# A METHOD FOR ESTIMATING PORE WATER DRAINAGE FROM MARSH SOILS USING RAINFALL AND WELL RECORDS

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PIELTER6b.DOC (3-5-08)

**Abstract**

Rainfall events during low tide exposure cause the water table in marshes to rise. If one has long time series of both rain events and water levels in wells along transects from creek bank to marsh interior, one can correlate well response with rain amount. In cases examined so far the well response is found to be a linear function of rain amount. As it is reasonable to assume that the amount of tidal infiltration required to restore the water table to the elevation of the marsh surface is equal to the amount of rain that would be required to do so, one can estimate the annual drainage of pore water from a well site by dividing the mean drawdown of the water table at low tide by the slope of the response-versus-rain regression and then multiplying the result by the number of tidal drawdowns in a year. Integration of such results along the transect then gives an estimate of the total annual drainage. An example of the use of this method is given for two well transects in a Typha and a Spartina marsh at the Plum Island Estuary Long Term Ecological Research (PIE-LTER) site in Massachusetts, USA. Both transects yielded pore water drainage rates of about 160 $m^3$ $yr^{-1}$ per meter of channel length. Although the annual volume of pore water drainage is small compared to the annual volume of the tidal prism its impact on nutrient budgets in the estuary could be large because of the high concentrations of nutrients in marsh pore waters. We also discuss the possible effects of the capillary fringe, air entrapment and tidal forcing during rain events on these results.

## 1. Introduction

Pore waters in salt marsh soils commonly have nutrient concentrations that are one to two orders of magnitude greater than those in typical rivers and tidal channels (Krest et al., 2000). In particular, mean pore water concentrations of ammonia and orthophosphate in natural marsh soils at the PIE-LTER site are 98.6 (+/- 5.8) and 4.41 (+/- 0.38) uM respectively (http://ecosystems.mbl.edu/PIE/data/MAR/dataMAR-VA-Porewater.dat). In contrast mean concentrations in the surface waters of the adjacent estuary are only 2.52 (+/- 0.24) and 0.58 (+/- 0.02) uM respectively. As a result, drainage of pore water during low tide from a unit area of tidal marsh can potentially supply nutrients to an adjoining estuary in an amount comparable to that in runoff from ten to one hundred units of upland watershed (Gardner, 1975; Krest et al., 2000). The supply of nutrients from marsh pore waters to estuaries is also enhanced by the fact that the drainage density of tidal creeks in marsh basins is typically two to three times greater than that of terrestrial watersheds (Novakowski et al., 2004). In some areas, such as the Plum Island Estuary (Massachusettes), ditching of marshlands for mosquito control has greatly increased the drainage density of marshes and thus presumably the drainage of nutrients into estuarine waters. In Massachusetts there is currently discussion as to whether these ditches should be plugged in order to restore the marshes to their natural configuration (Susan Adamowicz, personal communication, 2007). Obviously one factor that should be considered in whether to implement such a policy is the role of ditches versus natural channels in supplying estuarine water with nutrients.

In the past, several methods have been used to estimate the drainage of marsh pore waters into tidal channels. One method is to employ a numerical or analytical groundwater flow model. Accurate results using this method depend on accurate measurements of marsh soil hydraulic properties (conductivity, porosity, compressibility, and soil water retention curves) and their spatial variability. Since the properties of marsh soils are typically nonhomogeneous and anisotrophic, numerous such measurements and associated stratigraphic investigations may be necessary. In any event, no fully calibrated and validated model currently exists for groundwater flow in an actual marsh. Alternatively one might attempt to measure drainage directly by placing seepage meters along a transect from creek levee to mid channel bottom. However, as shown by Gardner (2005) the distribution of seepage along the creek bank and bottom varies both spatially and temporally and depends also on marsh stratigraphy. In addition seepage meters are usually designed to work in subtidal environments and thus may not work on subaerial seepage faces. Alternatively one could install weirs in narrow channels or ditches to measure flow during tidal exposure of the weir notch (Gardner, 1975). However, some of the water passing through the weir may be delayed flow from depression storage on the marsh surface and/or channel bottom. Also, this method only measures the drainage of pore water occurring during the interval of weir exposure. If a pore water tracer, such as radium, is present, it may be possible to reliably estimate the fraction of the total surface flow resulting from pore water drainage (Krest et al., 2000). Finally, if a time series is available for water levels in wells along a transect perpendicular to the creek bank and the specific yield [which is the ratio of the volume of water that can ultimately drain from a saturated soil under the acceleration of gravity to the total volume of the soil thus drained (Fetter, 1994)] of a representative suite of soil samples has been measured, one could estimate the drainage derived from each well site by multiplying the well drawdown (relative to the surface elevation) at each site by the specific yield (C. Hopkinson, personal communication, 2007). Integration of the site values along the transect would then give an estimate of the total drainage of pore water for a given tidal cycle (or for an average tidal cycle). A problem with this method is that the measurement of specific yield typically is made on a time scale (e.g., 5 to 13 days; Roukamen and Klove, 2005) that is considerably longer than the duration of drainage during tidal exposure in regularly flooded marshes. Indeed Prill et al. (1965) claim that even with sand-size sediment months of drainage are required to reach exhaustion of the drainable pore water. Thus drainage estimates based on yields measured on cores are likely to overestimate the actual drainage unless the intervals between tidal inundation are on the order of ten or more tidal cycles. Also, the drainage of pore water from marsh soils is subject to variations in the duration and depth of tidally driven water-table drawdown. Such variations are not taken into account by the measurement of specific yield in a core of fixed length over a somewhat arbitrary interval of time. Furthermore, this method does not take into account the possibility that the tidal drawdown of the water table is greater than the drawdown of the level of total saturation because of the presence of a capillary fringe. In any case the quality of such estimates depend on the installation and monitoring of wells to the same extent as the method described below, and thus involve about the same amount of effort.

In view of these difficulties it would be desirable to develop a method for estimating the “effective” specific yield of marsh soils that is based largely on monitoring data and on a minimum of realistic assumptions. The purpose of this paper is to describe a method that is based on time series of water-table elevations and rainfall, and the assumption that the amount of tidal infiltration required to restore the marsh water table from a given drawdown to the marsh surface is the same as the amount of rain required to do so. Also, since the method involves the regression of water-table rise against rain amount over a number of discrete rain events, it should average out the effects on specific yield of variations in the duration and depth of the tidally driven drawdown preceding each rain event. The possible effects of the capillary fringe and air entrapment on this assumption and the results obtained thereby are also discussed.

## 2. Methods

### *2.1 Site description and data sources*

The method described here is based on a variation on the general water-table fluctuation (WTF) method used by hydrologists to estimate groundwater recharge in a variety of non-marine environments (Healy and Cook, 2002). It is based on precipitation and marsh water-table data collected in 2006 as part of the Plum Island Estuary, MA, Long Term Ecological Research (PIE-LTER) project funded by the U.S. National Science Foundation. The locations of two well transects, one in a Typha dominated marsh and one in a Spartina dominated marsh, are shown in Figure 1 along with the location of the recording rain gage used in this study. The topographic profiles of the two transects and the locations of wells thereon are shown in Figure 2. Measured saturated hydraulic conductivities and specific yields along these transects range from 0.008 to 0.0011 cm $s^{-1}$ and from 0.08 to 0.12 respectively (unpublished data). Porosity, bulk density and organic content have not been measured along these transects but measurements at 15 similar Spartina marsh sites in the Plum Island Estuary average .68 (+/- 0.1), 0.095 (+/- 0.01) g $cm^{-3}$, and 31 (+/-5) percent respectively in the top 50 cm of the soil (see http://ecosystems.mbl.edu/pie/data/mar/MAR-RO-Transects.htm).

Precipitation was measured at the Governer Dummer Academy, South Byefield, MA, at Lat. 42.75148419 N and Long. 70.9024065 W (Figure 1), using a Texas Electronics model TE525WS-L, 8” rain gage with a CS705 precipitation adapter for snow fall. Precipitation data were recorded at 15 minute intervals and was downloaded from the PIE-LTER web site (http://ecosystems.mbl.edu/pie/data.htm).

The 2006 water table data for the Typha and Spartina well transects were retrieved from the PIE-LTER web site (http://ecosystems.mbl.edu/pie/data/mar/MAR.htm). Each transect consists of a tide gauge and five wells oriented perpendicular to the channel of the Parker River (Figure 2). The Typha transect (at 42.75091 N, 70.91474303 W) is located about one kilometer west of the precipitation gage whereas the Spartina transect (at 42.761713N, 70.856083W) is about 3.5 km east of the rain gage. Details pertaining to the instrumentation installed in the wells can be found at http://ecosystems.mbl.edu/pie/data/mar/MAR-PR-Wtable-T-2006.htm and http://ecosystems.mbl.edu/pie/data/mar/MAR-PR-Wtable-RR-2006.htm. Water-table data were recorded at 10 minute intervals between 27 April 2006 and 5 December 2006 with two one-day interruptions for instrument servicing. No snow events occurred during this interval.

*2.2 Data analysis*

The water-table time series for each well on both transects were plotted for the entire record and the plot-zoom feature of the software was used to view the time series in detail for each time interval during which rainfall was reported. An example of such an interval is shown on Figure 3. The plus signs on the figure indicate well peaks due to tides, not all of which reached the elevation of the well site (3.155m). The letter "a" on the figure indicates the beginning of the rain response at year day 300.29 while "c" represents the point at which the water table reached the surface of the marsh at year day 300.39. The dashed line, with the small arrowhead, from "a" to "b" represents a linear extrapolation of the tidal recession that would have occurred up to point "c" in the absence of rain. As indicated by the plateau in the time series at about 3.155m, the rain that fell after this time ("c") was sufficient to maintain the water table at the marsh surface until the next tide flooded the marsh. During the interval from "a" to "c" the water table rose 289 mm from the elevation at "a" to that at "c".. However, during the interval between "a" and "c", tidal forcing would have caused the water table to drop to the elevation of point "b". Therefore we also determined a "tidally corrected" water-table response (elevation of "c" minus elevation of "b"), which in this example amounted to 320 mm. During the interval between "a" and "b" the rain record indicated that 9.4 mm of rain fell. Thus the raw and corrected response ratios for this event are 30.7 (289mm/9.4mm) and 34.0 (320mm/9.4mm), respectively. Note that only the amount of rain that fell during the response from “a” to “c” is correlated with the water-table response (be it raw or tidally corrected), not the total amount of rain that fell during this rain event, which began at year day 300.11. This procedure was applied to each of the wells along both transects and resulted in 20 to 53 pairs of rainfall and response for a given well. In cases where the rain event occurred during rising tide the tidally corrected response is less than the raw response. In most cases the corrected response was greater than the raw response because in all of the wells the duration of ebbing tide greatly exceeds that of rising tide (Figure 3). Note also that in calculating our response ratios we did not include any of the rain that fell before the response manifested itself at point “a” because there is no obvious way to estimate what effect it would have had on the ebbing water table. In most cases the rain events were of much shorter duration than the one shown on Figure 3 so the amount of pre-response rain was commonly negligible.

Since the sampling intervals for the rain and water level time series were not equal (15 versus 10 minutes), it was often necessary to interpolate the rain data. Also included in this database are some responses that did not reach the marsh surface because of insufficient rain. The decision to include such events was made in order to increase the sample size for statistical analysis and will be discussed below. For each well both the raw and tidally corrected water-table responses were regressed against rain amounts. Also, in order to assess the possible effects of the capillary fringe and/or air entrapment by a rainwater cap on the marsh surface (Gerla, 1992; Gillham, 1984; Heliotis and DeWitt, 1987) we preformed regressions on the tidally corrected data sets partitioned according to whether the water table at the beginning of an event was above or below a particular depth below the marsh surface (10 cm or 20 cm). Our expectation was that response events originating at shallow depths should be more sensitive to capillarity and air entrapment. These response mechanisms can occur without the actual entry of water into the soil and thus, if present, should be avoided or corrected for in the estimation of the specific yield. Finally we also regressed the rate of the water table response against the rate of rainfall during the event because Heliotis and deWitt (1987) found that a correlation between response rate and rain intensity only occurs during actual recharge. The method for estimating the annual drainage of pore water from marsh soils using the regression results is described in the Discussion as it depends on the evaluation of these results.

## 3. Results

The results of the regressions described above are summarized in Tables 1 and 2. Examples of the tidally corrected water-table responses versus rain amounts are shown on Figure 4 for Wells 1 to 4 on the Typha transect. As shown in Tables 1 and 2 the slopes of the regression lines for the raw and tidally corrected responses range from 8.4 to 34.5 on the Typha transect and from 7.8 to 18.3 on the Spartina transect. Tables 1 and 2 also show that for a particular well the regressions for the raw and tidally corrected responses generally are not significantly different, particularly as regards slopes and correlation coefficients. In all cases, however, the slopes and correlation coefficients are significantly different from zero and explain between 40 to 90 percent of the water table response. No tidal correction was possible at Well 5 on the Typha transect as no tidal signal was evident at this site. At six of the other nine wells, tidal correction resulted in a somewhat greater slope, as might be expected from the fact that most of the corrections occurred during ebb tide and increased the magnitudes of the responses. The standard errors on the slope estimates (Tables 1 and 2), however, are not small enough to conclude that the corrected slopes at a well are significantly larger. The response corrections also did not significantly improve the correlation coefficients indicating that better correlation is limited by uncertainties in the rain data (due to the remote location of the weather station) rather than in the response data. Interestingly the intercepts at some wells (e.g. Wells 4 and 5 on the Spartina transect) are two or more times larger than their standard errors, indicating that they are significantly greater than zero. Overall the results for the raw and tidally corrected responses indicate that on average one unit of rain produces 7.8 to 34.5 units of water-table response depending on well location. Possible explanations for the variation in the regression slopes along the transects are discussed below along with suggestions for improving this methodology.

The results for the effect of the starting depth of a rain response are more complex and less consistent than those described above. In general, when the regressions are restricted to responses that start at depths greater than 10 or 20 cm, the slopes and correlation coefficients for a given well are not significantly different from those of the raw data. Some exceptions on the Spartina transect are the somewhat lower slopes (~14 versus ~18) at Well 5 and the distinctly improved correlation coefficient (0.923 versus ~0.7) and larger intercept (121 versus ~30) for Well 4 (> 20cm). At Well 1 on the Typha transect the >20 cm partition also produced a somewhat larger correlation coefficient (0.649 versus ~0.4) and slope (20.9 versus ~13.5). In contrast when the regressions were restricted to responses that started above 10 cm depths both slopes and correlation coefficients commonly were greatly reduced in some cases to the level of statistical insignificance), with an exception perhaps at Well 5 on the Typha transect. In general, the regressions for responses starting above 20 cm produced results intermediate between those for the raw data and those for the above 10 cm data.

Finally the regressions of response rate versus rain intensity produced results generally similar to those for the raw and tidally corrected data with exceptions of Well 4 on the Spartina transect, where a distinctly lower slope and correlation coefficient resulted, and Wells 3 and 5, where substantially greater slopes and correlation coefficients resulted. Here, we note that the rate data differ from the raw data in that data points that plot near the origin in the raw data do not necessarily plot near the origin in the rate data, nor do data points near the high end of the raw plots remain there when converted to rates. In any case, all of the wells showed significant positive correlations between response rate and rain intensity, with the latter explaining 20 to 94 percent of the variation in the former.

## 4. Discussion

### *4.1 Mechanisms of water-table response*

There are three mechanisms that can cause the water table in a soil to rise in response to rainfall (Heliotis and DeWitt, 1987). The first is the entrapment of air and its subsequent pressurization, beyond that of the atmosphere, by a layer of rain water that might form on the surface of the soil (Gerla, 1992). Unless this water is actually drawn into the soil by capillary forces, the pressurization, and thus the resultant water level rise in a well, is limited by the thickness of the water layer that accumulates on the surface.

Indeed, if this is the only process controlling water-table responses in our wells, all of the regression slopes should have a value of 1.0. In this study the rain events had a mean magnitude of about four millimeters and a maximum of about 23 millimeters, which are small compared to the typical water-table responses of 100 millimeters that we observed. Thus we conclude that this simple pressurization process, if it occurs at all, would only have a significant impact on the accuracy of water-table responses that start at shallow depths (<10 cm). If, on the other hand, some of this water is drawn downward into the soil by capillary forces, then the entrapped air would be pressurized not only by the thickness of the layer of rainwater on the marsh surface but also by the capillary force exerted on the infiltrating rainwater. Thus the water table would rise not only by an amount equal to the depth of the ponded rainfall but in addition by an amount equal to the depth of penetration of the inverted zone of tension saturation (Gerla, 1992). Such events therefore may be as useful in estimating the effective specific yield of a soil as those that involve the downward movement of rainwater from the marsh surface to the top of the upright zone of tension saturation, that is, actual recharge. However, as it is likely that the unsaturated water content of near surface soil is lower than that of soil just above the upright zone of tension saturation, it might turn out that specific yield estimates based on actual recharge events are smaller than those based on the penetration of an inverted zone of tension saturation, particularly if the recharge is not great enough to bring the water table to the marsh surface. In any case we are interested in estimating the annual drainage of pore water from marshes so it may be appropriate to have specific yield estimates based not only on actual water table recharge but also on infiltration driven solely by capillary attraction.

The second mechanism that could cause the water-table to rise is the filling and flattening of the menisci in soil pores at the top of the capillary fringe by rainwater and the subsequent extinction of suction head in the zone of tension saturation. If the zone of tension saturation happened to extend to the soil surface at the onset of rainfall, the water table would rise rapidly, if not instantaneously, to the surface (Gillham, 1984). Otherwise the zone of tension saturation (and the water table) would rise towards the surface at a rate determined by the rate of recharge. Upon reaching the surface the next increment of rain would extinguish the suction head and cause a sudden rise of the water table to the surface. Again the impact of this process on the accuracy of recharge estimates would be most significant for response events that start at shallow depths as it might preclude the entry of any rain water into the soil. Unfortunately, the temporal resolution of our rain and water-level data is not fine enough to detect such effects. In any case, we think that the thickness of the capillary fringe in our soils is probably not greater than about 10 centimeters. We base this conclusion on four observations. First, the lack of any correlation between water-table rise and rain amount is limited to response events that start at depths above 10 centimeters (Tables 1 and 2). Second, as noted above, our peaty soils typically have porosities greater than 0.7 and dry-weight bulk densities below 0.14 g $cm^{-3}$. Peat soils with similar porosities and bulk densities are reported to show measurable water loss (~ 0.02 cm3 $cm^{-3}$) at suction heads as low as 5.0 centimeters (Boelter, 1964). Third, in their laboratory study of the capillary response to simulated rain in peat soils Heliotis and DeWitt (1987) found that the ratio of water-table rise to rain amount ranged from 90 to 110 during events dominated by capillary effects. Of the 370 rain events summarized in Tables 1 and 2 we found only 16 events that had a response ratio greater than 75. The means of the ratios for the various wells ranged from 12 to 47 with an overall mean of 25.2. This suggests that less than five percent of the responses in our data sets involved significant capillary rise effects. Fourthly, referring to Figure 3 we can surmise that the capillary fringe did not extend to the marsh surface at the beginning of the rain event (year day 300.11) nor did it extend to the marsh surface at the time the tidally driven water table reached its peak at year day 301.20. Thus the thickness of the capillary fringe could not have been greater than the distance between the marsh surface and the peak tide level in the well, that is, about 15 cm.

The third process that can cause the water table to rise during rain events is the entry of rain water into the soil and its downward percolation to the water table, that is, actual recharge. According to Heliotis and DeWitt (1987) this process is characterized by a good correlation between response rate and rain intensity. As shown in Tables 1 and 2 such correlations are present at most of our wells. Thus we conclude that water-table recharge is the primary process causing the response of the water table to rain events observed at our sites and that therefore it is reasonable to calculate “effective” specific yields from our data for use in estimating the drainage of pore waters from these marshes.

*4.2 Effective specific yields*

Specific yields have been measured on cores taken along the Typha and Spartina transects (E. Gaines, personal communication, 2006) and average 0.118 and 0.093 respectively. The inverse of the tidally corrected regression slopes in Tables 1 and 2 can be thought of as "effective specific yields" since they average out possible variations in the moisture content due to variations in the duration and depth of tidally driven drawdown preceding each rain event. Based on the response-versus-rain regressions the "effective specific yields" along the Typha transect range from 0.029 to 0.116 and average 0.059, which is about a factor of two smaller than the yields measured on cores. Effective specific yields on the Spartina transect range from 0.056 to 0.128 and average 0.073, which is about 20 percent lower than the average measured on cores. Thus, as noted in the Introduction, drainage estimates based on yields measured on cores can be too large. It is also worth noting that specific yields based on our rain and well data represent a greater volume of soil than those based on cores with diameters equal to the well diameters. For example a typical rain event that raises the water table by 20 cm in a soil with a specific yield of 0.1 requires the seepage of 0.91 liters of water into a three-inch well with a radius of 3.8 cm (that is pi times 3.8 cm times 3.8 cm times 20 cm). With a specific yield of 0.1 the volume of soil from which this water is derived is 0.91 liters divided by 0.1 or 9.1 liters. With a thickness of 20 cm this volume of soil would have a radius of about 13 cm. Thus it would take about ten cores with 7.6 cm diameters to sample the same volume of soil contributing water to account for the 20 centimeters of water level rise in the well.

*4.3 Pore water drainage estimates*

The data needed to estimate the annual drainage of pore water from the two transects are summarized in Table 3. The drainage (per meter of channel length) over an average tidal cycle from a well site is computed by multiplying the length (portion) of transect represented by the well times the mean drawdown and dividing the result by the slope of the tidally corrected response versus rain regression. The annual drainage from a well site is obtained by multiplying this result by the number of tides per year. In this exercise the representative width associated with a well site is the distance between the midpoints between adjacent wells. The mean drawdown at a well was estimated by subtracting the mean elevation of the water table at low tide from the elevation of the well site. However, as shown on Figure 3, the well sites are not flooded on each tide. Nevertheless, with the exception of Well 5 on the Typha transect, tidal fluctuations in the channel propagate into the marsh ground water, albeit with attenuated amplitudes. Thus the drawdown associated with drainage during non-flooding tides would be more accurately determined by subtracting the elevation of the water table at low tide from that at the previous high tide. Given the remote location of the rain gauge and its coarser temporal resolution, and the fact that the purpose of this paper is to merely demonstrate the method, it was not deemed worthwhile to undertake this more laborious exercise. In addition the overestimation introduced by this approximation is likely to be small because even the highest site is flooded by ~60 percent of the tides.

It should be noted that the drawdowns at Well 5 on the Typha transect are due entirely to evapotranspiration (ET). This is evidenced by the fact that during periods of non-flooding tides in summer the pattern of drawdown is step-like, with declines in the water table occurring only during daylight and essentially no changes at night. (This, incidentally, is further evidence that well drawdowns associated with tides most likely involve the actual removal of water from the soil and not just the development of a zone of tension saturation extending to the marsh surface). Since drawdown caused by ET does not contribute to pore water drainage and because the vegetated marsh platform landward of Wells 2 on both transects presumably looses water via ET (although such losses cannot be discerned against the background of much larger losses via drainage in Wells 2, 3 and 4 on both transects), a correction is required for this effect. In Table 3 this correction is implemented by assigning a minus sign to the mean drawdown for Well 5 on the Typha transect and by assigning Well 5 a representative width that is equal to the sum of the widths for Wells 2 through 4. Also, since ET only occurs during daylight during the six warmest months, the number of such events is approximately one fourth of the number of diurnal tides in a year (705/4=176). With this correction the annual drainage from the Typha transect is equal to 167.0 $m^3$ per meter of channel length. On the Spartina transect it was possible at Well 5 to estimate components of drawdown due to drainage from those due to ET because water levels during tidal exposure at night often declined but at a rate distinctly slower than during the day.. As shown, the yearly drainage at the Spartina transect is 157.6 $m^3$ per meter of channel length, similar to that at the Typha transect. Again, given the remote location of the rain gauge and the coarser temporal resolution of the rain data, these numbers should be considered as merely rough estimates. If true, however, and representative of marshes in the Plum Island Estuary watershed, these estimates indicate that drainage of nutrients from marsh soils could exceed their input via runoff from the uplands of the watershed (J. Morris, personal communication, 2007).

*4.4 Further considerations*

If the method presented here is to be credible, some explanation is required for the apparently unsystematic variation in the "effective specific yields" observed along the transects. In this regard we note first that specific yield measurements (unpublished data) made on cores taken along transects in the PIE marshes similar to those in this study also failed to show systematic variation. Thus there may simply be inherent unsystematic variation in soil properties associated with variations in organic matter, root densities and burrows. Burrows and cracks (which sometimes appear during low tide) appear to be more abundant on creekbanks and levees and might be responsible for some of the high effective specific yields found there. Also these sites have steep topographic slopes so they are more likely than the marsh platform to transform rainfall into surface runoff, rather than recharge, and thereby dampen the water-table response to rainfall (or enhance it at receiving sites lower on the creek bank). Errors due to runoff are less likely on the marsh platform because runoff from nearly horizontal areas will only begin after the depression storage associated with the microtopography of marsh surface has been satisfied.

If the water level response in our wells is due primarily to the infiltration of runoff from higher areas of the marsh, one might expect the response to begin later in wells closer to the creek. Allowing for the greater effect of the tide on wells close to the creek, this does not appear to be the case. For example, a rain event that began at 12:30 pm (EST) on May 8, 2006, during ebb tide, and continued for the rest of the day had the following effects on the wells of the two transects. On the Spartina transect Wells 2 to 5 began their responses within ten minutes from the first recorded rain. Well 1 began its response about an hour after the beginning of the storm but during this time the tide fell from 1.88 meters to 1.05 meters (low tide at 0.95 meters occurred about an hour later), so it appears that drainage driven by the falling tide exceeded rainfall infiltration. Water levels in Wells 4 and 5 on the Typha transect also began to rise within ten minutes of the onset of rain but responses in Wells 2 and 3 were delayed by about an hour. This could be due to the much greater rates of drainage at Wells 2 and 3 on the Typha transect as compared to their counterparts on the Spartina transect (Tables 3 and 4). Thus infiltration of rainfall at Wells 2 and 3 on the Typha transect probably could not overcome the loss of water by drainage during the time of rapidly falling tide. It thus appears that well responses to rain events are probably not driven by surface runoff.

Another issue is whether the wetting and draining limbs of the soil water retention curve for a marsh soil coincide over the range of moisture changes experienced by the soil. If not, one could argue that the amount of water lost via drainage and ET is different than the amount acquired during rain events, in which case the fundamental assumption of the method is violated. However since the wetting and draining limbs converge at saturation, this could only be a problem for rain events that are too small to raise the water table to the marsh surface. In such cases some of the rain may be retained in the unsaturated soil above the water table. In such events the water table response to a given amount of rain would be smaller than that which would otherwise occur. Had such events been omitted from this analysis, the regression slopes shown on Figure 4 and Tables 1 and 2 might be higher and the drainage estimates lower. This effect, however, is likely to be small because in these highly porous soils drainage and ET probably do not remove more than a quarter of the water present at saturation. Thus wetting does not likely begin at the residual water content and follow the main wetting curve but rather departs from a point on the main drying curve and follows a path towards saturation that lies between the two main curves (Simunek et al., 1999).

It should also be noted that this method is not likely to work well in regularly flooded marshes with microtopography that is capable of storing several millimeters (depth-equivalent) of water. This is because drawdown can only occur after depression storage has been consumed to balance losses by ET and/or drainage. Except during summer (or near creek banks) there may not be enough time between regular flooding events to exhaust the depression storage. Even at the irregularly flooded marshes of the Plum Island Estuary the water level data at Well 5 on the Spartina transect often show that the water table remains at the marsh surface for up to ten hours after tidal exposure before dropping because of ET and/or drainage. During such intervals water may be draining from the marsh soil at this site but it is immediately replaced by infiltration from depression storage. We have not attempted to estimate how much water drains from the marsh soil during such intervals but such estimates might be made by extrapolating the rates of drawdown observed at the onset of drawdown during nighttime exposure of the marsh.

Good results using this method also require proper well construction and installation. Care should be taken to insure that the well casing does not move and that an annular space does not develop in the soil surrounding the casing. If such occurs, rain water will attempt to fill this artificial storage and thereby delay and/or dampen the well response. Also, in order to enhance (and quicken) the response of the well to changes in the external water table, the pressure sensor should be housed at the bottom of a pipe that has an outer diameter that is only slightly smaller that the internal diameter of the well casing. This will minimize the volume of water (and thus the response time) that has to enter or leave the well in response to changes in the external water table, but unfortunately will also minimize the radius of contribution. Thus a compromise may be necessary.

Finally, if we are to improve our understanding of the mechanisms driving water-table responses to rain events in marsh soils under field conditions and thereby obtain more accurate estimates of recharge and drainage, it is imperative that rain gauges be installed at the well transects and that well water levels and rain be measured at the highest possible frequency over long periods of time. With such high quality data it might be possible to study many individual rain events in detail and thereby more clearly identify the effects of capillarity, air entrapment, rain intensity and starting depth on water-table response. We also speculate that the regression intercepts, if greater than zero, might turn out to be a measure of the mean thickness of the zone of tension saturation.

## 5. Acknowledgements

Partial funding for this work was provided by National Science Foundation Grant Number OCE-0423565. This is contribution number **** of the Belle W. Baruch Institute for Marine Biology and Coastal Research. We thank Professors Franco Montalto, Raymond Torres and Alicia Wilson for their helpful discussions and comments on an early draft. We also thank two anonymous reviewers for their valuable comments. Finally we acknowledge Joe Vallino for providing the location map in Figure 1.

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Table 1. Water table regression results for Typha transect with standard errors in parentheses. Units for intercepts are in mm (or mm/hr for rates). R squares with astericks are not significantly different from zero.

| **Well** | **Data** | **Intercept** | **Slope** | $R^2$ | **N** |
|---|---|---|---|---|---|
| 1 | Raw | 15.5 (9.2) | 12.9 (2.3) | 0.416 | 47 |
| 1 | Tide corr. | 25.3 (10.1) | 13.9 (2.5) | 0.412 | 47 |
| 1 | >10cm | 37.3 (12.9) | 13.3 (2.8) | 0.408 | 33 |
| 1 | >20cm | 21.7 (20.1) | 20.9 (4.4) | 0.649 | 14 |
| 1 | <10cm | 23.9 (8.3) | 4.7 (2.9) | 0.176* | 14 |
| 1 | <20cm | 35.5 (9.2) | 7.9 (2.4) | 0.261 | 33 |
| 1 | Rates | 63.1 (17.0) | 11.0 (2.0) | 0.412 | 47 |
| 2 | Raw | 3.2 (7.2) | 8.4 (0.7) | 0.672 | 32 |
| 2 | Tide corr. | 7.2 (7.4) | 9.6 (0.7) | 0.716 | 32 |
| 2 | Rates | 12.0 (7.9) | 8.6 (1.2) | 0.632 | 32 |
| 3 | Raw | 29.6 (22.4) | 33.9 (4.3) | 0.545 | 53 |
| 3 | Tide corr. | 33.4 (21.3) | 34.5 (4.1) | 0.577 | 53 |
| 3 | >10cm | 53.6 (23.5) | 32.7 (4.3) | 0.573 | 45 |
| 3 | >20cm | 67.0 (29.7) | 33.7 (5.0) | 0.602 | 32 |
| 3 | <10cm | 75.8 (37.7) | -6.0 (13.4) | 0.032* | 8 |
| 3 | <20 cm | 49.3 (18.1) | 14.3 (5.1) | 0.289 | 21 |
| 3 | Rates | -34.8 (34.2) | 50.8 (2.9) | 0.855 | 53 |
| 4 | Raw | -5.1 (10.7) | 16.5 (1.5) | 0.721 | 47 |
| 4 | Tide corr. | -6.7 (12.5) | 18.9 (1.8) | 0.715 | 47 |
| 4 | >10cm | 20.5 (18.7) | 19.3 (2.1) | 0.810 | 22 |
| 4 | >20cm | 74.2 (71.2) | 15.8 (5.5) | 0.544 | 9 |
| 4 | <10cm | 26.9 (4.2) | 3.8 (0.9) | 0.445 | 25 |
| 4 | <20cm | 29.2 (9.6) | 7.1 (2.1) | 0.240 | 38 |

| | | | | | |
|---|---|---|---|---|---|
| 4 | Rates | -30.3 (19.4 | 21.1 (1.9) | 0.741 | 47 |
| 5 | Raw | 16.7 (7.9) | 8.5 (1.2) | 0.722 | 20 |
| 5 | >10cm | 40.2 (18.1) | 6.5 (2.1) | 0.622 | 8 |
| 5 | <10cm | 12.3 (10.2) | 8.4 (2.6) | 0.515 | 12 |
| 5 | Rates | -16.9 (10.0) | 18.6 (1.4) | 0.902 | 20 |

Table 2. Water table regression results for Spartina transect with standard errors in parentheses. Units for intercepts are in mm (or mm/hr for rates). R squares with astericks are not significantly different from zero.

| **Well** | **Data** | **Intercept** | **Slope** | **$R^2$** | **N** |
|---|---|---|---|---|---|
| 1 | Raw | 29.1 (12.4) | 16.7 (1.9) | 0.603 | 51 |
| 1 | Tide corr. | 40.8 (12.7) | 17.4 (2.0) | 0.611 | 51 |
| 1 | >20cm | 46.1 (14.1) | 16.9 (2.1) | 0.591 | 46 |
| 1 | <20cm | 25.6 (35.2) | 15.5 (10.8) | 0.408 | 5 |
| 1 | Rates | 80.7 (20.8) | 13.2 (1.4) | 0.640 | 51 |
| 2 | Raw | 9.7 (7.2) | 7.9 (1.0) | 0.704 | 30 |
| 2 | Tide corr. | 18.3 (7.7) | 7.8 (1.0) | 0.672 | 30 |
| 2 | >20cm | 28.0 (11.7) | 7.4 (1.3) | 0.642 | 16 |
| 2 | <20cm | 19.5 (4.0) | 4.3 (0.7) | 0.745 | 14 |
| 2 | Rates | 13.4 (15.6) | 9.7 (1.5) | 0.604 | 30 |
| 3 | Raw | 10.1 (6.2) | 13.3 (0.8) | 0.895 | 34 |
| 3 | Tide corr. | 15.3 (7.1) | 14.5 (0.9) | 0.866 | 34 |
| 3 | >10cm | 26.9 (11.7) | 13.7 (1.2) | 0.872 | 21 |
| 3 | >20cm | 17.4 (18.7) | 15.1 (1.4) | 0.941 | 9 |
| 3 | <10cm | 33.4 (8.0) | -0.5 (3.9) | 0.001* | 13 |
| 3 | <20 cm | 25.9 (8.3) | 10.4 (1.9) | 0.567 | 25 |
| 3 | Rates | 20.4 (13.8) | 13.6 (1.6) | 0.674 | 34 |
| 4 | Raw | 28.7 (10.9) | 11.0 (1.4) | 0.683 | 29 |
| 4 | Tide corr. | 33.6 (10.6) | 10.8 (1.4) | 0.688 | 29 |
| 4 | >10cm | 65.0 (13.2) | 9.1 (1.4) | 0.735 | 17 |
| 4 | >20cm | 121.0 (11.6) | 7.1 (0.9) | 0.923 | 7 |
| 4 | <10cm | 32.9 (7.4) | 1.6 (2.0) | 0.063* | 12 |
| 4 | <20cm | 32.4 (11.4) | 8.2 (2.3) | 0.400 | 22 |

| | | | | | |
|---|---|---|---|---|---|
| 4 | Rates | 48.5 (13.1) | 6.0 (2.3) | 0.200 | 29 |
| 5 | Raw | 41.5 (11.6) | 18.3 (2.0) | 0.765 | 27 |
| 5 | Tide corr. | 49.9 (11.2) | 18.0 (1.9) | 0.773 | 27 |
| 5 | >10cm | 84.8 (15.6) | 13.8 (2.3) | 0.673 | 19 |
| 5 | >20cm | 79.1 (32.4) | 14.1 (3.8) | 0.736 | 7 |
| 5 | <10cm | 28.0 (15.4) | 17.2 (9.2) | 0.370* | 8 |
| 5 | <20cm | 37.7 (13.0) | 21.5 (3.0) | 0.739 | 20 |
| 5 | Rates | 32.3 (7.4) | 17.7 (0.9) | 0.937 | 27 |

Table 3. Drainage Computations for the Typha and Spartina Transects.

| Well # | Representative Width (m) | Mean Drawdown m/Tide | Regression Slope | Drainage $m^3$/Tide | Events /year | Drainage $m^3$/year |
|---|---|---|---|---|---|---|
| T 1 | 2.5 | 0.20 | 13.9 | 0.036 | 705 | 25.4 |
| T 2 | 1.5 | 0.71 | 9.6 | 0.111 | 705 | 78.2 |
| T 3 | 2.0 | 0.40 | 34.5 | 0.023 | 705 | 16.3 |
| T 4 | 7.5 | 0.22 | 18.9 | 0.087 | 705 | 61.5 |
| T 5[a] | 10.0 | -0.07 | 8.5 | -0.082 | 176 | -14.4 |
| Typha total | | | | | | 167.0 |
| S 1 | 1.1 | 0.48 | 17.4 | 0.030 | 705 | 21.4 |
| S 2 | 1.2 | 0.33 | 7.8 | 0.051 | 705 | 36.1 |
| S 3 | 1.8 | 0.20 | 14.5 | 0.025 | 705 | 17.5 |
| S 4 | 8.4 | 0.15 | 10.8 | 0.117 | 705 | 82.3 |
| S 5[b] | 14.7 | 0.01 | 18.0 | 0.001 | 705 | 5.4 |
| S 5[c] | 26.1 | -0.02 | 18.0 | -0.029 | 176 | -5.1 |
| Spartina total | | | | | | 157.6 |

a. At Well T 5 drawdowns are entirely due to ET and thus do not contribute to drainage. However, some of the drawdown at other well sites is presumably due to ET and thus a correction for ET is required. This correction is indicated by the minus sign for the mean drawdown at Well T 5 and is applied over the vegetated marsh from T 2 to T4 (i.e. 10m).

b and c. At Well S 5 drawdowns can be decomposed into drainage and ET. Since ET does not contribute to drainage it is assigned negative values and is applied over the vegetated marsh from Well S 2 to Well S 5 (i.e. 26.1m).

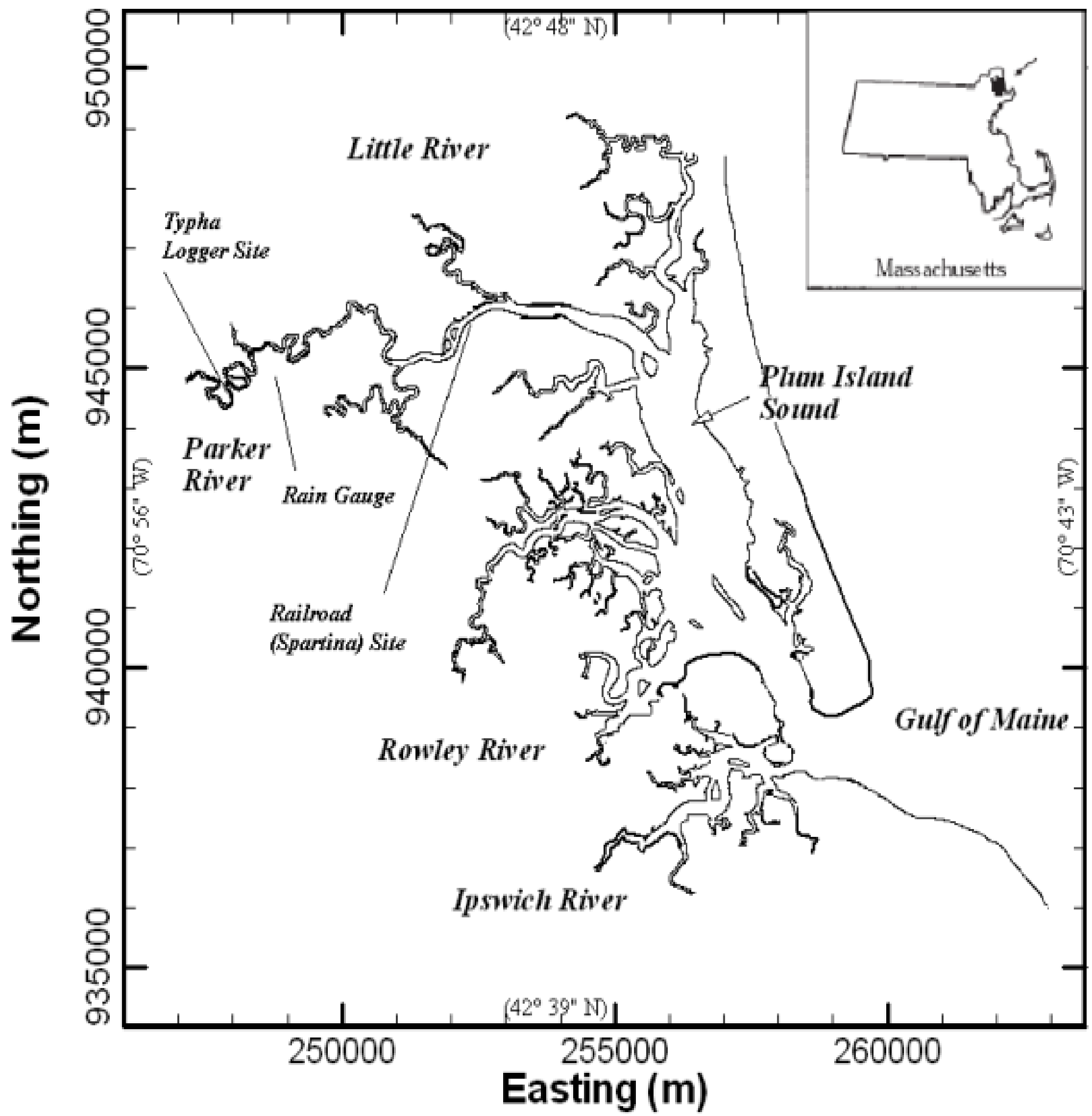
FIGURE CAPTIONS

1. Map showing the locations of well transects and weather station.

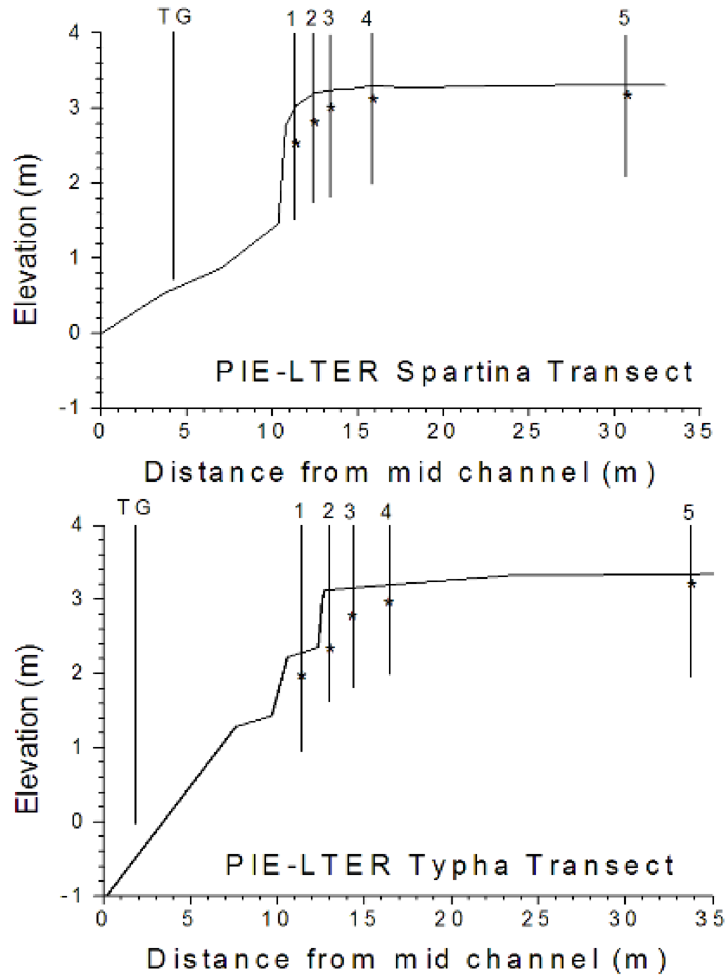
2. Topographic profiles along the Spartina and Typha transects showing well locations and mean water levels at low tide (stars).

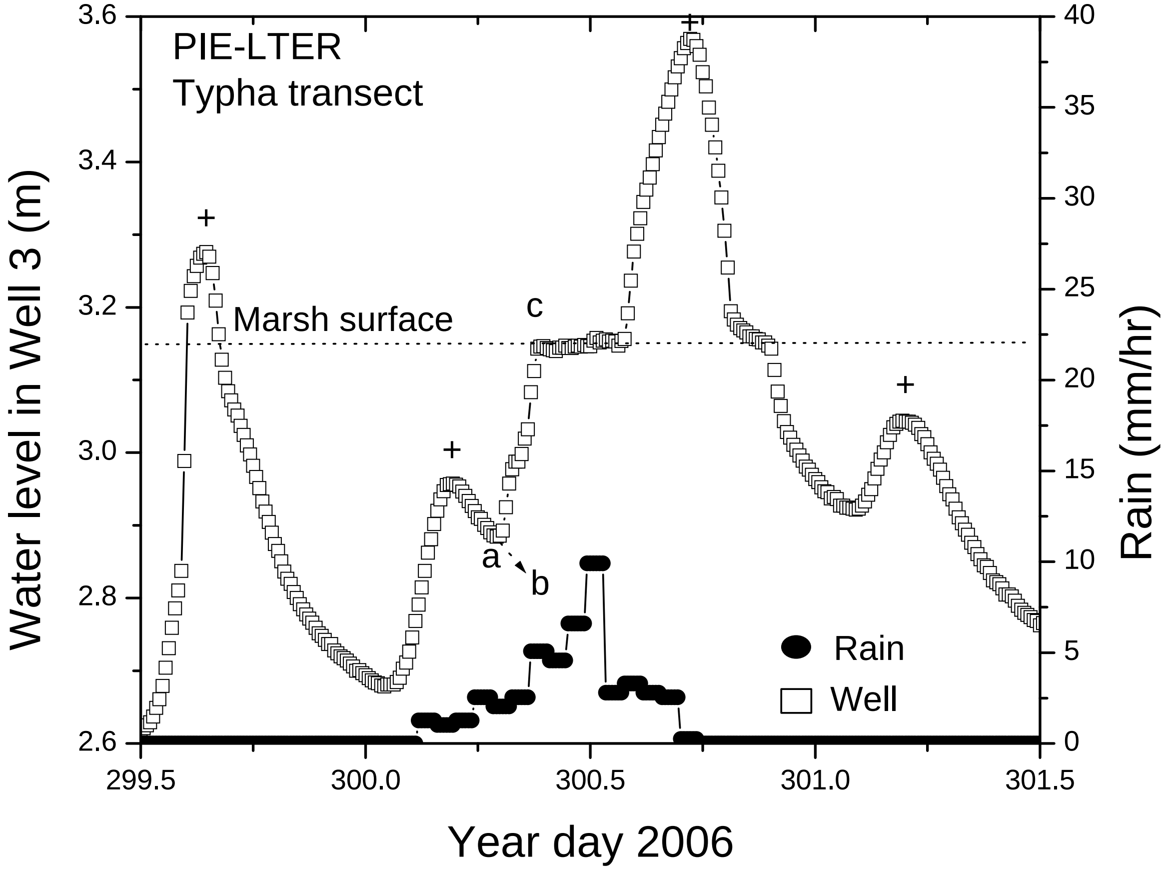
3. Time series of water levels in Typha Well 3 showing a water level response to a rain event starting at point “a” . Plus signs mark water-level peaks due to tides.

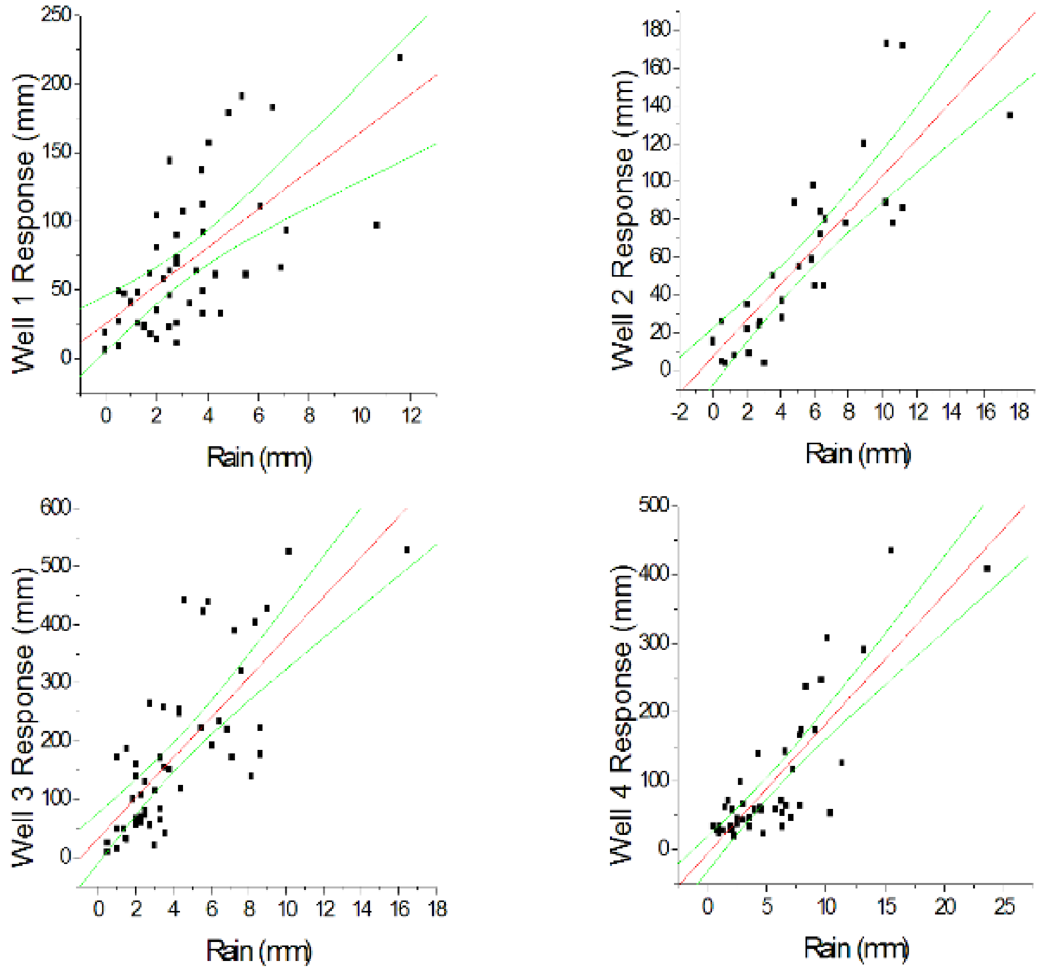
4. Scatter diagrams showing water level responses to rain events in Typha Wells 1 to 4 with regression lines and 95 percent confidence limits.



(42° 48" N)
(42° 39" N)
(70° 56" W)
(70° 43" W)
Massachusetts
Little River
Typha
Logger Site
Parker
River
Rain Gauge
Railroad
(Spartina) Site
Plum Island
Sound
Gulf of Maine
Rowley River
Ipswich River
Northing (m)
950000
945000
940000
935000
Easting (m)
250000
255000
260000


TG
1 2 3
4
5
Elevation (m)
PIE-LTER Spartina Transect
Distance from mid channel (m)
TG
1 2 3
4
5
Elevation (m)
PIE-LTER Typha Transect
Distance from mid channel (m)


PIE-LTER
Typha transect
Marsh surface
Rain
Well
a
b
c
Water level in Well 3 (m)
Rain (mm/hr)
Year day 2006
3.6
3.4
3.2
3.0
2.8
2.6
40
35
30
25
20
15
10
5
0
299.5
300.0
300.5
301.0
301.5


Well 1 Response (mm)
Rain (mm)
Well 2 Response (mm)
Rain (mm)
Well 3 Response (mm)
Rain (mm)
Well 4 Response (mm)
Rain (mm)