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Modeling the hydrologic response of groundwater dominated wetlands to transient boundary conditions: Implications for wetland restoration

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Summary A variably-saturated groundwater model, based on that of Freeze [Freeze, R.A., 1971. Three-dimensional, transient, saturated–unsaturated flow in a groundwater basin. Water Resources Research 7, 347–366.], was used to analyze the details of surface–groundwater interaction and resulting hydroperiods of a site undergoing wetland restoration (the Lake Station Wetland Restoration Site in Northwest Indiana, USA). The three-dimensional groundwater flow model couples the saturated and unsaturated zones through the use of van Genuchten's [van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.] characteristic equations. Initial estimates of hydraulic parameters were refined through a calibration exercise aimed at minimizing the discrepancy between simulated and measured water levels in seven wells within the study. Numerical simulations using the calibrated model, and driven by annual time series of rainfall and potential evaporation, were used to generate hydroperiod maps of surface saturation and root-zone saturation over a three-year period of study. This allowed identification of regularly saturated areas that would support hydric plants, as well as more rarely saturated areas that would require more dry tolerant species or additional hydrological remediation. The simulations also revealed the critical roles that topography, rainfall history, and antecedent conditions play in the hydrology of degraded wetlands that have been targeted for restoration.

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Introduction

Wetlands, with their high biodiversity of flora and fauna, have been classified as some of the richest ecosystems on Earth. Unfortunately, many previously existing wetlands have been destroyed by hydrologic alteration, but an increasing appreciation of the benefits that wetlands have on the environment (see Sather and Smith, 1984 for a review) has resulted in policies being developed to protect and/or restore them. When a site is selected for restoration, it is not obvious what the acreage of restored wetland will be because destroyed wetlands are not easily returned to their previous condition. Past experience has shown that subtle variations in topography and other site characteristics can strongly condition what the new hydroperiods will be (Lewis, 2001). Hydrologic models provide a potentially useful tool in projecting what the hydroperiods will be in areas that have been targeted for wetland restoration.

The purpose of this paper is to demonstrate the feasibility of using a variably-saturated groundwater flow model to evaluate the hydrologic conditions (specifically hydroperiods) in a groundwater controlled wetland restoration site. The site that was selected for study had been monitored for several years so a large amount of hydrological data have been collected there. Also restoration of wetland conditions at the study site has not been completely successful, so hydrologic modeling of the site has implications for many other ditched and drained wetlands that are being targeted for restoration. A groundwater flow model was used to predict hydroperiods at the scale of a 15 m × 15 m grid. The model was calibrated using records of water level fluctuations from seven wells collected over a period of three years. The calibrated model was then used to study local flow systems and to elucidate spatio-temporal variations in the hydroperiods that had developed during the initial phase of the wetland restoration period.

Study site

The study site is known as the Lake Station Wetland Restoration Site (LSWRS) and is located in Lake County, Indiana, just southwest of the Indiana Dunes National Lakeshore (Fig. 1). The study area is part of the once extensive Great Marsh of Northwest Indiana that was ditched and drained to promote farming and other types of development during the late 19th and early 20th centuries. Shedlock et al. (1993, 1994) studied the hydrogeology of the Great Marsh region and showed that wetland surface waters were usually derived from local subsurface flow systems. The local flow regimes are recharged through the dune complexes and discharged by evapotranspiration and seepage into wetlands and streams. The soils of the LSWRS are characterized by a thin black muck organic layer overlying very poorly draining black and brown marl beds (Persinger, 1972). The LSWRS is bounded by a natural dune complex to the north and an artificial drainage ditch (Burns Ditch) to the south. The marl is approximately 2 m thick and is locally underlain by alluvial sand. The entire site is underlain by a thick and continuous layer of clay-rich glacial till that serves as a barrier to vertical flow. Restoration activities included removal of drainage tiles and installation of a water control structure to stop discharge through a tributary ditch that previously drained water from the LSWRS directly into Burns Ditch. Seepage continues along the boundary of Burns Ditch, which presents a problem to successful restoration.

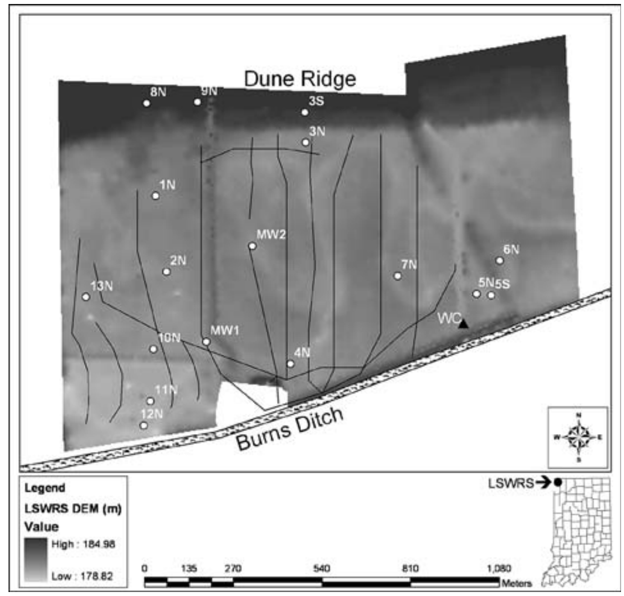

Figure 1 Map of the Lake Station Wetland Restoration Site in Northwest Indiana, USA. The 1 km^2 study area is bounded on the north by a dune ridge, and on the south by Burns ditch, the artificial channel of the Little Calumet River (discharge boundary). The drainage tiles (solid lines) were removed as part of the restoration effort, and a water control structure (WC) was installed to limit discharge from a ditch that previously drained the eastern portion of the site. The locations of monitoring wells are shown as white circles. The water levels at MW1 and MW2 were monitored continuously using electronic transducers and the other wells were hand measured every 2–4 weeks during the course of the investigation.

Groundwater model

A literature search concerning application of groundwater models to wetland hydrologic systems revealed that few papers have been published on this seemingly important topic. The papers that do exist have pointed to the significance of hydraulic conductivity in controlling the size and persistence of wetland complexes (Gilvear et al., 1993), the effects that even subtle topographic changes can have on the movement of water and the distribution of wetland cells (Reeve et al., 2001) and the critical role of unsaturated zone dynamics on recharge and water table fluctuations (Bradley and Gilvear, 2000). The current study adopts the philosophy of Winter (1978, 1983, 1999) that to fully model the dynamics of lakes (or wetlands in this instance) as coupled ground and surface water systems, due consideration must be given to the three-dimensional transient nature of the flow systems as well as the complexities of variably-saturated porous media and their response to infiltration and evapotranspiration.

The groundwater model that was applied to the LSWRS is based on that of Freeze (1971). The model treats the entire subsurface, both saturated and unsaturated, as a whole. The main simplifying assumptions are that saturated flow is laminar, and that inertial forces, velocity heads, temperature gradients, osmotic gradients, and chemical concentration gradients are negligible in the saturated zone. Moreover, in the unsaturated zone the soils are assumed to be non-swelling, and the air phase is always at external atmospheric pressure. The governing partial differential equation can be written as follows (cf. Freeze, 1971, p. 349):

$$\rho\left(\frac{\partial}{\partial x}\left[K(\Psi)\frac{\partial\Psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(\Psi)\frac{\partial\Psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K(\Psi)\left\{\frac{\partial\Psi}{\partial z}+1\right\}\right]\right) = \left[\frac{\rho\theta}{n}(\alpha+\beta n)+\rho C(\Psi)\right]\frac{\partial\Psi}{\partial t} \tag{1}$$

where x,y,z are the coordinate directions [cm]; t is the time [s]; Ψ is the pressure head (tension in unsaturated zone) [cm]; ρ is the density of water [g/cm^3]; α is the coefficient of vertical formation compressibility [cm^{-1}]; β is the coefficient of water compressibility [cm^{-1}]; n is the soil porosity [–]; θ is the volumetric soil moisture content [–]; $C(\Psi)$ is the pressure head dependent specific moisture capacity [cm^{-1}]; and $K(\Psi)$ is the pressure head dependent hydraulic conductivity [cm/s].

In shallow systems such as the one studied here, Eq. (1) can be further simplified because the compressibility of porous media and water are negligible (first term on the RHS = 0 and density cancels). However, the nonlinear parameters, hydraulic conductivity ($K(\Psi)$) and specific moisture capacity ($C(\Psi)$), are critical to variably-saturated flow and need to be explicitly incorporated into a wetland groundwater flow model. We used the parametric equations of van Genuchten (1980) to represent the characteristic curves of the unsaturated hydraulic parameters. These equations utilize the concept of effective saturation, defined by the relationship of actual moisture content to the saturated and residual values, and can be expressed as a function of the pressure head as follows:

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \left(\frac{1}{1+|\alpha\Psi|^n}\right)^m \tag{2}$$

where S_e is the effective saturation [–]; θ is the volumetric moisture content; θ_s is the saturated moisture content; θ_r is the residual moisture content; and m, n, and α are empirical fitting parameters.

$$K(\Psi) = K_s S_e^{1/2}[1-(1-S_e^{1/m})^m]^2 \tag{3}$$

where K_s is the saturated hydraulic conductivity [cm/s] and

$$C(\Psi) = \frac{\partial\theta}{\partial\Psi} = \frac{mn\alpha^n\cdot(\theta_s-\theta_r)\cdot|\Psi|^{n-1}}{[1+\alpha|\Psi|^n]^2}\left(\frac{1}{1+\alpha|\Psi|^n}\right)^{m-1} \tag{4}$$

which was derived by differentiation of Eq. (2).

The system of Eqs. (1)–(4) was solved numerically by discretizing the study area into finite cells with nodes at their centers. An implicit finite difference approximation based on that of Freeze (1971, p. 351) was used to solve the system equations subject to boundary conditions imposed on all sides of the solution domain. Input parameters included values of saturated hydraulic conductivity (K_s), saturated soil moisture content (θ_s), residual soil moisture content (θ_r), and empirical parameters α, m and n, which dictate the steepness and curvature of the van Genuchten functions. Uncertainty in modeling unsaturated flow comes from the difficulty of determining representative values of van Genuchten's parameters (Schaap et al., 2000). In this study parameterization was primarily accomplished by matching modeled calculations to observed data whenever possible.

Much of the site was surveyed with a laser transit before restoration was attempted. Monitoring wells and additional areas of the LSWRS were surveyed later. A total of 3465 points were used to develop a digital elevation model (DEM) for the LSWRS. A simple geologic model of the site was developed from the materials observed in 47 soil borings taken across the site and observations of exposures and geomorphic features along the site margins. The resulting model includes a basal layer of clay-rich glacial till that is overlain locally by thin lenses of alluvial sand. The alluvial sand and till are, in turn, overlain by layer of marl that averages 1.2 m in thickness and interfingers with dune sands along the northern boundary of the study site. The DEM was used to define the upper surface of the geologic model. A finite difference grid was superimposed on the geologic model. The three-dimensional grid consisted of 72 cells longitudinally, 102 cells laterally, and 32 cells vertically, resulting in a total of 235,008 cells. The horizontal dimensions of the grid cells were uniform (15 m × 15 m), but the vertical spacing was varied as follows: layers 1–16 along the bottom of the grid and layers 26–32 in the dune field had a vertical grid spacing of 0.28 m, while layers 17–25, which represent the majority of near surface cells across the LSWRS, were assigned a smaller vertical grid spacing of 0.14 m, in order to increase detail near the unsaturated–saturated zone interface in the marl.

Hydraulic parameters and boundary conditions

Aluminum access tubes for a neutron moisture gauge were installed at two of the monitoring stations (MW1 and MW2, Fig. 1) and vertical profiles of soil moisture were measured at these locations on 27 occasions between June 24, 1998 and April 4, 2000. Gypsum blocks were also installed at sites MW1 and MW2 to measure soil water tension. The gypsum blocks were installed in marl at depths of 15 cm and 50 cm at MW1 and MW2. The matched pairs of the volumetric moisture content and soil tension were used to calculate best-fitting moisture retention curve (Eq. (2)) parameters for the marl, but parameters for the alluvial sand, and eolian sand, had to be obtained from a look-up table in Schaap et al. (2000, p. 505)) because no field data were available to constrain the values used for those material types. The estimated retention curve parameters (Table 1) were assumed

Table 1 Estimated values of moisture retention curve parameters for materials at the study site

	θ_s	θ_r	α	m
Marl	0.475	0.080	0.007	0.30
Eolian sand	0.420	0.055	0.010	0.35
Alluvial sand	0.380	0.045	0.010	0.40

to be average values and no attempt was made to differentiate between wetting and drying curves.

Initial estimates of saturated hydraulic conductivity were based on slug tests of wells installed in the alluvial sand, marl, and eolian sand at the study site. The slug tests indicated that the conductivity of the marl is about 3×10^{-5} cm/s, the conductivity of the alluvial sand is about 1×10^{-3} cm/s, and the conductivity of the eolian sand is about 4×10^{-3} cm/s. A pumping test was performed at well 3S (eolian sand) and curve matching indicated that the dune sand has a saturated hydraulic conductivity of 5.0×10^{-3} cm/s. The hydraulic conductivity of the till was assumed to be so low that it could be considered to constitute a no flow boundary.

Data on precipitation and potential evapotransporation provided the main basis for driving the transient simulations. A rain gauge installed at well MW1 provided a record of precipitation (P). Potential evapotransporation (PE) was approximated using evaporation pan data obtained from a nearby weather station (Valparaiso Waterworks). Meteorological data collected in 1997 from a nearby study site in the Great Marsh allowed calculation of Penman potential evaporation that facilitated comparison and adjustment of the pan evaporation data. The Penman (1948) calculations were based on a meteorological mast that contained a net radiometer, temperature and relative humidity sensors, and an anemometer. A correlation analysis indicated that the pan data overestimated PE by an average of 20% so the data from the Valparaiso Water Works were adjusted accordingly. The daily totals of precipitation and adjusted pan evaporation for the period of modeling are presented in Fig. 2. Precipitation and evaporation data for the years of 1970–2002 were also compiled in an effort to gain insight into the normal weather patterns of the area (Table 2). This made it possible to put the three years of data used in this study into context. The compiled totals of annual net surface flux indicate that, 1999–2000 was wetter than average, 2000–2001 was about average, and 2001–2002 was drier than average.

The LSWRS is bounded to the north by a linear dune ridge, to the south by Burns Ditch, to the west by a road, and to the east by an agricultural field. The model simulations employed transient specified head conditions for the northern (dune edge) and southern (Burns Ditch) boundaries (Fig. 3), but the east and west boundaries were assumed to be no-flow because observations in monitoring wells indicated that the flow was parallel to those boundaries. The water levels in Burns Ditch were obtained from a nearby gauging station operated by the United States Geological Survey (adjusted for a slight difference in elevation), and the water levels at the dune edge were interpolated from spot measurements in a monitoring well that was screened in the dune sand (well 3S, Fig. 1).

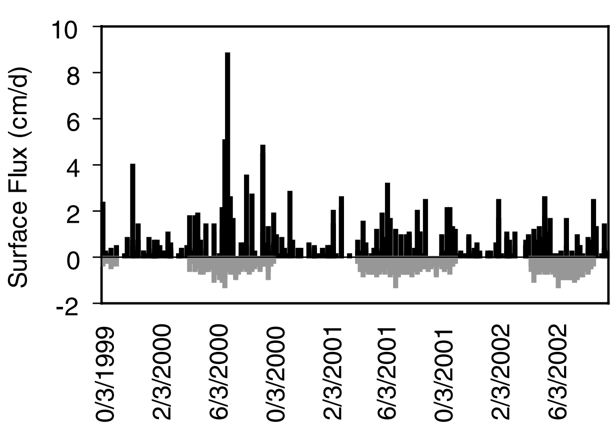

Figure 2 Daily totals of precipitation (black bars directed upward) and potential evaporation (grey bars directed downward) used as surface boundary conditions to drive the variably-saturated groundwater simulation model.

Table 2 Annual precipitation and evaporation during the period of monitoring and modeling

Water year	Precipitation (cm)	Evaporation (cm)	Net flux (cm)
1999–2000	95.0	72.6	22.4
2000–2001	81.7	72.5	9.2
2001–2002	94.6	97.4	−2.8
32 year average	92.9	81.6	11.3

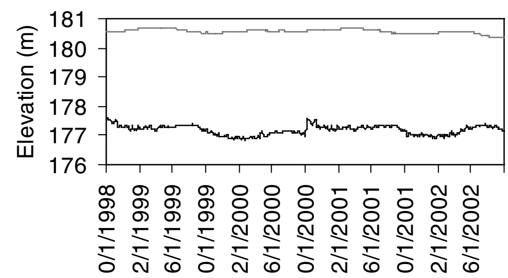

Figure 3 Hydrographs of water levels at the northern (upper curve) and southern boundaries (lower curve) of the LSWRS. The hydrograph for the northern boundary had to be interpolated from spot measurements at well 3S, but a continuous hydrograph for the southern boundary was obtained from a nearby USGS stream gauging station.

Sensitivity analysis and model calibration

A sensitivity analysis was conducted using the groundwater model to determine which input parameters most strongly affected the simulated water level hydrographs. The parameters that were analyzed include K_s, θ_s, θ_r, α and m for each of the four material types. Values of K_s were varied ± one order of magnitude and the other parameters were varied ±one standard deviation of the initial values. Results of the sensitivity analysis (see Boswell, 2005, for details) indicated that the water level hydrographs are most sensitive to the saturated hydraulic conductivity value, and more specifically, to that of the marl, which is the dominant material at the study site.

The groundwater model was calibrated to fit measured water levels from seven wells across the site (MW1, MW2, 1N, 2N, 4N, 5N, and 6N, Fig. 1), each of which had been monitored for the entire period of simulation. Six of the wells were screened totally or partially in marl, two were partly in alluvial sand, and one was screened totally in eolian sand. All of the wells had 1.5 m of screen so the modeled heads were taken as an equal average of heads over the screened interval (cf. Hill et al., 2000). Calibration consisted of determining best-fit average hydraulic conductivity values of each of the three material types for each of the water years 1999–2000, 2000–2001, and 2001–2002. Initial head values for the 1999–2000 water year were estimated by running the model in steady-state mode. This involved applying a constant pressure head to each of the surface cells. The steady-state run that matched measured heads of the seven target wells (based on the root mean squared error, RMSE) was retained as input to the transient simulations for the 1999–2000 water year. In subsequent transient simulations, the hydraulic conductivity value for one substrate (target material) was varied while keeping the conductivities of the other materials, as well as all other parameters constant. The average saturated hydraulic conductivity value that resulted in the smallest mean absolute error (MAE) between measured and modeled hydraulic heads was considered the ''best fit'' for the targeted material and kept for successive calibration runs. This process was repeated for all three substrate types and then iterated in an attempt to insure that the optimum set of average hydraulic conductivities had been determined.

The best fit model for the 1999–2000 water year produced a MAE of 0.30 m. The best-fit hydraulic conductivity for the 1999–2000 water year was used as input for simulations of the 2000–2001 and 2001–2002 water years. The simulated heads produced a reasonable match to the measured heads, but the match between observed and simulated hydraulic heads decreased somewhat compared to that of the 1999–2000 water year. Additional manual calibration was conducted for the 2000–2001 and 2001–2002 water years. The final best-fit K_s values (those used for hydroperiod simulations), were defined as the average of the best-fit K_s determined for each of the three water years and of the slug tests (Mean K_s, Table 3). The MAE for all the data is 0.48 m. Data for wells MW2, 1N, and 2N, had the smallest MAE values (0.33, 0.28, and 0.29, respectively) and wells 4N and 5N had the largest MAE values (0.71, 0.65). The first three wells are inside the LSWRS proper and are representative of most of its acreage, whereas the latter two wells are located near the southern edge of the LSWRS where the effects of Burns Ditch (fixed head boundary condition) are strongest.

As shown in Table 3, the best fit hydraulic conductivity of the marl is substantially higher than the value determined from slug tests. One potential reason for this difference is that the upper soil zone of the marl contains secondary permeability. On numerous occasions, animal burrows and open cracks were observed across the site and these would have led to a much more permeable surface layer. Also, during one site visit, pits were excavated to a depth of 1.5 m and non-matrix flow was observed through fractures in the saturated part of the marl. These sources of secondary permeability would not likely be identified by well tests because the well tests only evaluate the conductivity at depth and the microfractures are easily smeared out during well installation. Other possible sources of discrepancy between model calculations and field measurements include: (1) uncertainty in the soil moisture parameter values (especially those derived from look-up tables) that are utilized in van Genuchten's equations; (2) possible errors in the geologic model which was based on all available information from the site but which only encountered the alluvial sand at a few locations; and (3) errors in the data, especially the surface fluxes, which are impossible to completely overcome. Recall that an attempt was made to adjust pan evaporation data from the Valparaiso Waterworks, but no amount of adjustment can turn a pan derived value into a real value of evapotranspiration (Lott and Hunt, 2001). In addition, precipitation tends to be underestimated by tipping bucket rain gauges, and this is especially the case during periods of snowfall and high rainfall intensity.

Modeling results

Unsaturated zone dynamics

The unsaturated zone is of considerable importance to wetland hydrology because it provides the link between net surface flux and water table response. This is particularly evident during times of low water tables when a widespread and thick zone of partial saturation occurs in the overlying sediments. The transient simulations of variably-saturated flow at the LSWRS provide insight into the dynamics of storage and flow during a storm period. Initial conditions for the storm simulations correspond to the low water table elevation that existed on December 7, 1999. In the storm simulations rainfall intensities of 1.3 cm, 2.5 cm, and 5.1 cm per day were considered. The resulting output indicated that a rainfall total of 2.5 cm/d is sufficient to recharge the water table, but that rainfall totals of $\leqslant$1.3 cm/d are entirely taken up as storage in the unsaturated zone when the initial water table is depressed. Data resulting from the 5.1 cm/d rainfall simulation were used to construct a cross-section of flow (Fig. 4). The two-dimensional flow vectors are indicative of the flow path; orange-yellow colors indicate unsaturated flow and the blue colors indicate satu-

Table 3 Best-fit values of K_s resulting from calibration of the three-dimensional model. Note that the calibrated hydraulic conductivity values are all within an order of magnitude of the Hvorslev slug test results

Saturated hydraulic conductivity values (cm/s)					
Material type	Best-fit 1999–2000	Best-fit 2000–2001	Best-fit 2001–2002	Hvorslev slug test data	Mean K_s
Marl	1.25×10^{-4}	2.5×10^{-4}	1.0×10^{-4}	3.5×10^{-5}	1.28×10^{-4}
Eolian Sand	7.5×10^{-3}	2.5×10^{-3}	5.0×10^{-3}	4.0×10^{-3}	3.85×10^{-3}
Alluvial Sand	5.0×10^{-4}	1.0×10^{-3}	1.25×10^{-3}	1.0×10^{-3}	9.38×10^{-4}

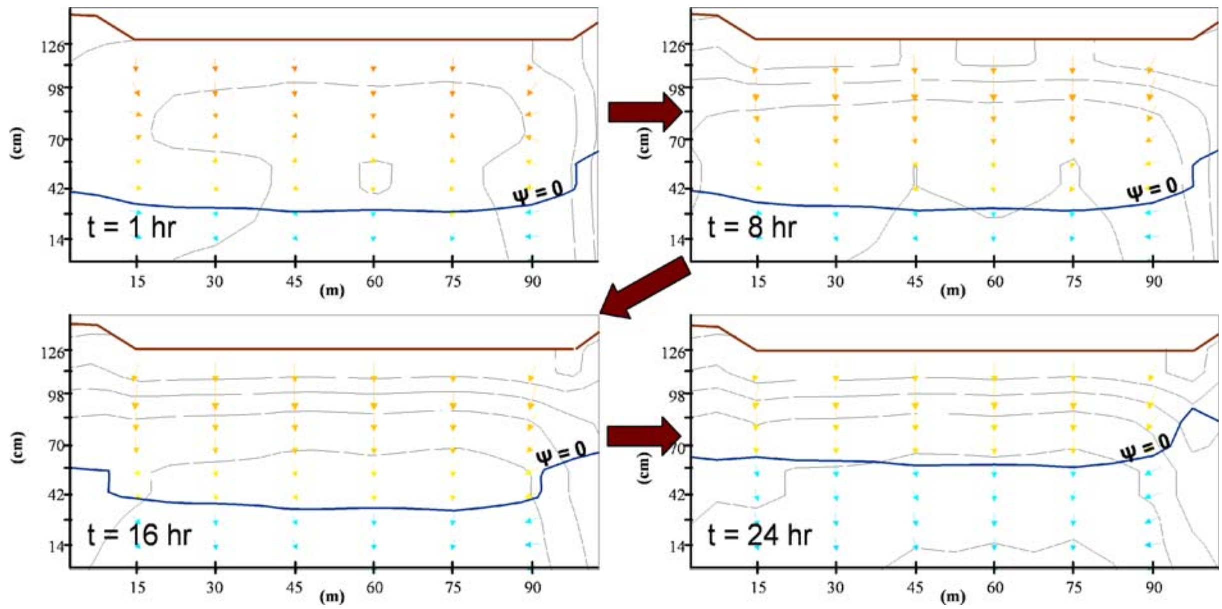

Figure 4 North-south cross-sections depicting variably-saturated groundwater flow near well 4N. The blue line represents the water table and the arrows indicate flow directions. The evolving cross-sections are responding to a 5.1 cm rainfall event.

rated flow. As shown in the cross-section, flow is still upward in the lower unsaturated zone after an hour of rainfall, but after 8 h of steady rain the flow throughout the entire unsaturated zone is directed downward. Over time, the pressure head in the unsaturated zone steadily increases and by the end of a day the water table (blue line) has risen (indicating recharge) about 14 cm. Due to the dry antecedent conditions, it takes a relatively large rainstorm such as this one several hours to produce a water table rise. This underscores the importance of unsaturated flow and the storage potential of the vadose zone to the understanding of how groundwater dominated wetlands respond to changing weather conditions.

The storm simulations also demonstrate the need for detailed topographic information in wetland assessments. The two ridges bordering the vernal pool depicted in Fig. 4 direct the flow of water towards the middle and downward through the substrate. Indeed, a detailed analysis of the three-dimensional model output indicated that many small vertical flow cells develop across the wetland, and these cells are located in small and sometimes subtle depressions and ridges in the landscape. Visualizations of the water table over the course of the study indicated that at times up to 28 vernal pools existed at the LSWRS.

Hydroperiod simulations

For the purposes of this study, the hydroperiod was defined as the number of days when saturation occurred at the surface during the growing season (April 15—October 15). Wetland hydroperiods are commonly determined from water well hydrographs (e.g. Hunt et al., 1999). At the LSWRS, the water levels in MW1 and MW2 were continuously monitored using calibrated pressure transducers that corrected for atmospheric pressure fluctuations. The hydrographs of water levels are presented in Fig. 5. Notice that the hydrograph of water levels at MW1 exhibits much more fluctuation than the one derived from measurements at MW2. This may be due to the fact that MW1 is screened in relatively permeable alluvial sand which can transmit water laterally at a faster rate than the marl at MW2. MW1 is also screened closer to the surface than the screened interval at MW2 and this can contribute to the quicker response to surface fluxes. Notice that while the hydrograph of MW1 fluctuates more, it is MW2 that has the longer hydroperiods (the ground surface elevation at MW2 is 179.75 m).

One advantage of using groundwater modeling to determine ground saturation is that a model can provide complete aerial coverage of the site so that both temporal and spatial dynamics of a wetland hydroperiod can be inferred. Using the output from the calibrated model simulations, hydroperiod durations were computed for each of the three water years of study. The criterion for determining saturation in the model calculations was that the hydraulic head ($h = \psi + z$) of the surface node was higher than the ground surface. Root zone saturation was similarly determined by comparing hydraulic head to the surface elevation minus 30 cm. Special attention was given to identifying areas of the LSWRS that are regularly saturated as opposed to those that are rarely saturated. Such information can aid in the restoration efforts by targeting areas that are both likely and not likely to support hydrophytes. Frequencies of saturation, expressed as the percentage of total growing season days, are depicted as spatial distributions in Fig. 6. These maps show that the areas with the greatest propensity for saturation occur adjacent to the seepage faces of the northern and eastern sectors. There are also wet zones in the western portion of the west sector, and at various low spots in the vicinity of wells 7 N, 5N, and 6N.

Hydroperiod durations were calculated across the wetland for each simulated water-year and summary statistics are presented in Table 4. The most common shared characteristics are the median values at low durations and the strong positive skewness of the hydroperiod distributions. These indicate that even in the wettest year, the majority of the LSWRS remained unsaturated for most of the growing season, but that there were also zones of perennial or near perennial saturation. The wettest year, in terms of simulated hydroperiod duration, was the 2000–2001 water year, which had an average of 44 days of saturation, and a median value of 29 days (Table 4). The skewness coefficient for 2000–2001 was also the lowest of the three simulated growing seasons indicating a more even distribution of saturation conditions during that water year. Simulations for the 1999–2000 water year produced a mean saturation duration of 17 days and a median value of 3 days during the growing season. The low median, relative to the mean shows that while some cells were saturated for most of the growing season (e.g. cells along the northern seepage face), most cells were not saturated for prolonged periods. Indeed many areas of the LSWRS were only saturated following the storm events in mid-June 2000 (Fig. 2) when 13.8 cm of rainfall occurred over a four day period. The simulations for the 2001–2002 water year yielded even drier conditions than those exhibited during 1999–2000; mean saturation during the growing season was just 6 days and the median condition was for no days of saturation at all.

Another important characteristic of wetlands is the percent of the wetland area covered by ponded water. Not only does ponded water affect the underlying soil characteristics by generating anoxic conditions that eventually lead to the production of hydric soils, but it also provides important habitat for wetland flora and fauna (Mitsch and Gosselink, 2000). Ideally, a wetland will have some continuous areas of ponded water throughout the year. As shown in Fig. 7, the LSWRS experiences high variability in the percent area covered by ponded water. Large increases and decreases in percent coverage correspond to intense precipitation and evaporation events, and are a result of the low topographic gradient across the site. One extreme example of this is the 8 cm rainfall on June 24, 2000 that increased the ponded area from less than 5% to over 65%. This occurred because the rainfall rate exceeded the infiltration

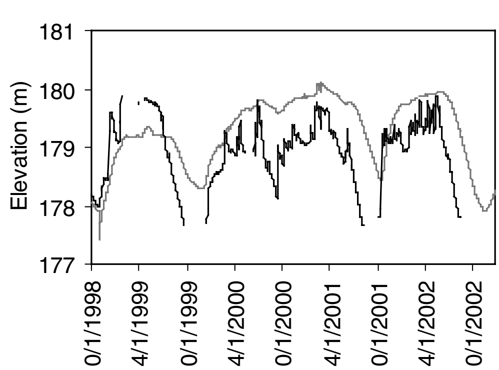

Figure 5 Hydrographs of measured water levels in MW1 (lower curve) and MW2 (upper curve) during the course of the simulation period. The hydrographs are from calibrated pressure transducers. The gaps in the record of MW1 are periods when the well was dry.

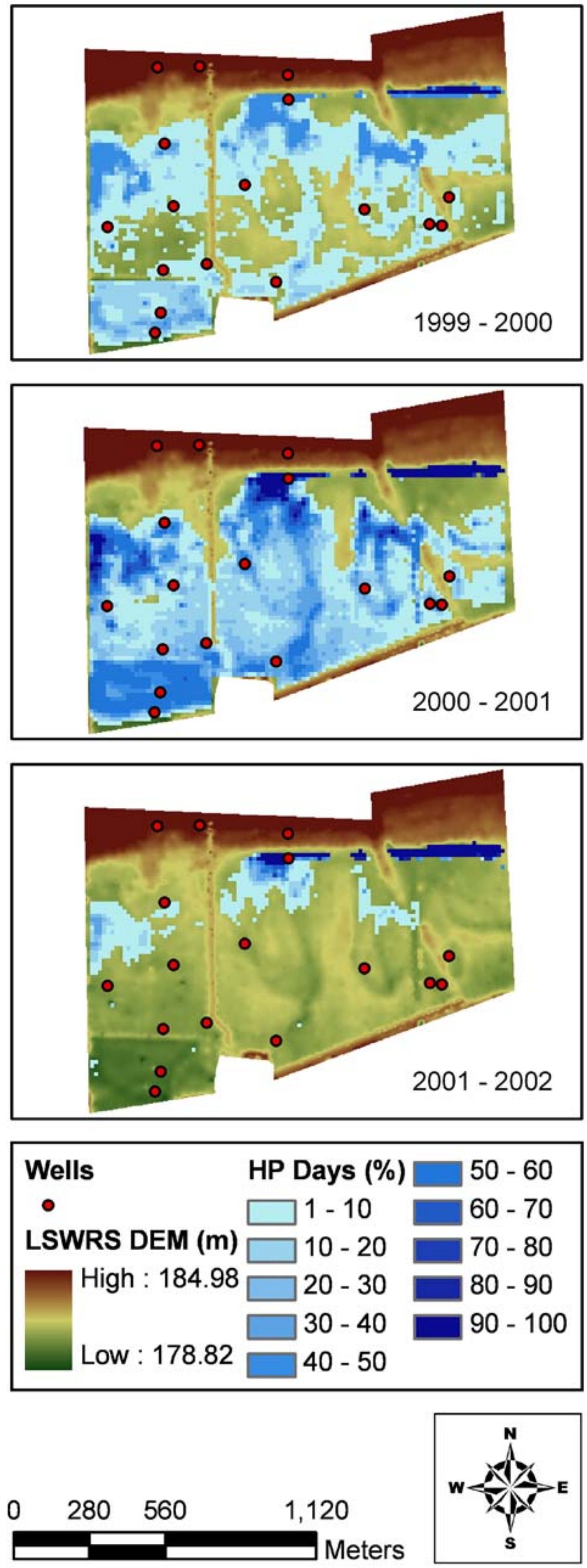

Figure 6 Maps showing the spatial distributions of hydroperiod duration that resulted from the three-year period of hydrologic simulation.

capacity of the marl. Based on the model simulation, it took approximately 8 days for evapotranspiration and infiltration to reduce the area of ponding to its pre-storm conditions.

Root zone saturation is important to wetland plant type and productivity and is considered to be a criterion for defining hydroperiods in many wetland delineation manuals (Mitsch and Gosselink, 2000). Simulations using the groundwater flow model indicate that root zone saturation at the LSWRS is typically more extensive than surface saturation, but the patterns also vary between different water years. During the 2001—2002 (year of least surface saturation) the area achieving root zone saturation was nearly 20% larger than the area of surface saturation. In contrast, the 1999—2000 simulation resulted in a root zone saturation area that was very similar to the ponded area and that exhibited similar fluctuations over time (Fig. 7). These fluctuations result from wetting fronts associated with the more intense precipitation that occurred that summer. Fluctuations in root zone saturated area were muted in 2000—2001 because the unsaturated zone was thinner during the course of that simulation. This variable type of hydrologic response, with recurring wetting and drying of the surface and the root zone, is of considerable importance to overlying vegetation because it affects both the physical and chemical properties of the root zone (Hunt et al., 1999). Minimum and maximum aerial distributions of ponding are presented in Fig. 8. These coverages correspond to simulated conditions on 12/7/1999 and 2/20/2001, respectively. The maximum ponded area is 79% and the minimum ponded area is only 3% of the total LSWRS. The maximum ponded area distribution shows that almost all of the low lying areas of the LSWRS are saturated, while the minimum ponded area shows that only the northern seepage face of the dune ridge in the eastern sector is saturated. These simulated distributions are consistent with distributions of saturated areas noted during site visits.

Discussion and conclusions

This study has shown that groundwater modeling can be used to reproduce measured conditions at specific points and to extrapolate the results to infer spatial and temporal distributions of soil moisture and water levels over an entire wetland area for extended time periods. The model simulations showed that differences in hydroperiod duration result from differences in antecedent moisture conditions including water table elevation and soil moisture conditions, as well as the timing of precipitation events over the annual cycle. At the LSWRS the highest net annual surface flux occurred during the 1999—2000 growing season, but this was not reflected in the hydroperiod durations because that year had the lowest initial water table elevations. Moreover, a large fraction of the precipitation occurred during two events in the middle of the growing season, when potential evapotranspiration was high. In contrast, the computer simulations indicated that the 2000—2001 growing season at the LSWS (which experienced a lower net surface flux than 1999—2000) had the highest surface saturation durations. This was due, in part, to a high initial water table elevation and soil moisture content across the site that resulted from above average precipitation during the preceding winter. The simulated hydroperiods for the 2001—2002 growing season were very low not only because it was the driest year in terms of net surface flux, but also because precipitation during the preceding winter was below average for the region. These findings indicate that precipitation during the recharge season is just as important in controlling wetland

Table 4 Hydroperiod statistics for the number of days of surface saturation (based on 15×15 m calculation cells)

Water year	Mean	Geometric mean	Median	Standard deviation	Skewness coefficient	Maximum	Minimum
1999—2000	17	7	3	31	2.86	205	0
2000—2001	44	36	29	50	1.34	209	0
2001—2002	6	5	0	29	5.61	187	0

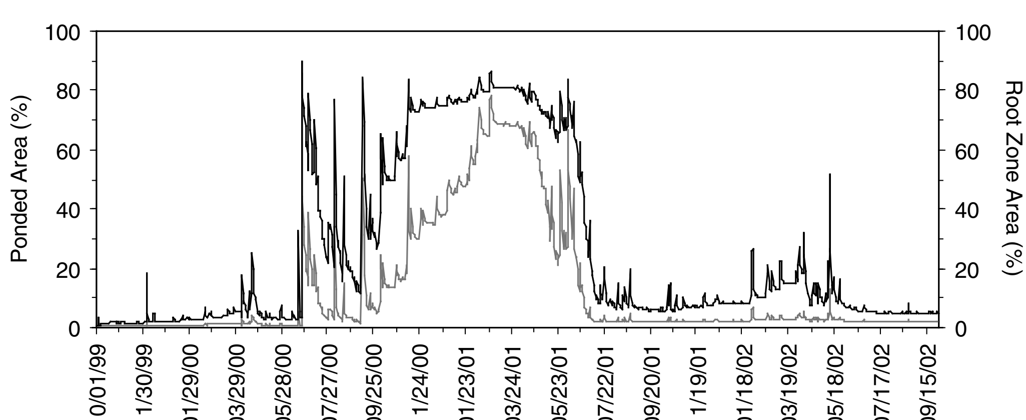

Figure 7 Hydrographs depicting percentage of the LSWRS meeting hydroperiod criteria (surface ponding in grey, root zone saturation in black) generated from the three-year hydrologic simulation.

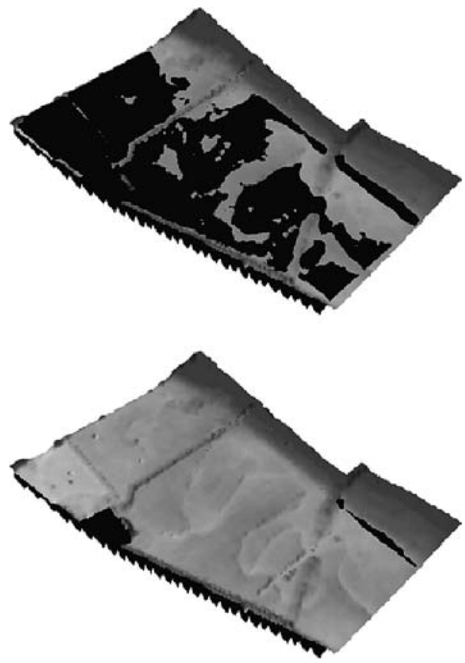

Figure 8 Maps showing the maximum (upper) and maximum (lower) areas of ponding at the LSWRS generated from the three-year hydrologic simulation.

hydroperiods as is the balance between precipitation and evapotranspiration during the growing season.

An analysis of a cross-section across a vernal pool indicated that small scale vertical flow cells occur in the topographic swale. Additional inspection of the simulated output revealed that such flow cells are common to the LSWRS and demonstrate the importance of topographic irregularities within a wetland complex. Despite its close proximity to Burns Ditch, the low hydraulic conductivity value of the marl (3.5×10^{-5} cm/s based on slug tests) at the LSWRS prohibits rapid drawdown of the water table and allows a restored wetland to exist.

In conclusion, this study has provided detailed examples of how numerical models can be used to study both short term and long term changes in the flow regime of a groundwater dominated wetland site (cf. McKillop et al., 1999). The sensitivity analysis showed that water levels were most sensitive to hydraulic conductivity values, and specifically that of the dominant surface material (cf. Bravo and Brown, 1998; McKillop et al., 1999). Future progress in this domain of ecohydrology should involve development of direct correlations between hydrologic conditions and plant community distributions. The groundwater modeling results, which can be calculated on a fine grid basis, could be compared to a grid of vegetation cover. Critical hydrologic variables include duration of saturation at the surface, saturation in the root zone, and distribution of open water. Hypothesized relationships include low lying wetter areas being associated with hydrophytic plants that are adapted to open water and/or saturated conditions, and higher drier areas around the site being associated with mesic plants better adapted to unsaturated conditions. We believe that hydrologic modeling has great implications for predicting the outcome of wetland remediation efforts and should be employed in preliminary planning and prioritization of wetland restoration efforts. However, the models are only as good as the data that goes into them so a significant cost would be associated with their accurate usage. Given the monetary value of prime wetlands, this should be a worthwhile expenditure.

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