 1971, Twilley 1985). The net result may depend on site-specific conditions, but tidal amplitude and frequency can indicate the potential for import and export.

To estimate the contribution of tidal exchanges to sediment deposition, nutrient cycling, and organic matter export, cumulative tidal rises for an average month were quantified for each site by season. This value was obtained by multiplying the frequency of tidal inputs in a month by the average tidal input, and correcting for the number of months (Figures 8c, 11, 15, and 19). A positive relationship between cumulative rise and sediment input was assumed. It also assumes that the sediment supply remains constant across seasons and years. As a reference for the other sites, the creekbank sites had an average of 240 cm of tidal rises per month (Table 4). Theoretically, sedimentation rates and organic carbon export would be greatest at this site, and nutrient cycles would be open. The mainland midmarsh and island high marsh were found to have similar

Table 4. Tidal exchanges with the estuary. Cumulative rises above ground surface from tides, the average number of tidal inputs per month, the number of extreme tidal events per year, and the amplitude of extreme events are used to characterize tidal exchanges.

SITE	∑ tidal rises avg. month	avg. # tidal inputs/ month	# of extreme tidal inputs/ year	amplitude of extreme events
Creekbank Sites				
(all seasons)	240 cm	60.0	3.0	130 cm
Mainland Midmarsh				
Winter	9 cm	3.0	0.3	30 cm
Spring	34 cm	3.0	0.5	35 cm
Summer	21 cm	3.0	0.5	25 cm
Fall	45 cm	3.0	0.6	50 cm
Mainland High Marsh				
Winter	1 cm	0.1	0.0	0 cm
Spring	7 cm	0.6	0.2	20 cm
Summer	0.6 cm	0.1	0.2	8 cm
Fall	12 cm	1.07	0.7	23 cm
Island High Marsh				
Winter	3 cm	0.75	0.3	0 cm
Spring	13 cm	1.0	0.6	28 cm
Summer	3 cm	0.2	0.0	0 cm
Fall	33 cm	1.7	0.3	52 cm

potentials for exchange, with cumulative rises highest in fall. These sites may be functioning more similarly than would be expected based solely on their position in the marsh. The mainland high marsh was very different from all the sites, having a low of 0.6 tidal exchanges in the summer to a high of 12 cm in the fall. This site would be expected to have little sediment import, closed nutrient cycles, and little organic carbon export. Field observations at this site support the low exchange values, as this site is currently subsiding, partially from a lack of sediment input (Brinson and Christian 1998).

Many factors affect deposition and nutrient cycling but they can not be addressed based on hydrographic data alone. For example, the velocity of flow, marsh surface vegetation, tidal amplitude, and sediment concentration are important factors in deposition (Christiansen 1998). Because so many other factors contribute to deposition, cumulative tidal rises can not be translated into actual deposition rates. However, the metric does provide a meaningful quantitative number with which sites can be compared and probable differences in functions identified.

Depressional Storage of Water and Maintenance of Aquatic Habitat

Storage of water in depressional areas on the marsh surface is ecologically significant in at least two ways. As ET begins in the spring or summer, depressional storage acts a reserve of water that keeps the site wet for longer periods of the growing season than would be expected at a site without depressional storage. The resulting flood stress would be expected to promote the maintenance of hydrophytic plant species and to exclude non-tolerant species. Also, Kneib (1997) points out that shallow, microtopographical depressions on marsh surfaces are particularly good habitat for resident nekton. For these reasons, both the depth and duration of flooding in depressional storage would contribute to favorable habitat conditions (Yozzo and Smith 1998). Consequently, integrating the amount of above ground flooding, as defined in the depth-duration graphs, can be used to quantify the hydrologic contribution to maintaining these habitats. Depth of flooding was multiplied by the hours at that depth, and all depths were summed by season. Depths of +5 cm or greater were used, and the resulting value is expressed as m*h. It is assumed that flooding at +5 cm for one hour constitutes storage and is the minimum for viable resident nekton habitat. The mainland midmarsh and high marsh sites had a higher potential to provide nekton habitat and promote extended flood stress than the island site which had virtually no capacity for these functions (Table 5). Extension of flood stress into the summer and likely exclusion of stress on previously established non-flood plant tolerant species was found to be possible at the mainland sites only. The mainland midmarsh stored 88 m*h and the mainland high marsh site stored 116 m*h in summer. The mainland sites also had the highest potential to serve as aquatic habitat year-round. In addition to the storage value (m*h), mean depth of flooding and the ratio of freshwater to saltwater inputs were used to further describe the possible habitat (Table 5). Mean flood depths +5 cm and +10 cm suggest that larger nekton species may be excluded from these sites, a concept supported by Yozzo et al. (1994). The freshwater input to salt water input ratio indicates that the high marsh site has a higher potential to support freshwater species. Because the depth duration graphs summed flood depths in 1-hr increments over several years, the m*h values have the potential to over-estimate the potential for nekton habitat with life histories of days to

Table 5. Depressional storage and aquatic habitat characteristics. The cumulative height of flooding in depressional storage is multiplied by the hours at flood depths (m*h) to indicate the potential for depressional storage. The mean depth of flooding and the ratio of freshwater to saltwater inputs are shown for relation to possible aquatic habitat.

SITE	**m*h**	**Avg. flood depth (cm)**	**freshwater: saltwater**
Mainland Midmarsh			
Winter	407	10	1:9
Spring	243	8	1:9
Summer	88	6	1:9
Fall	337	8	1:9
Mainland Highmarsh			
Winter	421	10	9:1
Spring	631	7	5:5
Summer	116	5	0.5:9.5
Fall	212	7	3:2
Island Highmarsh			
Winter	0	1	--------
Spring	0	2	--------
Summer	0	0	--------
Fall	4	2	negligible inputs

weeks. A large number of very short-term flood events could, cumulatively, result in long durations at a depth but may not be ecologically significant in terms of providing resident nekton habitat for the longer lived species. Some portions of the high marsh are very hummocky with large depressions devoid of rooted vegetation. From field observations, this region would appear to store more water in depressional storage than the midmarsh region, a level of detail that may not be discerned from the data. Factors such as temperature, salinity, oxygen availability, and sulfide accumulation strongly influence which species utilize the habitat. Although water source is known, none of these factors were directly measured in the field in this study. This limits the data to a general, hydrologic description of aquatic habitat characteristic to the sites, which may not have the detail to relate the data to the requirements of individual species. Regardless of these limitations, the approach taken illustrates major differences in depressional storage among sites. The seasonal separation and the ability to quantitatively estimate the amount of water stored, the mean flood depth, and the source of water in storage is, at the least, more useful for relating hydrologic characteristics to ecological processes than the typically used parameter of annual duration of flooding.

Recruitment of Nekton and Pelagic Exchanges

In addition to particulate and dissolved matter exchanges, astronomic tides are also important for pelagic exchanges while extreme tidal inputs, normally from storm events, provide the opportunity for recruitment into the marsh by marsh resident species (Kneib 1997). It is somewhat difficult to link pelagic exchanges and recruitment of resident species to cumulative tidal rises, because they are dependent on the frequency and amplitude of tidal events. For this reason, the average number of tidal inputs per month, the number of extreme tidal inputs per year, and the amplitude of the extreme events were used as indicators of possible hydrologic contribution to this function (Table 4). An extreme tidal event was defined as a tidal input which was 5 cm or greater in amplitude than the average tidal amplitude. The midmarsh site averaged 3 tidal exchanges per month across all seasons, indicating a potential for pelagic exchange. Extreme tidal events also occurred every season at a frequency 0.3 to 0.6 per year and with amplitudes of up to 50 cm, indicating the potential for recruitment. The mainland high marsh showed an equivalent potential only in the fall when the site received an average 1.07 tidal inputs per month. Extreme events were absent in the winter, but occurred at a frequency of 0.2 to 0.7 per year during other seasons, with amplitudes up to 23 cm. When relating these data to possible function, the potential for aquatic habitat also must be considered. The island high marsh receives tidal inputs, and based on these data alone would have the potential for pelagic exchange. However, the site does not provide aquatic habitat, which would make the possibility for pelagic exchange or recruitment meaningless.

Biogeochemical Cycling

Biogeochemical cycling encompasses an inter-connected set of processes such as decomposition, biological transformations, and chemical transformations, most of which occur below ground. On the broadest scale, the hydrodynamic pattern that collectively promotes these processes is an alteration between saturation and desaturation (Brinson 1977, Patrick and Tusneem 1972, Reddy and Patrick 1975, Smith and DeLaune 1983, Wharton 1982). A lack of alternating saturation and desaturation cycles, with water levels at or above ground surface, is assumed to create persistently reduced soil conditions. This end of the oxidation/reduction continuum would result in slower turnover rates, burial of nutrients, and organic matter accumulation. Day and Megonigal (1993) correlated the length of soil saturation with rates of decomposition and found rates in freshwater swamps to be lowest where saturation was highest. They also pointed out that below ground parameters must be used when investigating root decomposition rates and cautioned against inference of below ground parameters based on above ground flooding data.

To better characterize the potential for biogeochemical cycling of the study sites, regardless of water source, the number of paired switches at -10 cm over 1 month time periods was determined. A minimum length of one day below and one day above -10 cm was required to count as a switch to eliminate ephemeral water table responses that most likely would not establish an oxidized or reduced condition. This is based on the assumption that a water table drawdown event of at least one day is sufficient to raise redox potentials within the surface sediments to increase cycling relative to conditions of more static water tables. The depth of -10 cm was assumed to compensate for a capillary fringe, since water tables higher than -10 cm are likely to be saturated to the surface. A value of 0.5 paired switches per month was assigned for the lowest threshold whereby a month of oxidized and a month of reduced conditions occurred. One paired switch per month indicated approximately 2 weeks of oxidized and two weeks of reduced conditions. A value of zero switches, combined with water tables above -10 cm, indicated maximum potential for organic matter accumulation and other processes dependent on reducing conditions (Table 6). The mainland midmarsh and high marsh sites were never de-saturated during the winter and spring months, suggesting these sites would have the greatest potential to accumulate organic matter. Furthermore, the mainland midmarsh was virtually never oxidized in any season, and only 1 month contained switches over the 6-year study period. The mainland high marsh did have a potential for complete biogeochemical cycling in summer and fall, when 4 of 16 and 2 of 9 months, respectively, contained a paired switch. In winter and spring months, the site was continuously saturated, promoting processes associated with reduced soil conditions, such as organic matter accumulation. The island high marsh showed the greatest potential for biogeochemical cycling with 1-2 paired switches in 4 of 10 spring months, 3 of 9 fall months, 4 of 12 summer months. Although the *Myrica* site exhibited extreme variations in water table fluctuations, there were no switches at -10 cm. The depth-duration graphs indicated that mean water tables are well below -10 cm, and this site represented the oxidized end-point.

Water Table Dynamics and Maintenance of Characteristic Plant Communities

Characterization of water table dynamics and its relationship to wetland processes has been one of the most overlooked aspects of wetland studies (Carter 1986). In fact, hydroperiod, as noted earlier, is commonly defined as the "depth, duration, frequency, and seasonality of flooding" (Mitsch and Gosselink 1993). This definition excludes aspects of below ground dynamics, which are ecologically important as they occur in the root zone and are responsible for the oxidation/reduction state of soils. Day and

Table 6. Biogeochemical cycling parameters. The fraction of months containing switches are indicated by season. The number of switches per month is also indicated.

SITE	**fraction of months with switches**	**# of paired switches**
Creekbank Sites		
(all seasons)	0/6	0
Mainland Midmarsh		
Winter	0/13	0
Spring	0/12	0
Summer	1/12	3
Fall	0/14	0
Mainland Highmarsh		
Winter	0/11	0
Spring	0/9	0
Summer	4/16	0.5-1
Fall	2/9	1
Island Highmarsh		
Winter	0/8	0
Spring	4/10	2
Summer	4/12	1
Fall	3/9	2
Island Myrica		
Winter	0/9	0
Spring	0/12	0
Summer	0/13	0
Fall	0/13	0

Megonigal (1993) cautioned against the inference of processes based on above ground flooding alone. In many systems, such as forested freshwater wetlands, processes are found to be highly dependent on below ground dynamics (Brinson et al. 1981, Day and Megonigal 1993, Rheinhardt and Hershner 1993). Quantitative characterizations of water table dynamics would serve two purposes. The first would be the opportunity to expand upon and improve the current definition of wetland hydroperiod. The second would be the ability to relate specific aspects of the dynamics to ecological processes, such as the maintenance of characteristic plant distributions.

This study quantitatively described the depth, duration, frequency, source and seasonality of flooding of below ground dynamics. While this information generally contributes to the first purpose, the parameters depth and duration were isolated to relate the data to maintenance of characteristic plant communities. Flooding across the root zone, 0 to -30 cm, was integrated by multiplying the depth of flooding in the root zone by the percent of time at that depth and summing for all depths (Figures 9, 13, 17, and 21). When the water table was at ground surface, depth of flooding in the root zone was 30 cm. Likewise, flooding at -5 cm represented 25 cm of flooding; -10 cm represented 20 cm of flooding, etc. The resulting values had units of cm and were calculated for spring and summer only. It was assumed that anoxic conditions exist at and below the water table which, by exerting a stress on plants, selects for flood tolerant species. This condition would not act as stressor during dormant periods, and spring and summer were assumed to represent the most active part of the growing season. A continuum of root zone saturation was found from the creekbank site to the high marsh sites, with the

Myrica site virtually never flooded in the root zone (Table 7). The creekbank site and the mainland midmarsh were flooded across the root zone during all of the growing season and received values near the maximum of 30 cm. The mainland and island high marsh sites had considerably lower flooding in the root zone, 5 and 7 cm, during summer. The *Myrica* site received values of 1 and 4. Correlation between plant zonation and these values is loose. Creekbank vegetation certainly differs from *Myrica*, but in other cases, the midpoints of the continuum are not as easily related to species distribution.

There are several limitations to these data including the lack of actual field measurements of oxidation/reduction potentials. It is possible that microbial respiration could produce anoxic conditions in unsaturated soils, in which case the hydrologic data alone would underestimate stress. Likewise, these data do not account for saturation above the water table by a capillary fringe. Finally, there are many other factors such as salinity, disturbance, and inter-specific competition (Bertness 1991) which contribute to plant distributions. These factors may be particularly important in salt marshes and may weaken the correlation between root zone saturation and plant zonation, and may explain the inability to discern differences in depressional storage between the middle and high marsh sites (Brinson and Christian 1998). However, long durations of flooding in the root zone may promote another process, ecosystem state change, as extended stress in high marsh leads to plant death, deterioration of the marsh, and formation of hummocks (Reed and Cahoon 1992, Brinson et al. 1995). A strong correlation between saturation of the root zone and plant distribution has been found in other wetland types. Rheinhardt and Hershner (1993) found mean depth of the water table to be the best parameter for

Table 7. Centimeters of water in 30 cm of root zone.

SITE		**flooding in root zone (cm)**
Creekbank Sites		
	Spring	30
	Summer	30
Mainland Midmarsh		
	Spring	30
	Summer	28.5
Mainland Highmarsh		
	Spring	30
	Summer	7
Island Highmarsh		
	Spring	21
	Summer	5
Island Myrica		
	Spring	4
	Summer	1

correlating the distribution of tree species in tidal freshwater swamps. Although the ability to correlate flooding in the root zone with plant distributions varies between systems, the hydrologic parameters described here provide an approach for quantitatively linking below ground hydrology and processes useful on a general scale.

Conclusions

The sites in this study exhibited hydrologic variation that has typically not been defined within wetland types. These sites are not hydrologically equivalent, and the use of ecologically important parameters indicated that processes may differ significantly among sites. Based on interpretation of the data, the creekbank site has a high potential for above ground dependent functions such as exchanges of sediment, organic matter, and pelagic organisms. It does not, though, have the ability to serve as long term aquatic habitat. While this is commonly accepted, the hydrologic data also suggest that the two high marsh sites do not perform similar functions. The mainland high marsh site has seasonal capacities for depressional storage, aquatic habitat, infrequent tidal exchanges, a high potential for flood stress, and closed biogeochemical cycles. The island high marsh provides virtually no aquatic habitat, has much less potential for flood stress, and is likely to have intermediate rates of biogeochemical cycling. Processes at the *Myrica* site are likely to be more similar to upland processes than wetland processes, and this site is an end-point reference.

It is hoped that this study highlights the need to quantify hydrologic parameters with greater attention to their ecological significance. The approach chosen provides one possible method for accomplishing this goal. Similar hydrologic descriptions may be useful in other wetland types, and adjustment of the parameters used may be necessary. Such information may contribute greatly to our ability to better understand and manage these systems.

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