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Reading ③

CHARACTERIZING HYDROLOGY AND THE IMPORTANCE OF GROUND-WATER DISCHARGE IN NATURAL AND CONSTRUCTED WETLANDS

Randall J. Hunt, John F. Walker, and David P. Krabbenhoft
US Geological Survey—Water Resources Division
8505 Research Way
Middleton, Wisconsin, USA 53562
rjhunt@usgs.gov

Abstract: Although considered the most important component for the establishment and persistence of wetlands, hydrology has been hard to characterize and linkages between hydrology and other environmental conditions are often poorly understood. In this work, methods for characterizing a wetland's hydrology from hydrographs were developed, and the importance of ground water to the physical and geochemical conditions in the root zone was investigated Detailed sampling of nearly continuous hydrographs showed that sites with greater ground-water discharge had higher water tables and more stable hydrographs. Subsampling of the continuous hydrograph failed to characterize the sites correctly, even though the wetland complex is located in a strong regional ground-water-discharge area By comparing soil-moisture-potential measurements to the water-table hydrograph at one site, we noted that the amount of root-zone saturation was not necessarily driven by the water-table hydrograph but can be a result of other soil parameters (i e , soil texture and associated capillary fringe). Ground-water discharge was not a significant determinant of maximum or average temperatures in the root zone High ground-water discharge was associated with earliest date of thaw and shortest period of time that the root zone was frozen, however Finally, the direction and magnitude of shallow ground-water flow was found to affect the migration and importance of a geochemical species. Areas of higher ground-water discharge had less downward penetration of CO_2 generated in the root zone In contrast, biotically derived CO_2 was able to penetrate the deeper ground-water system in areas of ground-water recharge Although ground-water flows are difficult to characterize, understanding these components is critical to the success of wetland restoration and creation efforts

Key Words: hydrology, ground water, hydrogeology, Monte Carlo, temperature, geochemistry

INTRODUCTION

Wetland hydrology is widely recognized as the primary influence on wetland ecology, development, and persistence (Carter 1986, Erwin 1989, Mitsch and Gosselink 1993) and is essential to understanding and quantifying wetland functions and processes (e.g , Good et al. 1978, Greeson et al. 1979, Ivanov 1981). Hydrology has been linked to specific wetland type (e g , calcareous fens) and forms the basis of a recent wetland classification methodology (Brinson 1993). However, the linkages between water-budget components and their importance to the physical and chemical environment of the wetland root zone are not well known, due in large part to poor understanding of how ground water flows into and out of wetlands.

Ground-water flow has been shown to be a significant determinant for the physical and chemical environment of other aquatic systems (e.g , Hurley et al. 1985, Anderson and Bowser 1986). The amount of ions carried by ground water is typically much higher than surface water and can have a profound influence on the pH and nutrient status of the wetland (e.g , Hunt et al. 1997) In addition, water-level fluctuations associated with ground-water systems are generally smaller than surface-water or precipitation-dominated systems (Novitzki 1982, Zimmerman 1987). A few recent studies have characterized ground water and its relation to wetland plant communities and function (e g , Ray Benayas 1990, Ashworth 1997, Cole et al. 1997), but it is widely recognized that more work is needed (e g , Carter 1996).

Ground-water systems are difficult to characterize, thus, ground water is generally considered the most difficult component of the wetland water budget to quantify (Carter 1986, LaBaugh 1986, Mitsch and Gosselink 1993). Previous work on ground water in wetlands has often relied on methods used in aquifer-scale studies, such as widely spaced sample intervals and traditional aquifer tests (e g., slug tests). The use of these traditional methods has had limited success in elucidating the effect of ground water on the wetland physical and chemical hydrology. Recently, non-traditional investigations of wetlands have shown substantial complexity within a given wetland's hydrologic system. Harvey and Nuttle (1995) showed that macropores can significantly affect water and solute fluxes. Hunt et al. (1996) quantified ground-water discharge in an adjacent natural and constructed wetland system and found that ground-water-flow magnitude and direction varied spatially, even though the wetland complex was located in a regional ground-water-discharge area. Moreover, although ground-water fluctuations are considered to be less variable than other systems, spatial (e g , Hite and Cheng 1996, Hunt et al. 1997) and transient (e.g , Siegel et al. 1998) considerations can have a marked effect on the wetland porewaters. While problems associated with ignoring the ground-water term are well known (e g., Winter 1981), wetland hydrologists have had difficulty developing methods to characterize ground-water data, as well as demonstrating that ground-water flow is important to physical and chemical conditions that occur in the root zone. Thus, it is not surprising that many relationships between wetland plant communities and hydrology are not well understood.

This paper addresses two primary topics: 1) how hydrograph data can be used to characterize a wetland's hydrology and 2) the effect ground-water flow has on the environmental conditions experienced by a plant in that wetland. To address the first issue, we examine how a wetland's hydrology can be characterized using commonly collected water-table data and then formulate representative statistics that encompass the magnitude of fluctuation and duration of root zone inundation. Secondly, we tie this information to factors important to the wetland plant community by demonstrating that ground-water flow has profound effects on the physical and chemical environment of the root zone. While detailed discussion of the response of wetland vegetation to these changes in environment is beyond the scope of this paper, the work reported here elucidates some of the factors that connect hydrology to wetland plant establishment and persistence. Moreover, it shows scientific basis for the statement that "hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes" (Mitsch and Gosselink 1993). This work is unique in that it focuses on a gradient of ground-water-discharge regimes in one site area that includes both an adjacent natural and constructed wetland system. For clarity, ground-water discharge is defined here as flow *from* the ground-water system *to* the wetland root zone. In contrast, ground-water recharge is defined here as flow to the ground-water system from the wetland root zone.

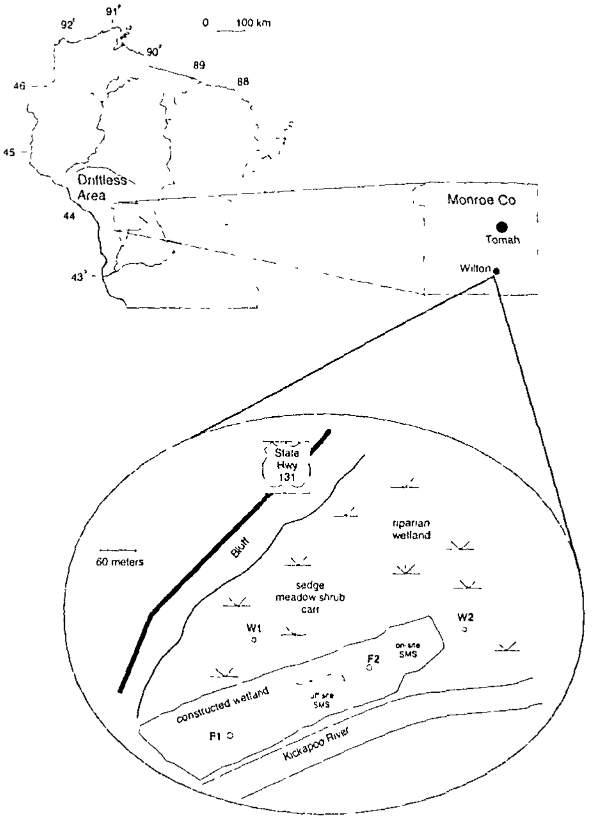


Figure 1 Schematic site map showing the locations of the two instrumented sites in the natural wetland (W1 and W2) encompassing the two vegetation types and two sites in the constructed wetland (F1 and F2) located in areas of on-site and off-site salvaged marsh surface (SMS) application.

SITE DESCRIPTION

The Wilton wetland complex is located along the Kickapoo River in Monroe County, in the unglaciated region of southwestern Wisconsin, USA (Figure 1). Hughes et al. (1981) describe the Kickapoo River basin as having steep slopes (30 to 40 percent), rounded ridges, and steep narrow valleys. Geology of the site consists of thin (< 5 m) fluvial/lacustrine sediments in the river bottoms; these sediments were derived from the Cambrian and Ordovician bedrock and overlie sandstone bedrock of Cambrian age. Adjacent bluffs are comprised of Cambrian sandstone capped by Ordovician [illegible] Natural wetlands within the floodplain have thin accumulations of peat (ranging from 0.1 to 1 m) overlying fluvial deposits. The peat contains varying amounts of silt, influenced by agricultural practices in the adjacent highlands.

The natural wetlands consist of one hectare of natural shrub-carr/sedge meadow dominated by *Carex* spp. (predominantly *Carex tricocarpa* Muhl. and *Carex stricta* Lam.) and *Alnus rugosa* (Du Roi) Spreng, and 7.5 hectares of riparian wetland dominated by *Alnus rugosa, Ulmus americana* L., and *Fraxinus nigra* Marsh. During the summer of 1991, 3.8 hectares of an adjoining upland agricultural field were excavated as part of a project to mitigate wetland loss associated with an adjacent road project (Figure 1). The field was excavated to depths of two meters based on pre-construction water levels from 72 wells in the field and in the natural wetland. Salvaged marsh surface (SMS) from the destroyed wetland (0.4 hectare) was applied over the constructed wetland Additional SMS was obtained from an off-site wetland to complete the project. Embedded within the constructed wetland site are twenty-two 15.2-m × 15.2-m experimental plots where hydrologic and vegetational parameters were varied. As a result of the geomorphic setting, surface-water inflow and outflow are minimal components of the water budget for both the natural or constructed wetlands.

The physical hydrogeology of the Wilton wetland was previously investigated with an intensive network of nested wells that were monitored for eight years, continuous water-level monitoring, areal two-dimensional analytic element-flow modeling (Hunt 1992), three-dimensional ground-water-flow modeling (Brown 1996), stable isotope mass balance, temperature-profile modeling, and numerical water-balance modeling (Hunt et al 1996). This work has shown that the site lies within a regional ground-water-discharge area and is characterized by strong upward gradients (average 0.1 m/m and locally >0.2 m/m). The magnitude of ground-water discharge varies spatially but generally is characterized by increasing ground-water discharge near the Kickapoo River (Hunt et al. 1996).

FIELD AND LABORATORY METHODS

Two sites were instrumented in the natural wetland (W1 and W2) and two in the constructed wetlands (F1 and F2, Figure 1). W1 and W2 were selected to typify the two dominant wetland vegetation communities (shrub-carr/sedge meadow and riparian wetland), F1 and F2 were selected to include areas of both on-site and off-site SMS. The equipment consisted of 1) a well nest containing a water-table well and a deeper piezometer, 2) [illegible] installed at different depths in the soil column, 3) a cylindrical gypsum soil moisture block installed within the root zone, and 4) seven sampling points spaced at 0 15-m intervals below land surface to a total depth of 1 07 meters. The vertical profiles at each site spanned the mineral soil/hydric soil interface (approximately 1 m in the natural wetland and 0.15 m in the constructed wetland).

Water-table wells consisting of 3 8- or 5 1-cm-diameter PVC pipe with a 1-m screened interval were installed using a hand auger and placed so that the screen intersected the water table Deep piezometers consisted of 3.2-cm-diameter galvanized steel pipe with a 0.7-m stainless steel drive point at W1 and W2, a mini-piezometer (Lee and Cherry 1978) at F1, and a 3.8-cm-diameter PVC well with 1-m-long screened interval at F2. The PVC well at F2 was installed one meter below the fluvial sediment/Cambrian sandstone interface using mud rotary methods, all others were hand-driven to bedrock refusal (approximately 3 to 5 meters below land surface) Water-level measurements from the shallow and deep ground-water system were made at the sites using capacitance probes and potentiometers with data loggers and by hand with a steel tape. Datalogger measurements were taken daily during the non-growing season and hourly during the growing season; hourly data are considered "continuous" for the purposes of this study.

Porewater temperature was also monitored at the sites from 1992 through 1996 The data set contains over 100,000 data points that were collected hourly during the growing season and at least daily during the remainder of the year. A galvanized steel pipe was filled with water and allowed to equilibrate thermally with the ambient ground water The temperature profile within the pipe was measured at various depths using stationary thermocouples and a digital data logger.

Soil moisture data were collected using a gypsum cylindrical soil-moisture block installed in the wetland root zone (15 cm below ground surface). The ability of a gypsum block to conduct electricity is a function of the degree of wetness, thus, a coarse estimate of soil moisture can be obtained by measuring the voltage drop across the soil-moisture block The soil-moisture block was read hourly using the digital data logger, and a 5th order polynomial fit was applied to convert voltage differences to soil-moisture potential (Campbell Scientific 1990). The measurements are somewhat imprecise due to variations in soil type and wire length. Because the blocks were not calibrated to the peat soils investigated at the site, the measurements are expected to be reliable to only ±1 bar.

The vertical sampling points used for porewater sampling consisted of mini-piezometers and ceramic cup suction lysimeters. Samples were collected along a subsurface vertical profile extending from 15 to 107 cm below land surface at 15 cm intervals. This sampling scale was deemed appropriate based on the distribution of temporal and spatial chemical heterogeneity and the importance of sampling scale at this wetland complex reported elsewhere (Hunt et al. 1997). Samples were collected using a peristaltic pump or a hand-pump and were filtered in the field. Samples for alkalinity, dissolved inorganic carbon, and pH analyses were collected in October 1992 and measured in the laboratory using standard methods (APHA, 1995). Samples for Ca and Mg analyses were collected in September 1992 and analyzed using inductively coupled plasma (ICP) emission spectroscopy. Dissolved inorganic carbon was analyzed in the laboratory using an O.I. Model 700 TOC Analyzer. Partial pressures of carbon dioxide (PCO_2) in porewater were calculated from pH, alkalinity, and dissolved inorganic carbon data.

CHARACTERIZING HYDROLOGY

To facilitate comparisons between the four sites in the following discussion, it is useful to rank them by magnitude of ground-water-recharge or discharge. Hunt et al. (1996) measured inflow at the site using multiple techniques and concluded that stable isotope mass balance techniques were most accurate if the underlying assumptions were met (i e., the system is at isotopic and hydrologic steady-state and porewaters within the root zone are well mixed). Using these results, the sites were ranked as follows: F1 = no ground-water discharge, W1 = weak ground-water discharge, F2 = intermediate ground-water discharge, and W2 = strong ground-water discharge.

Investigating the Hydrograph

Physical hydrology of a wetland is often investigated by collecting water level data and formulating hydrographs. When continuous water-level data are collected, the extremely large data sets can make the task of summarizing formidable, but when periodic measurements are made, their ability to represent the temporal variations is questionable Others have tried to obtain hydrologic insight from hydrographs (e g , Cole et al 1997), with mixed success. In this work, we analyzed the hydrographs to formulate representative "hydroperiod statistics" that encompass magnitude of water-level fluctuation and duration of inundation of the root zone—the important characteristics of the hydrograph. In addition, the continuous data set was sampled at different intervals to assess the minimum data density needed to characterize the wetland hydrograph properly. These results were then combined with the independent estimates of ground-water discharge reported by Hunt et al. (1996) to determine the effects of ground water on the water-table hydrograph.

Continuous water-level data were collected from two sites in the natural wetlands (W1 and W2 in Figure 1), and two sites in the constructed wetland (F1 and F2 in Figure 1) during the 1996 growing season (Figure 2) The challenge in assessing the hydroperiod for a particular site is to determine an appropriate statistic or set of statistics to characterize the temporal variability of the hydrograph. In addition to the usual parametric and non-parametric measures of location (mean, median) and scale (standard deviation, interquartile range), we attempted to use harmonic analysis as described elsewhere (e.g , Long and Nestler 1996; Nuttle 1997). However, the hydrographs did not show statistically significant periodic components over the single growing season, perhaps due to the erratic nature of the hydrographs over shorter time scales (i.e., hourly and daily scales compared to monthly and annual scales). We then calculated the amount of time that the root zone is saturated. We estimated a "root-zone probability," which we defined as the proportion of measurements where the water level was at or above the depth of the root zone (taken as 30 cm below land surface). The selected statistics, computed for hourly measurements over the growing season (ice-out in late April through the end of September) were then summarized for the four sites (Table 1).

Hydroperiod characteristics were expected to have more uncertainty when water-level measurements were taken less frequently than hourly. To assess this uncertainty, we used a Monte Carlo experiment to subsample the hourly time series at several less frequent intervals, with an average period between measurements ranging from one to 28 days For each sampling interval, a variability about the interval was specified to simulate real world conditions—for example, accounting for field personnel making periodic measurements near but not exactly equal to the interval specified. The sampling interval variability ranged from a standard deviation of 6 hours for the daily measurements to a standard deviation of 1 week for the measurements every 28 days For each sampling interval, random data sets for the growing season were drawn from the hourly measurements and used to compute the five selected hydroperiod statistics (mean, standard deviation, median, inter-quartile range, and root-zone probability). For each hydroperiod statistic a random data set was compared to the values computed for the hourly data ('true' values in Table 1) to determine the error based on the random sample The number of random data sets to be drawn was determined by varying the number of realizations from 50 to 50,000 for site

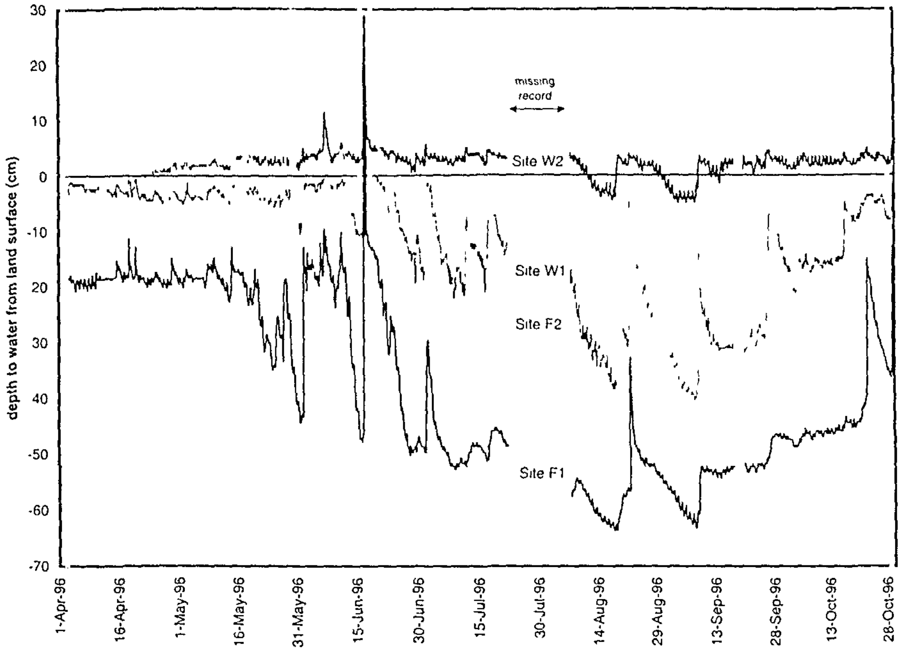


Figure 2. Water-table hydrographs for the instrumented sites for the period April through October 1996.

F1; at 5,000 realizations, the bias and root-mean-squared errors leveled off and became stable. An overall root-mean-squared error for each hydroperiod statistic was determined for the 5,000 realizations and is presented for each measurement interval (Table 2). In general, errors can be represented by two components: accuracy, represented by the measurement bias, and precision, represented by the measurement variability. We chose to use root-mean-squared error because it is a measure that incorporates both bias and variability and is an overall indicator of measurement uncertainty.

To put the results into perspective, we considered the uncertainty of the water-level measurements. The continuous water-level recorders used to obtain the hourly measurements are considered to have an error of roughly 0.009 m (95% confidence interval), which translates to an error standard deviation of 0.5 cm. Thus, to obtain results with comparable uncertainty at site F1 would require measurements roughly every 1 day for the mean water level (RMSE=0.46 cm in Table 2) or roughly every 2 days to characterize the standard deviation (RMSE=0.49 cm in Table 2). To characterize root-zone probability with an average error root-mean-squared error of roughly 20% would require weekly measurements at a minimum.

In addition to the water-table analyses, we also investigated the uncertainty of vertical gradients at one site in the natural wetland (W1 in Figure 1) for various measurement intervals. As with the uncertainty analysis for the hydroperiod statistics, we used a Monte Carlo experiment to subsample the hourly time series (shown in Figure 3) at several less frequent intervals. The average measurement intervals and the variability about those intervals were the same as those used previously. At this site, continuous records of the water table and deep piezometer (3.6 m below grade) were obtained for the 1996 growing season. Based on assumed measurement errors for the two recording de-

Table 1. True values for various hydroperiod statistics based on hourly water-level measurements using data from the 1996 hydrographs. Negative numbers represent depth below land surface.

Site	Median (cm)	Mean (cm)	Interquartile range (cm)	Standard deviation (cm)	Root-zone probability
F1	−44	−37	34	17	0.42
W1	−9.9	−14	22	12	0.84
F2	−7.9	−13	26	14	0.85
W2	2.5	2.2	1.8	2.5	1.00

Table 2. Root-mean-squared errors (RMSE) for the four sites determined by comparing samples generated with specified measurement intervals to the true values shown in Table 1

Measurement interval (days)	RMSE Median (cm)	RMSE Mean (cm)	RMSE Interquartile range (cm)	RMSE Standard deviation (cm)	RMSE Root-zone probability
			Site F1		
1	1.6	0.46	0.29	0.31	0.16
2	2.2	0.78	0.42	0.49	0.23
4	3	1.2	0.68	0.73	0.18
7	3.7	1.7	1.7	1.1	0.19
14	5.4	2.5	5.0	1.7	0.27
21	6.7	2.7	5.7	2.2	0.27
28	7.7	3.6	7.7	2.8	0.29
			Site W1		
1	0.64	0.29	1.1	0.15	0.011
2	1.1	0.52	1.5	0.25	0.016
4	1.7	0.69	2.5	0.41	0.025
7	2.4	0.97	4.1	0.67	0.038
14	3.3	1.6	5.6	1.4	0.13
21	4.4	1.8	5.6	1.6	0.18
28	4.8	2.3	6.4	2.2	0.17
			Site F2		
1	2.7	0.41	0.70	0.16	0.016
2	4.2	0.69	1.1	0.26	0.017
4	5.8	1.1	1.4	0.45	0.027
7	7.7	1.5	1.8	0.69	0.037
14	9.4	2.4	3.1	1.4	0.098
21	9.4	2.7	4.1	1.7	0.14
28	9.5	3.2	5.3	2.4	0.17
			Site W2		
1	0.019	0.076	0.30	0.22	0.00
2	0.098	0.12	0.33	0.35	0.00
4	0.21	0.21	0.37	0.52	0.00
7	0.31	0.29	0.43	0.63	0.00
14	0.39	0.52	0.59	0.94	0.00
21	0.43	0.64	0.87	1.2	0.00
28	0.48	0.76	1.2	1.3	0.00

vices (95% confidence intervals of 0.006 and 0.009 m for the deep and shallow wells, respectively), a 95% confidence interval for an indeterminate gradient measurement was calculated. For a particular measurement, an upward gradient was assumed if the gradient exceeded the upper level of the confidence interval, if the gradient was less than the lower limit of the confidence interval, a downward gradient was assumed. The number of measurements with upward gradients divided by the total number of measurements constituted an estimate of the probability of an upward gradient. For each measurement interval, random data sets were drawn from the hourly measurements and used to compute the upward-gradient probability. This probability was then compared to the value computed for the hourly data to determine the error based on each random sample. As with the Monte Carlo experiment for the hydroperiod statistics, the number of realizations was varied from 50 to 50,000, at 10,000 realizations, the bias and root-mean-squared error for the upward-gradient probability became stable. Using the continuous data set, the true values of percent time of vertical gradient direction were 66% upward gradient, 16% downward gradient, and 18% indeterminate for the W1 hydrograph shown in Figure 3. The overall root-mean-squared error (RMSE) was determined for the upward-gradient probability and each measurement interval (Table 3).

The RMSE in upward-gradient probability is less than 2 percent for a daily measurement interval and increases somewhat slowly to a value of 17% for measurements every 28 days. This can be thought of as

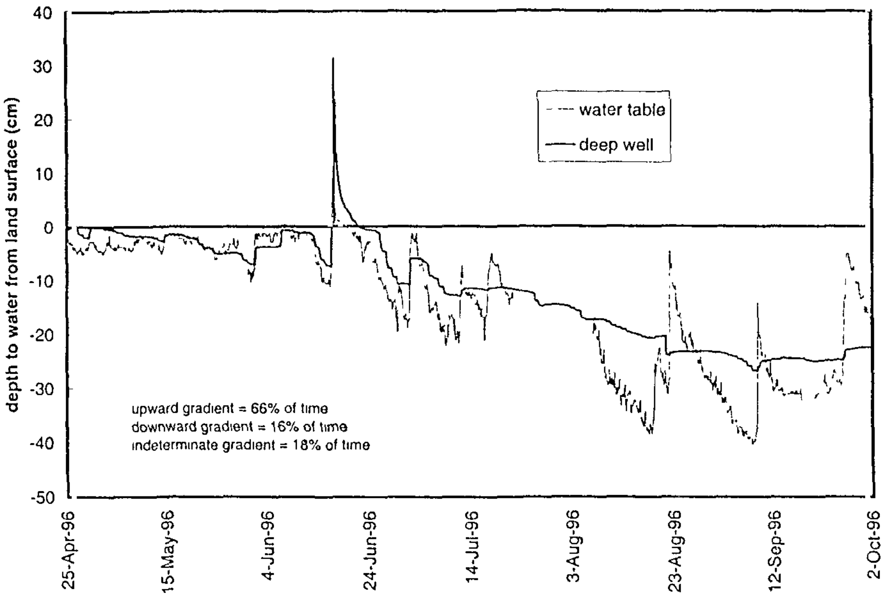


Figure 3. Hydrograph of water-table well and deep (3.8 m below ground surface) piezometer for site W1 in the natural wetland during the 1996 growing season.

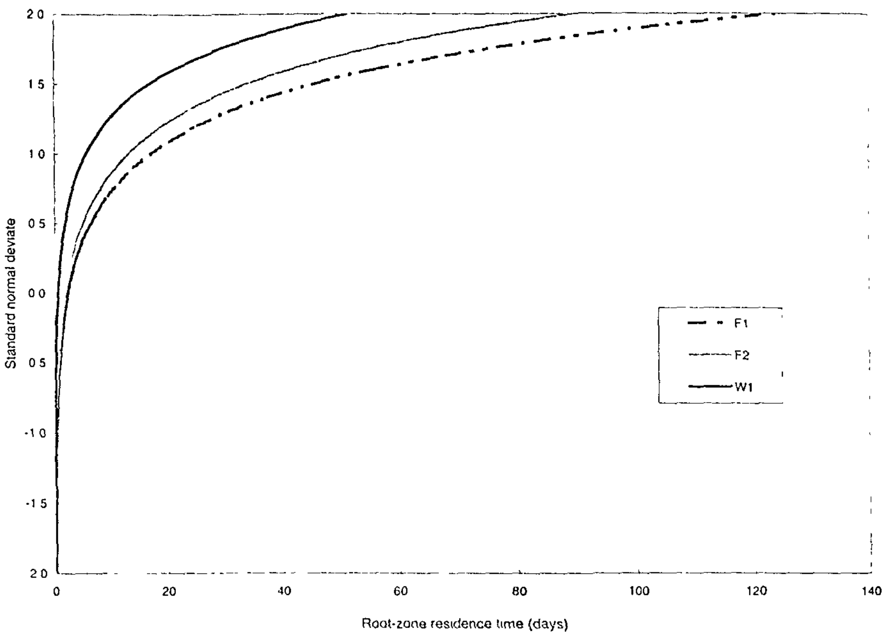
the uncertainty around the true value of 66% of the period of record that upward gradients were measured. If a root-mean-squared error somewhere between 5 and 10% was deemed acceptable, then measurements would be needed every 4 to 7 days. This is somewhat less frequent than is required to characterize the water-table hydrograph, due in part to the small degree of variation in the deeper piezometer resulting from the larger ground-water source and in part to the lumping of data into categories (upward, downward, and indeterminate) rather than estimating gradient magnitude. It is interesting to note that in previous work at the site by Hunt et al. (1998) a bi-weekly sampling interval of vertical gradients at sites F1 and W1 was not sufficient to identify the importance of transient vertical gradient reversals elucidated by stable isotopes of water.

Table 3. Root-mean-squared errors for upward-gradient probability at site W1 based on average water-level-measurement intervals. The root-zone probability based on hourly measurements is 0.655.

Measurement interval (days)	RMSE in Upward-gradient probability
1	0.018
2	0.031
4	0.051
7	0.077
14	0.116
21	0.143
28	0.172

Characterizing the Root-Zone Residence Time

Although the root-zone probability was originally intended to represent the residence time, the manner in which it is computed precludes it as a reasonable measure of actual residence time. Simply determining the proportion of time water is in the root zone ignores the small-scale temporal fluctuations in water levels, which could have a significant effect on the conditions present in the wetland. That is, a system where the water table moves into the root zone every other day (50% root-zone probability) will likely differ from one with the water table in the root zone only during the first half of the growing season (also 50% probability). As an alternative, we analyzed each hydrograph to determine the actual contiguous periods of time where the water level was at or above the root zone (taken to be 30 cm below the land surface). This results in a series of residence times that were assumed to come from a single population for each site. Thus, the root-zone residence-time distributed by the number of contiguous days is another means that can be used to compare wetland hydrographs. This measure is more consistent with the characteristic hydrologic thresholds discussed by the National Research Council (1995, p. 94) Using the hourly water-level measurements, the individual residence times were determined for each



[illegible] -zone inundation for the 1996 hydrographs. Site W2 could not be plotted because the water-table level never left the root zone during the entire 1996 growing season

of the four sites. Several distributional forms were considered, but the lognormal distribution fit the data the best. Continuous lognormal distributions were fit to the residence times for sites F1, F2, and W1 and are depicted as a standardized normal probability plot in Figure 4. In this figure, the standard normal deviate is a transformation that converts cumulative probability to a linear scale for the normal distribution, the values of −2, −1, 0, 1, and 2 correspond roughly to cumulative probabilities of 2.3%, 15.9%, 50%, 84.1%, and 97.7%, respectively. For the lognormal distribution, plotting the log of the residence time would result in a straight line; a linear axis was chosen because it showed a better separation of the curves. For site W2, there was only one residence time, corresponding to the length of the growing season. Hence, it was not possible to fit the lognormal distribution to these data. The distribution for the natural wetland (W1) differs considerably from the other two sites. In the natural wetland, there are much more frequent inundation periods of shorter duration, as indicated by the initial steepness of the distribution The two constructed wetland sites have much heavier tails, indicating that there is one episode (which occurs at the beginning of the growing season) of rather long duration. It is interesting to note that, although sites W1 and F2 have similar overall root-zone probabilities (0 84 and 0 85, respectively; Table 1), the residence times have strikingly different distributions.

CHARACTERIZING THE IMPORTANCE OF GROUND-WATER DISCHARGE

Effect of Ground-Water Discharge on the Hydrograph

Ground-water flows are only one portion of the wetland water budget and associated hydrograph. The hydrograph is also influenced by the amounts of other water added (precipitation), water subtracted (evapotranspiration), and the ability of the sediments to store water (i.e , the specific yield). In order to assess the importance of ground-water discharge to the measured hydrographs, a brief discussion of the other factors is needed.

Precipitation is assumed to be uniformly distributed over the site. Evapotranspiration (ET) rates are not uniformly distributed but are larger in the natural wetland (Lott 1997). In addition, Lott reports that specific yield values for the upper sediments in the natural wetland sites are roughly twice those measured in the constructed wetland (0.132 and 0 062, respectively). Although more subtle in effect, specific yields are an important consideration because they relate the soil zone's ability to store water to changes in water levels. For example, an undecomposed peat with high porosity will also have a high specific yield Thus, for a given ground-water discharge, the associated change in water level will be less than in a soil with a lower specific yield.

The effects of higher values of ET and specific yield on water levels in the natural wetland sites will offset one another to some extent but confound simple relationships between ground-water discharge and water-table variation. This fact notwithstanding, the site with no ground-water discharge (F1) has the lowest average and median water tables (deepest depth to water); the site with the highest ground-water discharge (W2) has the highest water table (Table 1). Likewise, site F1 has the highest variability in the water levels (inter-quartile range or standard deviation), and W2 has the lowest variability. The root-zone probabilities (Table 1) follow a similar trend. These results point to an interesting observation—ground-water discharge can influence root-zone saturation even though ground water may not be found in the root zone itself; that is, large ground-water discharge can be thought of as a "foundation" on which the precipitation-derived water is added.

The difference between the intermediary sites (W1 and F2) is less pronounced than the extreme sites (Table 1). We believe that the effect of higher ground-water discharge at the constructed wetland site F2 is offset by a lower specific yield value typical of the constructed wetland. It has a higher standard deviation than a site with a higher specific yield because a given stress cannot be significantly mitigated by soil-zone storage but is manifested in a change in water level. As a result, F2 has a flashy hydrograph (Figure 2) and a relatively large standard deviation for a site with significant ground-water discharge (Table 1). A notable finding of this analysis is that a low ground-water-discharge site with high specific yield can have a standard deviation similar to the high ground-water-discharge site with low specific yield. The effects of different specific yields are also likely present in the extremes of the measured standard deviation (F1 and W2; Table 1) and add to the effects of the different rates of ground-water discharge.

The concept of specific yield is important to the realization of in-kind mitigation. That is, can a wetland created on mineral soil be expected to have the same specific yield (thus hydrologic response to water additions and subtractions) as the natural wetland it was meant to replace? The results of this work indicate that it did not because the soil properties were significantly different. Restored wetlands may also fail to match natural wetlands in hydrology where the organic soil has been significantly altered by oxidation or decomposition. Thus, emphasis should move from a focus on hydrology to a more holistic consideration of physical conditions (e.g., sediment type and density) so the appropriate hydrology and vegetation can follow.

Relation of the Hydrograph to Root-Zone Saturation

The level where water resides in a well screened across the interface between the saturated and unsaturated zones is equal to the location where the pressure head equals zero (Freeze and Cherry 1979). The capillary fringe (or "tension saturated zone") is defined as a zone above the water table where all pore space is saturated but the pressure head is less than atmospheric. Water in the capillary fringe is held in the pore by negative pressure (or tension) that is a function of pore size and the surface tension of the water. The capillary fringe can extend meters above the water table in fine sediments (e.g., clay, decomposed peat) and can be less than one centimeter thick in coarser sediments (coarse sand and gravel).

Price (1997) noted a poor correlation between water-table depth and soil moisture in a Canadian bog late in the growing season, yet most wetland hydrologic characterization focuses on water-table data rather than capillary fringe data because of the ease of collection. A wetland plant, however, is influenced by local saturation of pore spaces in the area immediately adjacent to roots—whether the moisture comes into the root zone from water-table inundation or from a capillary fringe above the water table. Therefore, the presence of the capillary fringe can be a critical measurement in areas where the water table is below land surface. In this study, soil-moisture potential in the root zone (15 cm below ground surface) was measured and compared to the water-table hydrograph from late in the growing season (August to October). This is a period when the water table is most often below the root zone (Figure 2).

The soils appear to be saturated or nearly saturated at W1, as demonstrated by the low soil-moisture potential (<1.0 bars) observed in the root zone by the soil moisture block (Figure 5). For reference, soil-moisture potentials were observed to range from 1 to 17 bars in drier soils at the Wilton site. It is important to note, however, that the accuracy of the soil-moisture potential given by the uncalibrated gypsum block is not sufficient to resolve small changes in saturation at the wet end of the spectrum. The actual degree of saturation is therefore uncertain. This fact notwithstanding, the pattern of the response is indicative of what might be expected from a soil under capillary saturation. The sensor was generally unresponsive during periods of declining water table when the soil-moisture potential would be expected to rise in an unsaturated soil. Furthermore, this site was almost continually wet at the surface—boot footprints would fill with water—even during the height of the growing season. In addition, soils at the site are a mixture of peat, muck, and silty mineral soil that can be expected to have a

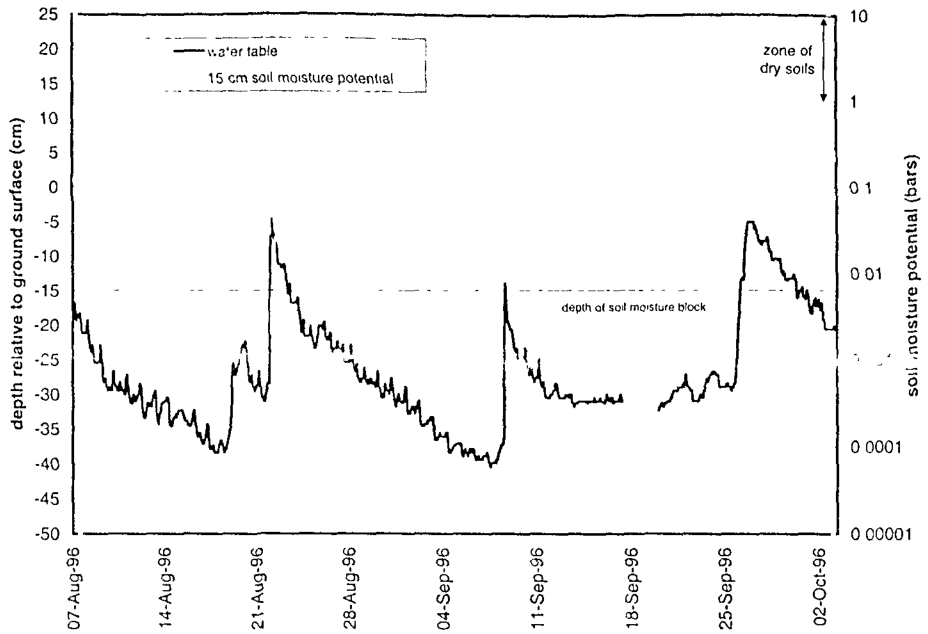


Figure 5. Soil-moisture potential and water-table hydrograph for the late 1996 growing season. The only deviations from baseline saturated conditions occur when the water table rises into the root zone where the soil moisture probe is located.

relatively high capillary fringe. From this we conclude that the capillary fringe was continuously present in the root zone.

Hydrograph fluctuations have very little effect on soil-moisture potential measured in the root zone; only a slight deviation from the baseline is observed when the water table rises into the location where the soil moisture block was located (e.g., August 23, September 26, Figure 5). These small deviations represent the transition from a low soil-moisture potential due to a location within the capillary fringe to zero soil-moisture potential (pressure head >0) below the water table. The apparent small fluctuations in the soil-moisture-potential data were not directly related to evapotranspiration effects, as might be expected, but were due to daily temperature differences that affect the resistance of the wire leading from the data logger to the soil moisture block. As noted in the methods section, we do not believe that soil moisture blocks have sufficient accuracy to discern small changes in soil-moisture potential (i.e., 0.1 bars).

These results demonstrate that the localized hydrologic conditions a root experiences may not always be directly related to the water-table hydrograph. Rather, the root zone at W1 is more appropriately characterized as a fully saturated zone that is fed by the water table via capillary forces, with occasional invasion by the water table. The times when the water table drops are not necessarily times of less saturation in the root zone but can conceivable be times when the capillary fringe is "stretched." The local geochemical environment associated with fully saturated conditions is expected to prevail as long as the water-table drop does not overcome the capillary force's ability to translocate water from the water table to the root zone.

Effect of Ground-Water Discharge on Soil Temperature

Soil temperature can be an important environmental variable for seed germination and plant persistence (e.g., Gerritsen and Greening 1989) and is an important determinant in the rate at which infiltrating waters become anoxic (National Research Council 1995) because respiration rates double for each 10° C increase in temperature (Peters 1983). One might expect that areas receiving large ground-water discharges would have distinct thermal histories (growing season maximum, minimum, and average temperatures) because deep ground-water sources have relatively invariant temperatures (Lapham 1989). Surprisingly, ground-water discharge was not a significant control on average or maximum values obtained from the hourly temperatures measured during the 1993 growing season (Figure 6). Rather, the controlling feature appears to be the age of the wetland, sites in the newly constructed wetland (2 years post-construction) had consistently higher temperatures. We attribute this finding to differences in shading that resulted from the smaller/less dense vegetative cover present in the construct-

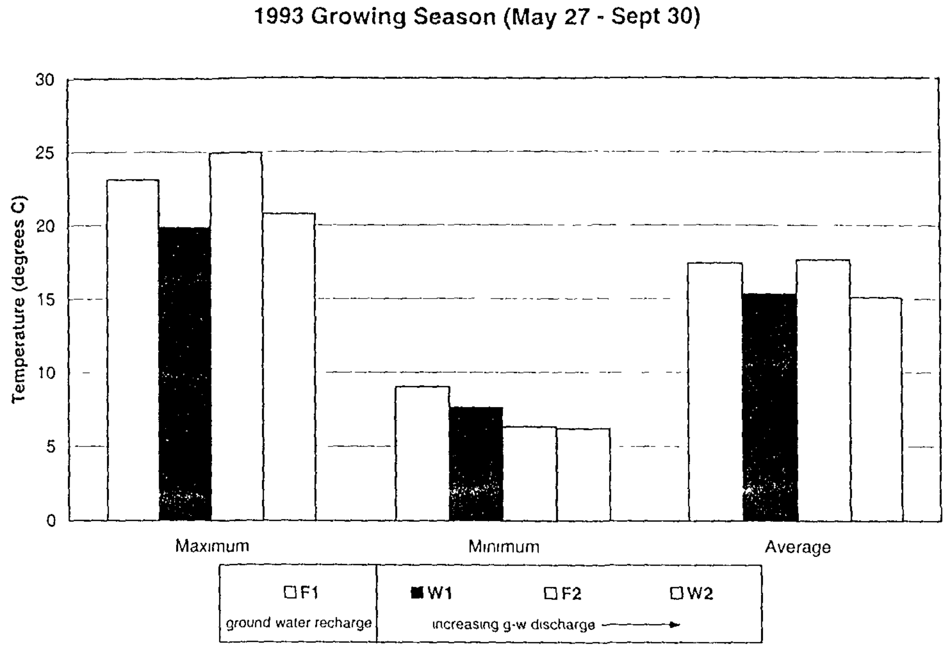


Figure 6. Maximum, minimum, and average temperatures for the 1993 growing season. Maximum and average temperatures are a result of the amount of shading from wetland vegetation, minimum temperatures are weakly correlated with amount of ground-water discharge.

ed wetland. Lott (1997) also notes greater vegetation height and density in the natural wetland in 1996—five years post-construction. In addition, the more dense, quartz-rich soils in the constructed wetland are better conductors of surface heat (Farouki, 1981). Less shading allows more solar radiation to warm the uppermost soil, which in turn can be more efficiently conducted by denser soils, these factors overwhelm the cooling associated with ground-water discharge. Minimum growing season temperatures, on the other hand, are weakly proportional to ground-water discharge (Figure 6) and may indicate that ground-water-discharge effects can be measurable if the solar radiation effects are relatively small.

Although general temperature statistics were not strongly correlated to the amount of ground-water discharge, the period during which the root zone is frozen was related to amount of ground-water discharge (Table 4). In the three sites with ground-water discharge, the amount of flow strongly influenced the date of freezing (i e., W1 was first to freeze, W2 was the last, Table 4). The site with low ground-water discharge (W1) was not only the first to freeze but also the last to thaw. As a result, the root zone and seeds contained therein were frozen longer at W1 than at the other sites. Site W2, on the other hand, was always the last to freeze, always thawed within 4 days of the same date, and usually had the shortest period that the root zone was frozen Site F2 was generally intermediate to these two extremes; the site always froze before W2 but occasionally thawed before W2 (Table 4) due presumably to the effects of reduced shading. Higher amounts of ground-water discharge also led to a more stable system from year to year (i.e , reduced variation in the length of time that the root zone was frozen) as evidenced by the standard deviation associated with the period of freezing.

The ground-water-recharge site (F1) had the most variation in the timing of freezing and thawing (standard deviation of 15.7 days, Table 4). This result is influenced by the variable depth to water (different distances to buffer the temperature changes at the air-soil interface) as well as lack of shading. For both the constructed wetland sites, the length of time that the root zone remains frozen increased post-construction due to the insulation by increased plant cover and litter accumulation This observation holds regardless of whether the site is in a zone of recharge or discharge. This phenomenon illustrates that constructed wetlands develop gradually and argues for a longer period of monitoring than five years The vegetation community is not likely to stabilize while the temperature regime in the root zone (as well as related penetration of sub-freezing temperatures and cold-stratification of the seed bank) is still changing Indeed, the longer and more variable period of freezing inherent to recharge

Table 4 Time of freezing and thawing for ground-water discharge and recharge sites, 1992 through 1996.

Ground-Water-Discharge Sites

	W1 (low ground-water discharge)			F2 (intermediate ground-water discharge)			W2 (high ground-water discharge)		
Year	Ice in	Ice out	Days frozen	Ice in	Ice out	Days frozen	Ice in	Ice out	Days frozen
1992–1993	27-Nov	23-Apr	147	15-Dec	21-Mar	96	23-Dec	7-Apr	105
1993–1994	27-Nov	24-Apr	148	21-Dec	7-Apr	107	22-Dec	11-Apr	110
1994–1995	MR	3-May		MR	12-Apr		MR	11-Apr	
1995–1996	13-Nov	19-Apr	158	9-Dec	3-Apr	116	26-Dec	10-Apr	106
		average	151			106			107
		standard deviation	7.1			6.4			2.8

Ground-Water-Recharge Site

	F1		
Year	Ice in	Ice out	Days frozen
1992–1993	MR	MR	
1993–1994	22-Dec	29-Mar	97
1994–1995	31-Dec	14-Apr	104
1995–1996	6-Dec	11-Apr	127
		average	109
		standard deviation	15.7

and low ground-water discharge may be an important forcing function for the vegetational community therein.

Effect of Ground-Water Discharge on Porewater Chemistry

The ability of CO_2 produced in the root zone to penetrate into the underlying peat column appears to be related to the direction and velocity of the ground-water flow (Figure 7), as well as the soil texture of the column. Regional ground water underlying the site has a PCO_2 ranging from −2.2 to −1.7 atm, apparently controlled by dolomite dissolution. At W1, where the plant community produces relatively large amounts of CO_2 and ground-water-discharge rates are relatively low, there is a relatively even distribution of soil-derived CO_2 throughout the upper 0.6 meters of the profile (Figure 7). At W2, a different PCO_2 profile is observed that we attribute to elevated ground-water-discharge rates that limit penetration of the CO_2 gradient. As a result, elevated root-derived CO_2 is restricted to the upper 0.3 m of the profile. The presence of relatively high PCO_2 levels affects the porewater microenvironment by enhancing dolomite dissolution and associated Ca+Mg concentrations (Hite and Cheng 1996).

At F2 [illegible] gradient decreases rapidly from the surface and is correlated to alkalinity and Ca+Mg concentration (Figure 7). Thus, we conclude that mineral soils in the constructed wetland and relatively high ground-water-discharge rates limit the penetration of CO_2 from the root zone. This analysis has been simplified in that it assumes the same rate of CO_2 production at the four sites and only qualitatively includes the soil texture differences between the natural and constructed wetlands. However, Hunt et al. (1997) also report CO_2 profiles measured in October 1994 that correlate well with the calculated PCO_2 profiles shown here, indicating that the relation holds over time.

The site of ground-water recharge (F1) provides an interesting contrast. At the sites with ground-water discharge (W1, W2, and F2), inorganically derived CO_2 from ground-water dissolution of carbonate aquifer minerals is a contributor to the PCO_2 profile (as evidenced by the close relation between alkalinity and Ca+Mg concentrations). At F1, on the other hand, there is very little inorganic CO_2, as demonstrated by low alkalinity levels. Moreover, the Ca+Mg profile does not correlate well with the alkalinity profile, indicating that dissolution of the source of Ca+Mg does not form large amounts of alkalinity and that these porewaters are relatively poorly buffered. These data indicate different source materials and controlling reactions than found at the other sites. Hunt et al. (1998) used Sr.Ca ratios to show that the solute source associated with the off-site peat at site F1 is different from the on-site sediments present at the other sites.

This difference in ancillary chemistry notwithstanding, the PCO_2 profile measured at F1 appears similar

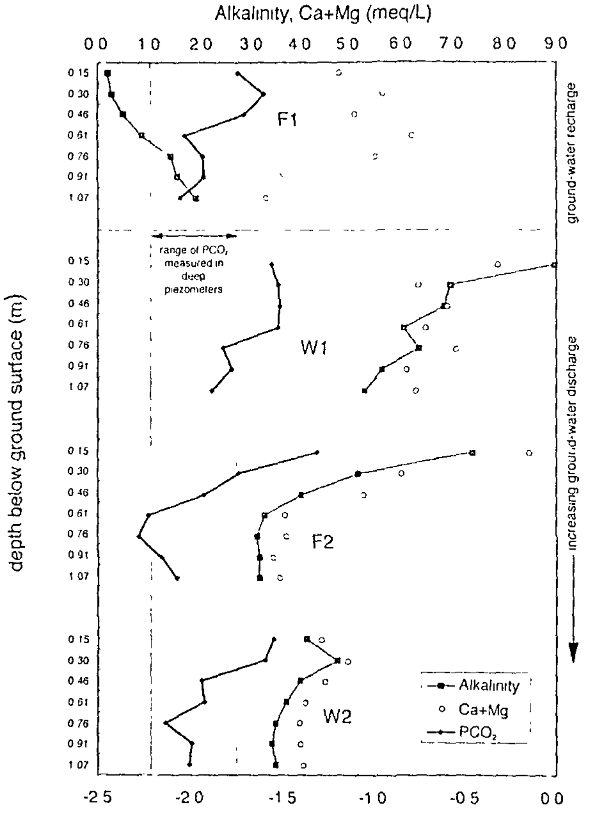


Figure 7. Vertical profiles of alkalinity, Ca+Mg, and PCO_2 for the four sites sampled in fall 1992. The range of PCO_2 measured in the deep ground-water system is also shown.

to the other natural wetland profiles measured on the [illegible] that organically derived CO_2 at site F1 penetrates significantly into the underlying sediments, facilitated by downward flow of ground water. These profiles demonstrate the importance of including data on hydrology (ground-water-flow rates and directions), ground-water chemistry, and the influence of near-surface processes (e.g., soil and root respiration) to infer the controlling factors of wetland biogeochemistry correctly.

IMPLICATIONS FOR WETLAND RESTORATION AND CREATION

The ability of a constructed wetland to replace the structure and function of another wetland is related to the ability to re-create the appropriate physical and chemical environment. Moreover, society's goal of mitigating wetland loss is predicated on the ability to characterize wetland hydrology by collecting appropriate data. These concerns not only exist in the design of the replacement wetland but in the characterization of wetlands prior to their destruction. We have shown that even in wetlands with relatively stable hydrographs (i.e., systems where ground water is an important contributor to the water budget), hourly measurements during the growing season are needed to characterize the hydrology properly (i.e., accurate estimates of mean, standard deviation of water levels, and root-zone probability were obtained). The error associated with longer measurement intervals can be variable on a site (as shown in this study) and can be expected to vary between wetlands. As self-contained, continuous water-level recorders become more affordable and robust, they become viable alternatives to hand measurements using 1-, 2-, or 4-day intervals. Continuous water-level records could be collected for one growing season and used to verify that a less-frequent sampling schedule is adequate. Because uncertainty in the water-table elevation will also affect vertical gradient measurements, continuous water-level monitoring is also required.

At the present time, most would agree that the understanding of wetland hydrology is not advanced enough to predict wetland hydrology and related hydrologic functions at the site scale (e.g., Bedford 1996, Zedler 1996). Indeed, Hunt et al. (1996) demonstrated that ground-water discharge can be variable at the site scale, even in a regional ground-water-discharge area. We have shown in this work how this variability has consequences on the ground-water system's interaction with vegetation (e.g., minimum temperatures and length of growing season), as well as how the vegetation interacts with the ground-water system (e.g., the propagation of root-derived PCO_2 into the underlying ground-water system). Furthermore, soil-moisture data demonstrate that, in some cases, the water-table hydrographs commonly measured in wetlands may poorly represent the root-zone saturation that wetland plants actually experience.

As a result of these deficiencies in understanding, the notion that planting plans can be designed based on predicted hydrology in the newly constructed wetland needs further thought. If hydrology is the most important determinant of wetland vegetation and our ability to predict hydrology is poor, detailed planting plans created prior to wetland construction projects are better thought of as optimistic and costly "throws of the dice." We propose that a more generalized, flexible, approach is warranted. This approach could include initial seeding of cover crops and native pioneer species with concurrent hydrologic investigation of the newly constructed wetland. After the hydrology of the site is characterized, a planting plan using the more expensive species can be developed and implemented. While this cannot guarantee the success of any given site, it does improve the chances that the designer will "reap what they sow."

CONCLUSIONS

Hydrology is considered the most important component for the establishment and persistence of wetlands, but elucidation of the relation between hydrology and other environmental conditions is limited. In this paper, the amount of ground-water discharge was shown to influence other environmental factors.

1. Physical hydrology. Detailed sampling of nearly continuous hydrographs showed that amount of ground-water discharge was correlated with high water tables in the natural and constructed wetlands. The sites with higher amounts of ground-water discharge also have less variability in their hydrographs. Although this wetland is located in a strong regional ground-water-discharge area, only continuous hydrographs could guarantee that all sites were correctly characterized. Different specific yields of the soils can also significantly influence the response of the water table to changing conditions. Thus, the variability within the hydrograph for a wetland can be controlled by low specific yield values (e.g , constructed wetland site F2), lower amounts of ground-water discharge (e.g., natural wetland site W1), or both (e.g , constructed wetland site F1).
2. Root-zone saturation. Root-zone saturation is not necessarily driven by the water-table hydrograph but can be influenced by other soil parameters (i.e , soil texture and associated capillary fringe). While likely not applicable to all wetland types (e g., wetlands established on sandy soils), it is a parameter commonly omitted in studies of wetland hydrology.
3. Root-zone temperatures. Ground-water discharge was not a significant factor in root-zone maximum or average temperatures because the effects of shading were dominant. High ground-water discharge resulted in the earliest date of thaw and shortest period of time that the root zone was frozen, however. Thus, cold stratification of the seed bank and length of the growing season are dependent on the amount of ground-water discharge for a given site
4. Porewater chemistry. The direction and magnitude of shallow ground-water flow can affect the migration and importance of geochemical species Areas of high ground-water discharge were found to reduce the downward penetration of CO_2 generated in the root zone. In areas of ground-water recharge, however, organically derived CO_2 was able to penetrate the deeper ground-water system. This allowed the formation of a root-derived CO_2 profile that closely resembled the PCO_2 profiles from sites where both abiotic and root-derived CO_2 were present.

These results demonstrate that quantifying ground-water flows is more than an academic concern for wetland restoration and creation. Although these flows are thought too difficult to characterize in common practice, this understanding, as well as the effects on physical conditions, is likely critical to the successful implementation of the sophisticated planting plans so prevalent in today's restoration and creation efforts.

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