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Hydrology and Geostatistics of a Vermont, USA Kettlehole Peatland

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Abstract

The ability to predict the response of peatland ecosystems to hydrologic changes is imperative for successful conservation and remediation efforts. We studied a 1.25-ha Vermont kettlehole bog for one year (September 2001–October 2002) to identify hydrologic controls, temporal and spatial variability in flow regimes, and to link hydrologic processes to density of the carnivorous plant (*Sarracenia purpurea*), an ombrotrophic bog specialist. Using a spatial array of nested piezometers, we measured surface and subsurface flow in shallow peat and surrounding mineral soil. Our unique sampling array was based on a repeated measures factorial design with: (1) incremental distances from a central kettlehole pond; (2) equal distances between piezometers; and (3) at three depths from the peat surface.

Local flow patterns in the peat were controlled by snowpack storage during winter and spring months and by evapotranspiration and pond water elevation during summer and fall months. Hydraulic head values showed a local reversal within the peat during spring months which was reflected in higher chemical constituent concentrations in these wells. On a regional scale, higher permeable soils diverted groundwater beneath the peatland to a nearby wetland complex. Horizontal water gradient magnitudes were larger in zones where the peatland was perched above regional groundwater and smaller in zones where a hydraulic connection existed between the peatland and the regional groundwater. The density of pitcher plants (*S. purpurea*) is strongly correlated to the distance from a central pond, [Fe^{3+}], [Na^{+}], [Cl^{-}], and [SO_4^{2-}]. The pH, conductivity, and [Ca^{2+}] had significant effects of depth and time with horizontal distance correlations between 20 and 26 m. The pH samples had temporal correlations between 27 and 79 days. The link between pitcher plants and ion chemistry; significant effects of peatland chemistry on distance, depth, and time; and spatial and temporal correlations are important considerations for peatland restoration strategies.

Keywords: Peatland; Geochemistry; Sarracenia; Pitcher plant; Variogram; Kriging

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1. Introduction

Long overlooked for their ecological and societal importance, wetlands are now regarded as important landscape features that regulate water tables, improve surrounding water quality, and provide habitat for numerous organisms (Mitsch and Gosselink, 2000; US EPA, 2002). Only recently have substantial steps been taken to reduce wetland losses in the United States after 53% of the Nation's 900,000 km^2 were destroyed (Dahl, 1990). Despite national protection and private conservation efforts, wetlands continue to be lost to development, agriculture, silviculture, and failed remediation projects. Remediation of cutover peatlands (wetlands with accumulations of undegraded organic matter at depths greater than 45 cm) is very difficult; natural regrowth is extremely slow and peat accumulation does not normally occur without immediate restoration activities (Price, 1997), proper vegetative re-colonization (Schipper et al., 2002), and managed hydrology (Ferland and Rochefort, 1997). Recently tested management techniques for remediation of cutover peatlands include establishment of a peat–ditch system (Schlotzhauer and Price, 1999) and microrelief topography (Ferland and Rochefort, 1997). However, guidelines for restoration have yet to be created and should be based on a thorough understanding of natural conditions in minimally impacted peatlands.

Locations within peatlands that are influenced by surface or groundwater are visible through surface vegetation (Damman, 1986; Verry and Boelter, 1978). Nutrient-poor ecosystems such as ombrotrophic bogs are extremely sensitive to increased nutrient input from the atmosphere or other local water sources. For example, the growth, morphology, and population dynamics of the northern pitcher plant (*Sarracenia purpurea*) changes rapidly in response to increased inputs of atmospheric nitrogen (Ellison and Gotelli, 2002; Gotelli and Ellison, 2002) and is likely to respond similarly to changes in other plant micronutrients (Ca, Na, Mg).

Peatland systems have historically been considered hydraulically disconnected from local or regional groundwater systems due to the low permeability of underlying mineral soils (Ingram, 1983). However, more recent studies have shown that bi-directional flow (groundwater discharge and recharge) does occur in some peatlands as frequent as annually (Bradley, 1996; Devito et al., 1997; Waddington and Roulet, 1997). Bi-directional flow implies that peatland development may be driven by processes other than evapotranspiration, even though peatlands are not connected to local groundwater or streams to the extent of other types of wetlands (Owen, 1995; Verry and Boelter, 1978). Many hydrologic studies have been completed within peatlands (Bradley, 1996; Devito et al., 1997; Fraser et al., 2001a; Kasenow, 1995; Lamers et al., 1999; Price, 1997; Schlotzhauer and Price, 1999; Verry and Boelter, 1978; Wilcox et al., 1986). The typical linear (Price, 1997; Waddington and Roulet, 1997) or perpendicular orientation of piezometers (Fraser et al., 2001a; Waddington and Roulet, 1997) is useful in representing hydrologic patterns for specific transects within a peatland, but does not provide an adequate spatial distribution of data and presents difficulties in developing flow nets (Bradley, 1996). If models are to be successfully applied to natural and restored peatland systems, we must understand hydrologic changes that govern peatland development on a vertical and horizontal spatial scale (i.e. peat water levels or pore-water chemistry) and identify their response to climatic events through time (i.e. precipitation or evapotranspiration).

The spatial variance of geohydrologic data can be described with a variogram, a visual representation of the correlation between a parameter, i.e. sodium ion concentration, and distance between sample locations. Variogram relationships are commonly used in least-squares regression techniques, called kriging methods, which estimate an parameter's value and error variance over a study area (Goovaerts, 1997; Isaaks and Srivastava, 1989). This method has rarely been used for peatland hydrologic studies with the exception of Bradley (1996) who used it for error estimation in a floodplain peatland MODFLOW 96 model and Petrone et al. (2004) who looked at the spatial correlation of soil moisture levels in a Canadian peatland.

We monitored a small kettlehole peatland in Vermont for approximately one year (September 2001–October 2002). Our objectives were to: (1) identify the hydrologic controls to Molly Bog on a local and regional scale; (2) analyze spatial and temporal variation in water flow and water chemistry, by using ANOVA and kriging of data from a spatial array of piezometers; and (3) link hydrologic spatial and temporal variability within Molly Bog to northern pitcher plant density.

2. Study area description

Molly Bog, a developing kettlehole peatland, is located between Stowe and Morristown, Vermont, USA (Fig. 1a). The climate at the site is one of cold winters and cool summers, with a mean annual temperature of 3.5 °C. The mean annual precipitation is approximately 105 cm water equivalent, with 25–33% falling as snow. The peatland is currently owned and managed by the University of Vermont (UVM) Natural Area Conservation Group. Vogelmann (1964) cited Molly Bog as a 'near-perfect example of a postglacial bog' and the National Park Service (1973) defined it as 'a classic example of a small, early successional, absolutely unspoiled cold northern bog.'

Molly Bog is situated between two other peatlands in the Molly Bog Peatland Complex, estimated at 25 ha in size (Sanderson et al., 1993), and is the only open pond peatland within the complex (Fig. 1a). The open pond portion of Molly Bog is approximately 1 ha and greater than 12 m deep at its center (Fig. 1b). It is surrounded by a floating peat mat (*Sphagnum spp.*) approximately 15 m wide. Outside the floating mat is a broad peatland that overlays mineral soil at depths greater than 2 m in some areas and extending a distance

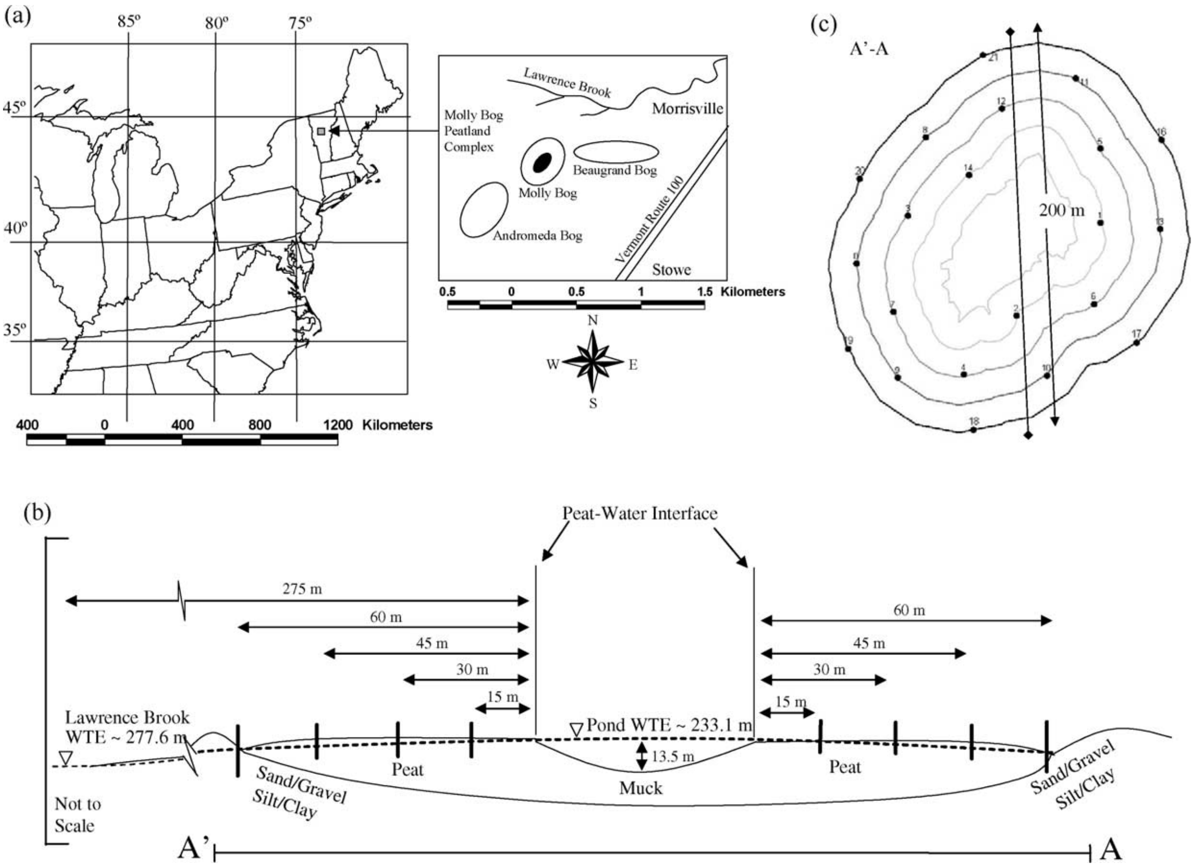

Fig. 1. (a) Location of Molly Bog in Vermont, USA. (b) Location of well nests (by ID) within Molly Bog. The central outline represents the peat–pond interface and concentric outlines represent 15, 30, 45 and 60 m from the central pond. (c) Cross-section of Molly Bog well placement design.

of more than 75 m from the open pond (Fig. 1c). Logging, farming, ditching and urban development in and around the complex caused Molly Bog to be listed as a threatened National Natural Landmark by the National Park Service in 1989 (Sanderson et al., 1993).

The Vermont landscape was most recently shaped by the Laurentide ice sheet, the last big continental-scale glacier that covered New England between 14,000 and 80,000 years ago (Wright and Larsen, 2001). The advancement and retreat of this ice sheet left surficial geology consisting of unsorted glacial till, with areas of ‘hardpan’ resulting from overburden pressures of over 2 km of ice in some areas. Stratigraphy of the Molly Bog Peatland Complex consists of poorly drained glacial till; lacustrine gravels, sands, silts and clays; and poorly drained peat and muck (Stewart, 1971; Wright, 1974). Bedrock consists primarily of highly metamorphosed gray to green Cambrian schists and phyllites (Doll, 1970; Wright, 1974). Core samples beneath the peat and around Molly Bog showed disjunctive layering of clays and silts under sands and gravels, suggesting Molly Bog may have developed in a poorly drained glacially made depression as a typical New England kettlehole bog (Johnson, 1985). A survey of open water table elevations surrounding Molly Bog indicate a head drop difference of approximately 5 m exists between the open pond portion and Lawrence Brook (Fig. 1c). The dominant plant species found in Molly Bog include leatherleaf (*Chamaedaphne calyculata*), bog cranberry (*Vaccinium oxycoccus*), bog rosemary (*Andromeda glaucophylla*), pitcher plant (*S. purpurea*), sundew (*Drosera intermedia*), beak rush (*Rhynchospora alba*), cotton grass (*Eriophorum spp.*), and peat mosses (*Sphagnum* spp.) (Sanderson et al., 1993). Surface vegetation varies with location around the open pond. The densest populations of pitcher plants are located in the northeast portion of the floating mat while other areas have limited or scarce densities of pitcher plants.

3. Methods

3.1. Hydrology

Molly Bog was instrumented for measurements of precipitation, groundwater table fluctuations, pore-water fluctuations, and geochemistry. Nested piezometers were installed at 15 locations within the peat (Fig. 1c). Each well nest (WN) location contained Poly Vinyl Chloride (PVC) piezometers at three depths, 0.5, 0.75 and 1 m, for a total of 45 piezometers within the peat boundary. The nests were located at distances of 15, 30, and 45 m from the pond–peat interface and were constructed of 3.175 cm OD Schedule 80 PVC, slotted over the bottom 10 cm and wired together to minimize movement after installation. In addition, total head measurements were monitored at six nested locations along the peatland perimeter. These monitoring wells were installed approximately 60 m (horizontally) from the pond–peat interface. These nests contained two steel piezometers installed to depths of 1 and 3 m. The steel wells were constructed of 1.91 cm OD piping connected to 22 cm stainless steel drive point piezometers (Solinst, Ont., Canada) with 1 cm inlet holes lined with a 0.5 mm filter screen.

Two-dimensional groundwater flow between WN locations (e.g. WN 8, 12, and 14) were calculated from total hydraulic head values measured using a water-level indicator (Solinst, Ont., Canada) and can be represented as a triangular water table elevation plane. Differentiation of the water table plane gives the hydraulic gradient with unit components i and j in the x and y direction of groundwater flow (1) (Freeze and Cherry, 1979)

$$v = \frac{\partial z}{\partial x} i + \frac{\partial z}{\partial y} j \tag{1}$$

where v is the hydraulic gradient, $\partial z/\partial x$ (m/m) and $\partial z/\partial y$ (m/m) are the components of flow in the x and y direction, respectively. Note that in the case of three wells to equal depths:

$$\frac{\partial z}{\partial x} = \frac{(z_1 - z_2)(y_2 - y_3) - (z_2 - z_3)(y_1 - y_2)}{(x_1 - x_2)(y_2 - y_3) - (x_2 - x_3)(y_1 - y_2)}$$

and

$$\frac{\partial z}{\partial y} = \frac{(z_1 - z_2)(x_2 - x_3) - (z_2 - z_3)(x_1 - x_2)}{(x_2 - x_3)(y_1 - y_2) - (x_1 - x_2)(y_2 - y_3)}$$

where x (m) and y (m) represent the horizontal well position, z (m) represents the manually measured total head value, and the subscripts 1, 2, and 3 represent the relative well position (Abriola and Pinder, 1982).

From Eq. (1), the magnitude and direction of groundwater flow can be calculated, Eqs. (2) and (3), respectively. Flow magnitudes and direction were calculated for each well screen depth and sample period.

$$v_{\mathrm{mag}} = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \quad (2)$$

$$v_{\mathrm{dir}} = \tan^{-1}\left(\frac{\partial z/\partial x}{\partial z/\partial y}\right) \quad (3)$$

where v_{mag} is the magnitude of groundwaterflow and v_{dir} is the direction of groundwater flow.

Three pressure transducers (Sensotec, Columbus, OH) were installed at WN 14 (Fig. 1c) to monitor continuous response of peat and pond water levels to precipitation events. One transducer was located within a stilling basin adjacent to the pond and the other two were located in the 0.5 and 1.0 m wells. Transducers were calibrated using a water column and datalogger prior to installation.

A tipping-bucket rain gauge and precipitation adapter (Campbell Scientific, Logan, UT) were used to measure precipitation. The rain gauge had a 20.32 cm collector with a 0.254 cm bucket tip. A CR10X datalogger (Campbell Scientific, Logan, UT), powered by a battery and solar panel, was used to store field data over the sample period. Evapotranspiration was estimated using the model developed by Priestly and Taylor (1972):

$$\mathrm{ET} = \alpha\left(\frac{s}{(s-q)}\right)\left(\frac{Q_{\mathrm{R}} - Q_{\mathrm{G}}}{\mathrm{L}\rho\rho}\right) \quad (4)$$

where ET is the actual evapotranspiration rate (mm day^{-1}), α is the ratio of actual to equilibrium evapotranspiration, s is the slope of the saturation vapor pressure-temperature (Pa $°\mathrm{C}^{-1}$), q is the psychrometric constant (0.0662 KPa$°\mathrm{C}^{-1}$ at 20 °C), Q_{R} is the net solar radiation flux (J day^{-1}), Q_{G} is the ground heat flux (J day^{-1}), L is the latent heat of vaporization (J kg^{-1}), and ρ is the density of water (kg m^{-3}). The α value was based on Price's (1997) value of 1.26 for peatland systems in Quebec, Canada. Net daily solar radiation flux was calculated from short and long-wave radiation data measured in Danville, Vermont (44°29′N, 72°09′W, 550-m elevation) at the US Army Corp of Engineers Cold Region Research and Environmental Laboratory (CRREL) Snow Research Station, located approximately 40 km from the study area and from radiation data collected in Jeffersonville, Vermont (44°39′N, 72°51′W, 174-m elevation) located approximately 24 km from the study area.

Weather data over the sample period were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2002) for the Morrisville-Stowe State Airport, (44°32′N, 72°37′W, 223.1-m elevation), located approximately 3 km north of the study area. We used the Morrisville-Stowe weather station data to verify weather data collected on site, to fill in missing data points, and to supplement data necessary for evapotranspiration estimates.

The definition of ombrotrophic is 'rain-fed' (Damman, 1986), therefore, a true ombrotrophic bog has no groundwater or surface water influences. If we assume Molly Bog is ombrotrophic, the hydrologic balance would be:

$$P - \mathrm{ET} = \Delta S \quad (5)$$

where P is precipitation (mm), ET is evapotranspiration (mm), and ΔS is the change in water storage (mm). A positive ΔS represents a net increase in water storage, while a negative ΔS represents a net loss in water storage.

3.2. Water chemistry

A YSI water quality probe (YSI Inc , Yellow Springs, OH) was installed in the 0.75 m well of WN 14 to track continuous changes in pH, redox, DO, electrical conductivity, temperature, and water levels. The YSI probe was calibrated on a monthly basis in the field using standard techniques established by the manufacturer (YSI, 2001).

Water samples were taken using a peristaltic pump (Solinst, Ont., Canada) after a low volume purge of 250 ml, and immediately refrigerated to 4 °C until they were analyzed within 14 days of sampling. Sample pH was measured using a glass electrode pH meter (Beckman Instruments Inc., Fullerton, CA) calibrated before use using a two-point calibration curve with standard buffer solutions of 4.0 and 7.0. Electrical conductivity was measured using a platinum electrode conductivity meter (VWR Scientific, West Chester, PA). Prior to measurement, the meter was calibrated to temperature and conductivity using a standard 0.01 KCl solution (Greenberg et al., 1992). Cation and anion concentrations were measured at the UVM Agricultural and Environmental Testing Laboratory using Perkin-Elmer Optima 300 DV ICP (Norwalk, CT) and Dionox DX600 IC (Sunnyvale, CA), respectively.

3.3. Pitcher plant density (*S. purpurea*)

The pitcher plant is one of the rare plant species found in Molly Bog and is easily identified due to its distinct physical appearance and clustered growth pattern. The name pitcher plant comes from a highly evolved vase-like pitcher filled with precipitation and digestive enzymes and lined with downward poking hairs to hold in its prey (Johnson, 1985). Insects caught within the pitcher eventually drown, are digested, and ultimately adsorbed to provide nutrients not available to the plant in other forms. Variations of *Sarracenia* are listed as endangered in many states (e.g. North Carolina, South Carolina, Alabama, Georgia, Tennessee) (US FWS, 2004), as changes in nutrient inputs in peatlands typically results in a loss of *Sarracenia* or other carnivorous plants to competitors (see Ellison, 2003). We utilized the sensitivity of pitcher plants as a hypothesized link to ion concentrations in peat pore-waters. The density of pitcher plant was estimated by measuring the distance from each piezometer to the five closest pitcher plants. Average distance was calculated for each well and used as an index of plant density: the smaller the average, the higher the plant density (Pielou, 1984).

3.4. Statistical analysis

Two statistical methods were used to evaluate data from this study, repeated measure (ANOVA) and ordinary kriging. Four types of data were evaluated: (1) water gradients ($n=1069$); (2) pH values ($n=246$); (3) electrical conductivity values, EC, ($n=145$); and (4) concentration of calcium ions, $[Ca^{2+}]$, ($n=90$), where n = the total number of samples.

A split-plot model for repeated measure design allows for analysis of time trends on the individual responses of factors (Kuehl, 2000). The experimental design for this study included three factors: (1) distance from the pond–peat interface; (2) location of WN; and (3) depth to well screen. Factor 1 contained three distances, 15, 30 and 45 m (60 m wells were not included in the statistical analysis), factor 2 contained fifteen well locations numbered 0 through 14, and factor 3 contained three depths, 0.5, 0.75 and 1 m. The total number of repeated samples was different for each of the measured variables: for water gradients $n=33$, for pH $n=6$, for EC $n=4$, and for $[Ca^{2+}]$ $n=3$. Statistical significance was determined at the $\alpha=0.05$ level. Water gradient magnitude and angles were calculated for each well depth (0.5, 0.75, 1.0 m) between the closest oriented wells based on the well location design for a total of 13 triangular planes. Samples were tested for normality using normal probability plots (Table 1). Based on these results, we log-transformed the gradient magnitudes and $[Ca^{2+}]$ before analysis. ANOVA was conducted using SAS Release 8.02 (SAS Institute Inc, Cary, NC).

Variogram formulation and kriging were used to evaluate the spatial and temporal continuity of selected geochemical parameters, to provide parameter estimates, and to evaluate parameter variance between sample locations at Molly Bog. Intuitively, samples that are spatially closer together will be more similar than those further from each other, therefore relationships can be developed which relate the distance between samples with the variance (variograms or semi-variograms) of the sample parameter.

Table 1
Normality results for water gradient magnitudes, pH, EC, and $[Ca^{2+}]$

	Water gradient magnitude	pH	EC (μS)	$[Ca^{2+}]$ (mg/l)
Sample size (*N*)	1069	246	165	90
Wilkes-Shapiro	0.9364	0.9716	0.8627	0.5343
Normal Prob. plot	Not normal-like	Normal-like	Normal-like	Not normal-like

Variogram relationships yield information on the distance at which sample values are no longer correlated, called the range, and the error variance when samples are no longer correlated, called the sill (de Marsily, 1986; Isaaks and Srivastava, 1989). While it may be difficult to obtain reliable estimates from small sample sets, geostatistics can be applied to small data sets provided caution is used during development and interpretation. Other sources of data or knowledge of similar sites can often be used to supplement sample information (Goovaerts, 1999).

Spatial variograms were developed for pH, EC, and [Ca^{2+}] and temporal variograms were developed only for pH. The Gaussian model was selected for all elements in our data set (de Marsily, 1986):

$$\gamma(h) = \omega\left\{1 - \exp\left[-\left(\frac{h}{a}\right)^2\right]\right\} \tag{6}$$

where γ is the variogram value, ω is the sill, a is the range, and h is the relative distance between wells or time between samples. Spatial variograms using Eq. (5) were fit to the data at one snapshot in time over all space. Temporal variograms were developed for individual wells at each horizontal depth (i.e. 0.5, 0.75, 1.0 m). Range and sill values estimated from the variogram models were used to estimate sample values and their error variance using Eqs. (7) and (8), respectively:

$$\tilde{\gamma}_{i0} = \sum_{j=1}^{n} w_j \tilde{\gamma}_{ij} - \mu \tag{7}$$

$$\tilde{\sigma}_R^2 = \sum_{i=1}^{n} w_i \tilde{\gamma}_{i0} + \mu \tag{8}$$

where $\tilde{\gamma}_{i0}$ is the estimated value of the variogram for the desired estimation point, $w_j$are the ordinary kriging weights as a function of n number of data points, $\tilde{\gamma}_{ij}$ is the estimated value of the variogram for $i=1,2,\ldots,n$, μ is the Lagrange parameter, and $\tilde{\sigma}_R^2$ is the estimated model error variance. For producing an unbiased estimator we require the constraint that the weights, w_i, sum to 1 (Isaaks and Srivastava, 1989). Eqs. (7) and (8) were used to map the sample elements and their error variance over space for each well depth (0.5, 0.75, and 1 m). The ranges and sill values were used in an ordinary kriging model developed in MATLAB version 6.1 (MathWorks, Inc, Natick, MA). Estimation points and their error variances were established every 1 m over a 220×220 m area for a total of 48,841 estimation points and plotted in MATLAB.

4. Results

4.1. Hydrology

4.1.1. Water balance

There was an overall net increase in water storage of 438 mm between September 2001 and October 2002 (Fig. 2). This corresponds closely with pore-water fluctuations shown in the 1 m-piezometers over the period, averaging a net gain of 330 mm. Our study began at the end of a dry year, 2001 precipitation was lower than average (750 mm), while 2002 precipitation (January through October) was higher than average (950 mm). Thus, the majority of net gain was likely a result of the peatland recovering from a drought condition.

The change in water storage, ΔS, for the wet portion of the hydrologic balance (1 June, 2002–26 September, 2002) was compared with on-site automated hydraulic head levels taken at the pond and 1 m well from WN 14 (Fig. 3). There was a calculated overall net gain of 64 mm, which compares closely with the net gain of 63 mm recorded by the automated pressure transducer. Although net gains for the Priestly–Taylor mass balance model and automated measurements agree over the four-month period, the mass balance model appears to slightly under compensate for evapotranspiration during wet periods (June–Sept. 2002) and overcompensate for evapotranspiration during dry periods (Sept. 2001–June 2002) (Fig. 2).

4.1.2. Hydraulic head measurements

The regional groundwater table is isolated from a perched local water table on the eastern portion of the bog while a hydraulic connection exists on the western portion of the bog Daily precipitation values were plotted with water levels in WN 17, 18, and 19 over the study period (Fig. 4). The water table position in all three 1 m wells from WN 17, 18 and 19 mimicked local hydrology; the pond water levels also fluctuated at elevations between 232.9 and 233.2 m.

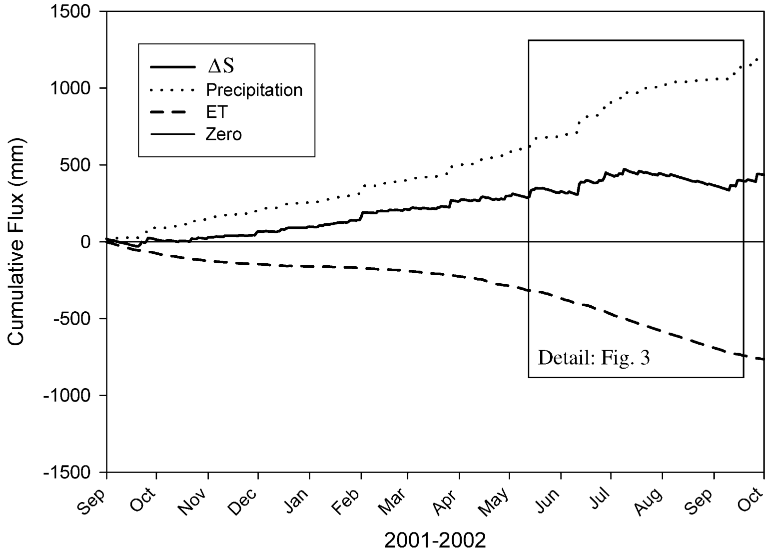

Fig. 2. Cumulative water balance between 1 September, 2001 and 1 October, 2002. Daily precipitation, evapotranspiration, and change in storage of the peat system are shown over the sample period.

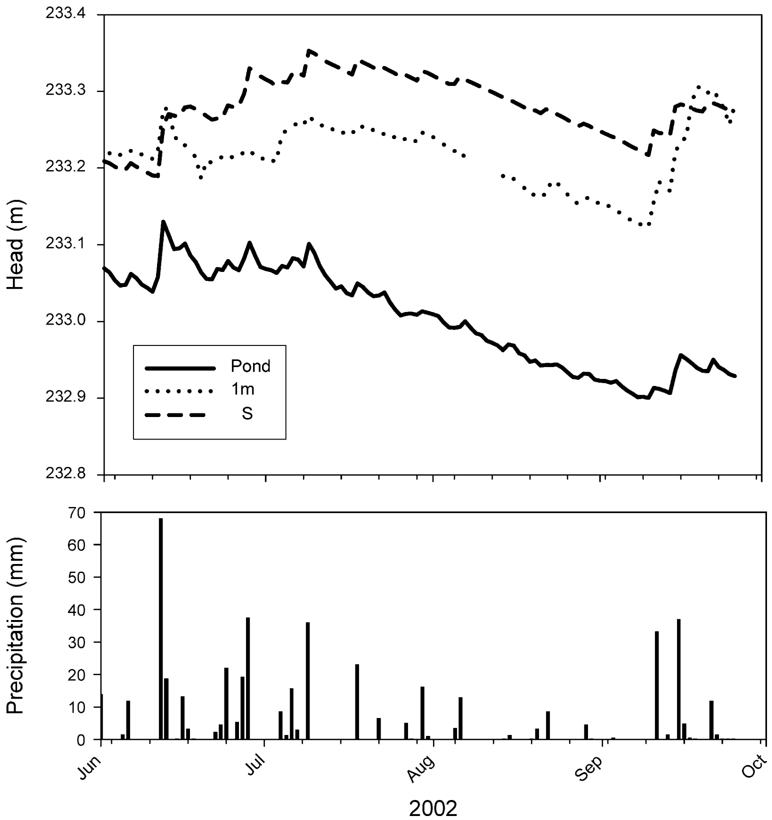

Fig. 3. Water balance detail for 1 June, 2002–26 September, 2002. Daily water levels from on-site transducers in the pond and 1 m well from WN 14 are compared to overall change in storage and precipitation over the sample period.

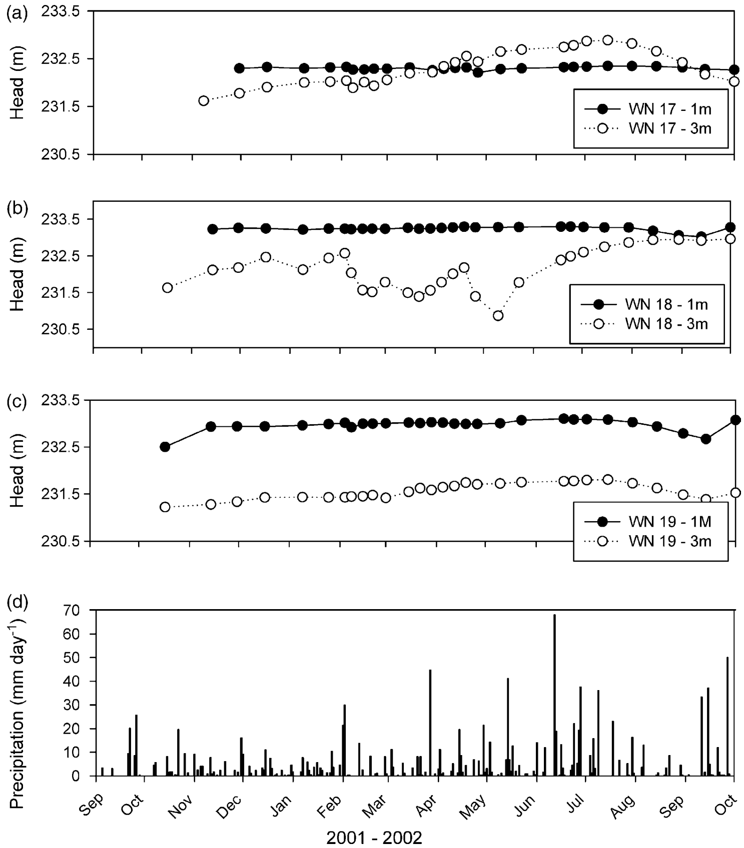

Fig. 4. WTEs in (a) WN 17, (b) WN 18, (c) WN 19, and (d) daily precipitation values from September 2001–October 2002.

Head measurements in the 3 m wells, however, varied by location. For example, the 3 m wells at WN 17 and 18 showed large responses to the regional groundwater table from precipitation events, particularly during the spring melt period, while the 3 m well at WN 19 showed more dampened responses to precipitation events. The 3 m well at WN 17 showed a higher hydraulic head than its corresponding 1 m well for 5 months during the sampling period (April–August 2002). Independence between the 1 and 3 m wells is also seen at WN 18; the 3 m rise and falls throughout the year with minimal changes in the 1 m well. In contrast, however, the 3 m well in WN 19 appears to mimic fluctuations the 1 m well with a slight delayed response.

4.1.3. Flow gradients

There was a local flow reversal between the wet (July 15, 2002) and dry period (September 13, 2002) in the northeast portion of the bog for all peat well screen depths (0.5, 0.75 and 1 m) (Fig. 5a and b). During the wet spring period the peatland was recharged from snowpack infiltration near WN 0, 3, 8, and 20, forming positive flow gradients into the central pond for this area. During dry periods water was flowing away from the pond in all directions, with the pond providing a constant head source. There were areas for both wet and dry periods where areas on the floating peat mat (WN 1 and WN 2) always had higher heads than the pond elevation.

Peat pore-water flow gradients were larger in the south and east portions of the bog than the north and west portions of the bog, showing significant location, depth and time effects at Molly Bog (Table 2). Gradient magnitudes ranged between 0.0009 and 0.0286 m/m, varying by triangular location (Fig. 6a) and increasing with well depth (Fig. 7a).

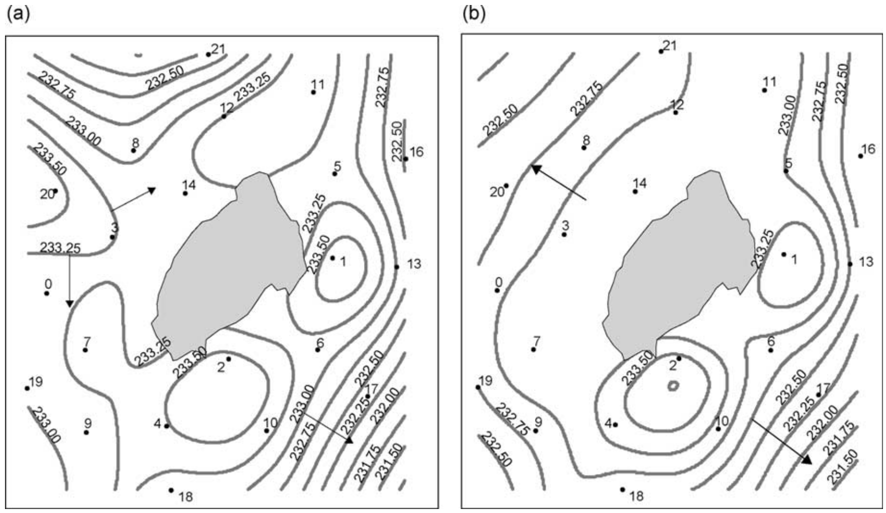

Fig. 5. WTEs in the 1 m wells on (a) 15 July, 2002 and (b) 13 September, 2002. Contours are labeled as total head in meters above sea level, the central pond is the gray area, well locations are numbered 0–21.

Table 2
ANOVA results for water gradient magnitude, pH, EC, and [Ca^{2+}]

	Source	d.f.[a]	Sum of squares	*F*-statistic	*P*-value
Gradient magnitude	Tloc[b]	12	89.1	728.10	<0.0001
	Depth	2	1.4	67.85	<0.0001
	Time	32	0.9	2.70	<0.0001
	Tloc×Depth	24	7.7	31.44	<0.0001
	Time×Tloc	321	6.1	1.87	<0.0001
	Time×Depth	63	0.8	1.27	0.0880
pH	Distance	2	2.1	0.34	0.7175
	Depth	2	13.8	20.60	<0.0001
	Time	5	24.4	22.55	<0.0001
	Distance×Depth	4	1.0	0.76	0.5608
	Time×Distance	10	2.8	1.30	0.2542
	Time×Depth	10	4.2	2.77	0.0047
	Distance×Depth×Time	20	2.8	0.94	0.5410
EC (μS/cm)	Distance	2	2732.3	0.36	0.7060
	Depth	2	10,582.9	6.99	0.0041
	Time	3	5087.1	2.54	0.0720
	Distance×Depth	4	11,888.5	3.92	0.0137
	Time×Distance	6	6076.7	1.52	0.2009
	Time×Depth	6	17,362.9	5.92	<0.0001
	Distance×Depth×Time	12	8627.3	1.47	0.1618
[Ca^{2+}] (mg/l)	Distance	2	1.0	3.27	0.0733
	Depth	2	1.6	21.02	<0.0001
	Time	2	3.1	54.60	<0.0001
	Distance×Depth	4	0.2	1.22	0.3324
	Time×Distance	4	0.9	7.92	0.0012
	Time×Depth	4	1.3	9.17	0.0006
	Distance×Depth×Time	8	0.6	2.08	0.1049

[a] Degrees of freedom.
[b] Triangular location.

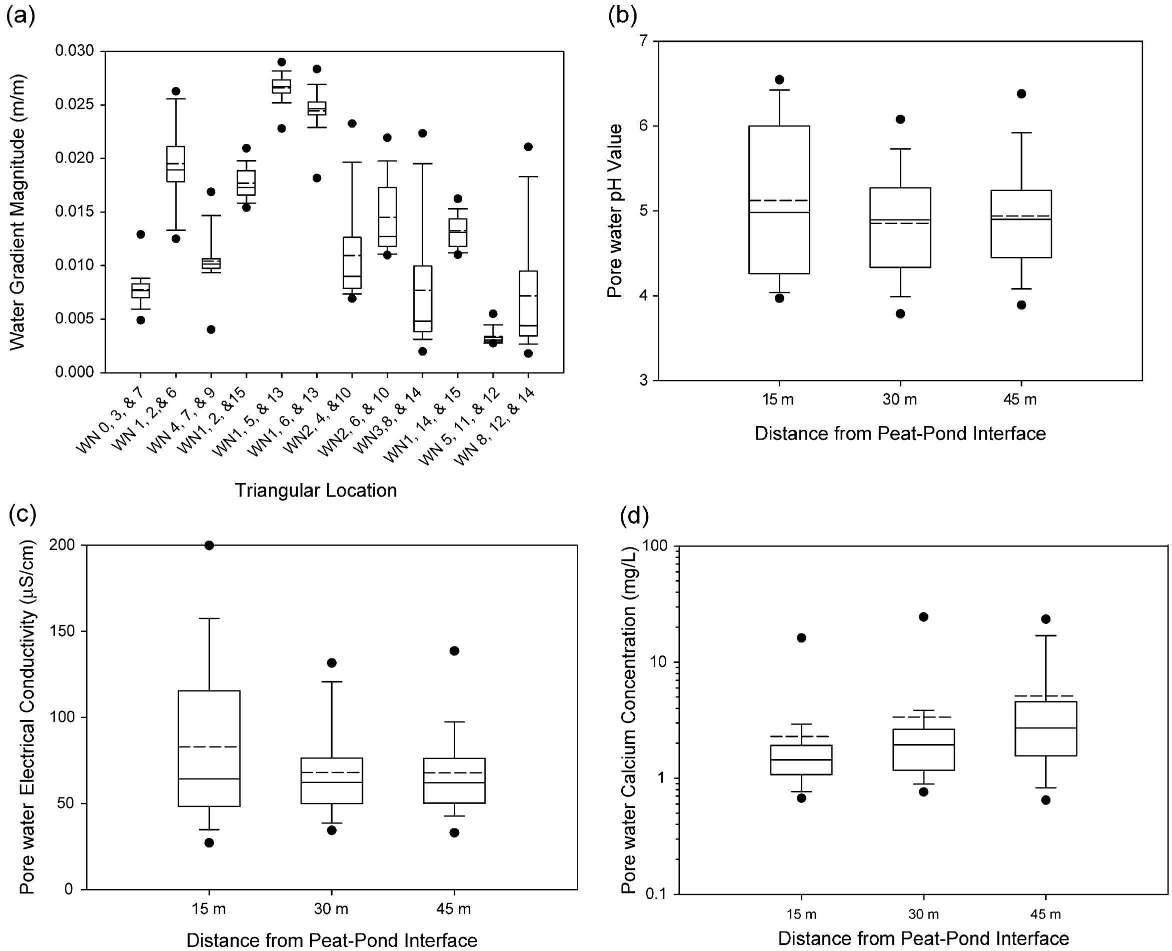

Fig. 6. Box plots versus distance (or location) from the peat–pond interface. The median, or 50th percentile, is the solid line that divides the box; the mean, or average value, is the broken line. The 25th and 75th percentiles are represented by the ends of the box. The 'whiskers' define the 10th and 90th percentile values. The solid circles represent the 5th and 95th percentiles. (a) Horizontal water gradient magnitudes (m/m), (b) pore-water pH values, (c) pore-water conductivity values (μS/cm), (d) [Ca^{2+}] in the peat pore-water (mg/l).

4.2. Geochemistry

4.2.1. Pore-water pH

There was a significant depth, time, and depth × time effect on pore-water pH values (Table 2). The mean pH values increased as well depth increased, 4.64, 4.92, and 5.29, respectively (Fig. 6b). Mean pH values decreased from 5.12 to 4.86 between 15 and 30 m from the peat–pond interface, yet increased from 4.86 to 4.94 between the 30 and 45 m distances (Fig. 7b).

Variograms developed for pH values showed the correlation distance to decrease with well screen depth while time correlation increased with well screen depth. Spatial variograms for pH exhibited range and sill values between $a=20$–22 m and $w=0.32$–0.45, respectively (Table 3). Temporal variograms for pH showed time lags between $a=27$–79 days and sill values between $w=0.32$ and 0.69 (Table 3). The kriged pH values and the error variance for a depth of 1 m are plotted over the study area (Fig. 8). Kriged pH values follow head levels; where pore-water head values were consistently higher than other locations of the bog, i.e.

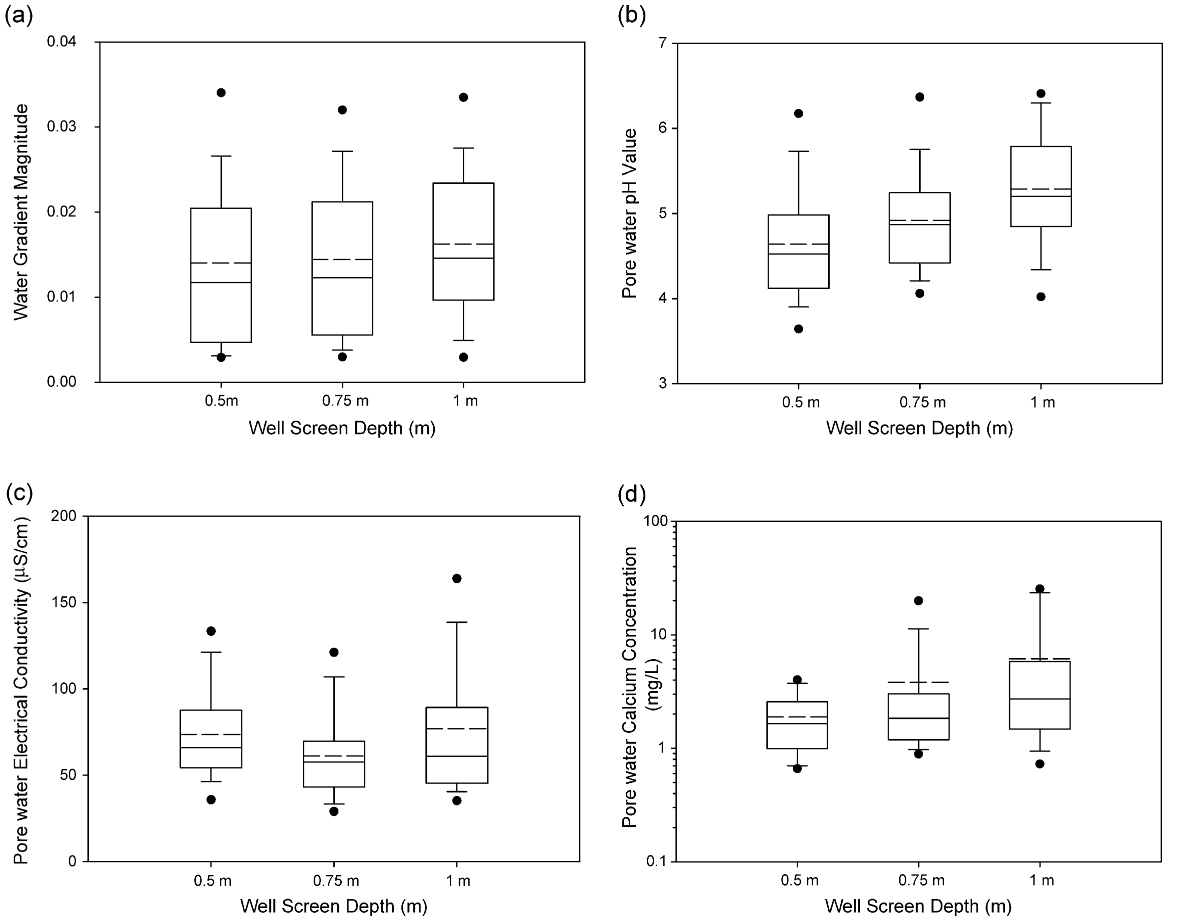

Fig. 7. Box plots versus well screen depth. (a) horizontal water gradient magnitudes, (b) pore-water pH values, (c) pore-water conductivity values (μS/cm), (d) [Ca^{2+}] in the peat pore-water (mg/l).

WN 2, the pH remained consistently acidic (pH ~ 4) at each screen depth. In locations where the flow reversal occurred (WN 3, 8, 20, 21), the pH was higher (more neutral) than other sections of the bog.

4.2.2. Pore-water electrical conductivity

The pore-water electrical conductivities showed a significant depth, distance × depth and depth × time effect (Table 2). Mean EC values decreased between

Table 3
Range and sills for pH, EC, and [Ca^{2+}] and Lag and sills for pH

Parameter	Well depth (m)	Range (*a*)	Spatial Sill (*w*)	Lag (*a*)	Temporal sill (*w*)
pH	0.50	22	0.43	27	0.32
pH	0.75	21	0.32	65	0.66
pH	1.0	20	0.40	79	0.69
EC (μS)	0.50	24	900	–	–
EC (μS)	0.75	23	600	–	–
EC (μS)	1.0	20	1,250	–	–
[Ca^{2+}] (mg/l)	0.50	26	1.1	–	–
[Ca^{2+}]	0.75	23	0.85	–	–
[Ca^{2+}]	1.0	26	1.7	–	–

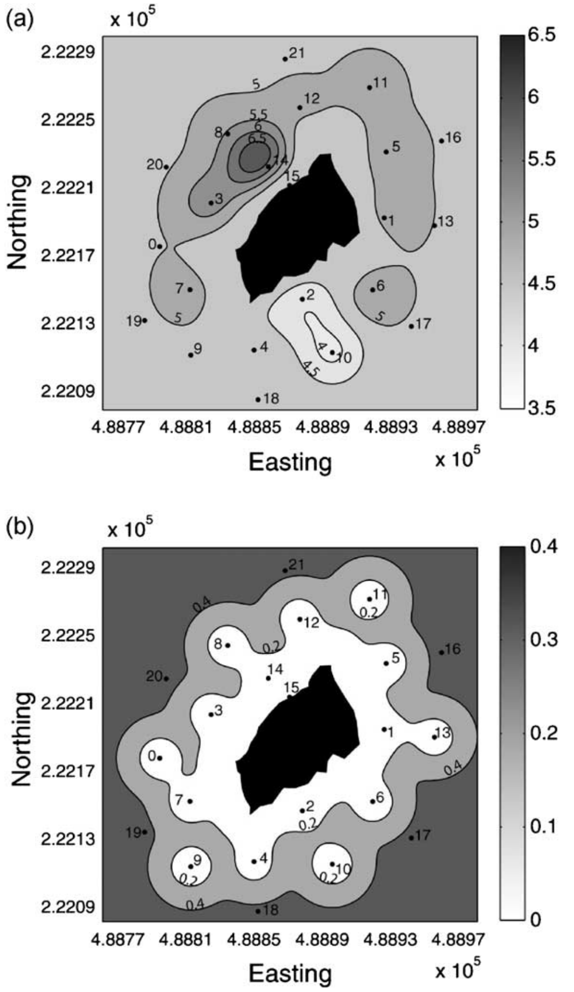

Fig. 8. Kriged pH values (a) for 1 m wells and (b) their error variance.

15 and 30 m from the pond–peat interface, but remained relatively the same between 30 and 45 m (Fig. 6c). Mean EC values decreased between the 0.5 and 0.75 m wells, but increased between the 0.75 and 1 m wells (Fig. 7c).

Spatial variogram ranges for EC varied between $a=20$–24 m, decreasing with well screen depth (Table 3). The sill values in the peat wells were much larger than expected ($w=600$–1250 μS/cm) indicating that more variance exists with the measurement of EC. EC values were largest in locations where hydraulic heads indicated a flow reversal, near WN 3 and 14, however, the large sill values indicate significant errors are associated with EC values.

4.2.3. Pore-water calcium ion concentration

The ANOVA on log-normally transformed pore-water [Ca^{2+}] indicated a significant depth, time, distance×time and depth×time effect (Table 2). Mean [Ca^{2+}] increased with distance from the pond, with mean concentrations of 2.29, 3.37, and 5.13 mg/l in the 15, 30 and 45 m wells, respectively (Fig. 6d); however, these effects were not statistically significant ($P=0.0733$, Table 2). The mean [Ca^{2+}] increased with well depth, with concentrations of 1.89, 3.81, and 6.16 mg/l in the 0.5, 0.75, and 1 m wells, respectively (Fig. 7d).

Spatial variogram range and sill values for [Ca^{2+}] showed no consistent trend with depth, ranging between $a=23$–26 m and $w=0.85$–1.7 mg/l, respectively (Table 3). The [Ca^{2+}] remained low in locations where hydraulic head values were typically higher than the pond elevation (WN 1 and 2) and were larger in locations where flow reversals occurred.

4.3. Pitcher plant density (S. purpurea)

A stepwise multiple regression model was constructed using depth, distance, and pore-water ion concentrations as the independent variables and pitcher plant density as the dependent variable. The distance from pond–peat interface (m), [Fe^{3+}], [Na^{+}], [Cl^{-}], and [SO_4^{2-}] had significant regression model results ($P<0.001$), $R^2=0.825$ (Fig. 9).

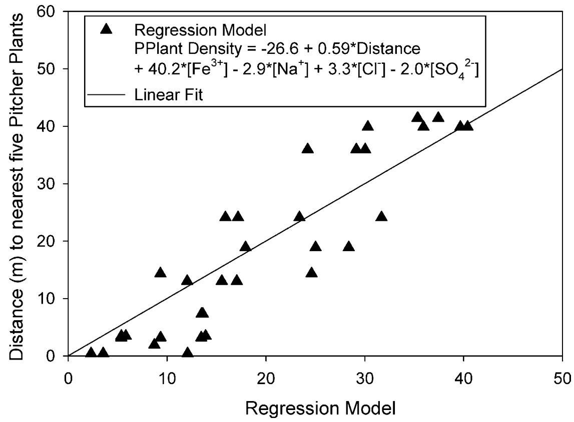

Fig. 9. Plot of regression model score of distance from the pond–peat interface (m), [Fe^{3+}], [Na^{+}], [Cl^{-}], and [SO_4^{2-}] versus average distance (m) to the nearest five pitcher plants (pplant) from well locations. Statistics from the regression model showed a $R^2=0.825$, F-stat$=33.01$, and significance ($P<0.001$).

As the regression model score increases (positive x) the distance to the nearest five pitcher plants (plant density) decreases (positive y). The largest pitcher plant density corresponded to distances closer to the peat–pond interface, lower concentrations of [Fe^{3+}] and [Cl^{-}], and higher concentrations of [Na^{+}] and [SO_4^{2-}].

5. Discussion

5.1. Water balance

Molly Bog is operating close to a true ombrotrophic bog, with the majority of inputs from precipitation and losses through evapotranspiration. Between September 2001 and October 2002, Molly Bog was recovering from a drought condition, with an overall increase of 438 mm water storage Similarities between the simplified water balance and pore-water hydraulic heads reflected in continuously monitored wells provided confidence in the use of the Priestly–Taylor model for evapotranspiration estimations. Precipitation events affected the pond and peat water elevations differently depending upon the season (Figs. 2 and 3). Rainfall events in June were reflected almost simultaneously in the pressure transducers. The impact from precipitation on the pore-water in peat peat was immediate and slightly dampened; precipitation moved quickly through the semi-saturated peat reaching equilibrium. In contrast, rainfall events recorded during August and September created only slight changes in pond water level, yet produced delayed and additive effects in the 1 m well. The peat was visibly much dryer during these months; therefore all precipitation was held tightly by peat capillary forces at the surface until additional rainfall events forced water deeper into the peat column.

A significant amount of annual precipitation at Molly Bog falls as snow and is frozen at the peat surface until the spring melt. This results in a continuous and slow recharge of water to the peatland between April and July of each year and a net storage gain in the water balance. During the spring melt period, infiltration drainage of snowpack dominates peat flow direction. Because a large portion of precipitation in Vermont is from snow, approximately 25%, this is an important process to consider in the development of kettlehole bogs. Snowpack may contribute a significant amount of excess water during times when evapotranspiration processes would typically dominate peatland water storage processes. Therefore, a dry winter may have detrimental effects on a peatland if evapotranspiration is much greater than spring precipitation.

5.2. Local and regional water table position

There is limited subsurface recharge and discharge based on the local-regional water table interactions between 1 and 3 m wells around the perimeter of the bog. The limiting factor is the rate at which water passes through the clay layer, whose thickness is non-homogeneous across the bog. The regional head drop between Molly Bog and Lawrence Brook suggests that a head gradient is present between the water bodies, however, transfer between peat and the clay layer is minimal according to our water budget. If head levels were to drop below their current level in Lawrence Brook, however, the rate of flow through the clay layer may increase to maintain equilibrium.

Hydraulic heads in shallow groundwater wells (1 m) located in the peat at distances of 60 m from the pond–peat interface typically fluctuated with the pond elevation. Heads in the deep groundwater wells (3 m) varied by location around the bog; the south and eastern portion of the bog are hydraulically isolated from peat pore-waters while the north and western portion of the bog are hydraulically connected to peat pore-waters. Hydraulic heads from WN 17 suggest there may be a confining layer acting as a shallow aquitard in this area, showing over 0.5 m greater than heads in its respective 1 m. In contrast, the 3 m well located at WN 19 appear to be changing with the 1 m wells, with a slight delayed response, showing an obvious hydraulic connection. Regionally, it makes sense that if a hydraulic connection existed, the peatland would drain to Lawrence Brook (located to the north) and corresponds to estimated flow patterns by Sanderson et al. (1993).

Hydraulic heads in peat show a flow reversal in the northwest portion of the bog between dry and wet periods of the year, which is also reflected by pH, EC, and [Ca^{2+}] values in WN 3, 8, 14, and 21. Fraser et al. (2001a) noticed EC values increased as much as 60%

during a flow reversal from groundwater discharge. On a local setting, Molly Bog has fluctuations based on dryness of the peat and the magnitude of evapotranspirative processes after precipitation events. On a regional scale, the bog appears to be slowly discharging to the wetland and Lawrence Brook, with a difference of water head elevation of approximately 5 m.

5.3. Flow patterns, geochemistry, and geostatistics

Water gradient magnitudes varied with triangular location with the largest gradients on the southern and eastern portion of the peatland and the smallest gradients on the northern and western portion of the peatland We hypothesize that larger gradients exist in the perched zone because precipitation and evaporation processes in the peat are isolated from the groundwater, making overall fluxes larger in this area. Gradient magnitudes were very similar to those reported by Reeve et al. (2000) and Fraser et al. (2001a).

Horizontal water gradient magnitudes, pH, EC, and $[Ca^{2+}]$ all had significant depth effects. Spatial variogram range (a) and sill (w) values were similar between chemical constituents and exhibited ranges smaller than expected ($\sim$22 m). Peatland studies with piezometers located at distances $>$22 m (Bradley, 1996; Fraser et al., 2001a) may be missing flow reversal locations. Additionally, our well placement design allowed identification of current and historical flow reversals. This may not be possible with parallel and/or perpendicular piezometer transects seen in previous studies (Price, 1997; Waddington and Roulet, 1997; Fraser et al., 2001b). Temporal lag (a) and sill (w) values for pH significantly increased with well depth. The increased variability at the surface may be due to increased biological activity and aerobic degradation. The upper peat profile (top 0.5 m) is the location where the majority of oxygen is present, resulting in increased decay activity. The correlation in the deep peat profile is also an indication of the rate at which water is moving in this zone; precipitation and evapotranspiration process are altering pH values in the shallow peat surface while these processes have a limited effect in the deeper peat.

No significant distance effects were shown for any chemical constituents, indicating horizontal flow does not appear to be contributing the largest variability to pore-water chemistry at Molly Bog. Water gradient magnitude, pH, and $[Ca^{2+}]$ had significant time effects, an expected result if precipitation and evapotranspiration are dominant hydrologic processes. No significant temporal effect was shown for EC. Since values of EC are a relative measure of the combined source waters, it is dominated more by seasonal flow reversals and groundwater discharge. Therefore, effects may be significant when evaluated on a longer time period. The three water chemical components had significant depth$\times$time interaction effects, indicating that our depth measurements are time dependent. This indicates that additional processes are contributing to changes in chemical components between well screen depths and through time.

Despite the high error variance associated with sill values for EC, the higher kriged pH values correlated nicely with the location of the flow reversal (WN 0, 3, 8, and 20) while low kriged pH values were located in areas with the highest head values (WN 1, 2).

5.4. Pitcher plant density (*S. purpurea*)

At broader spatial scales, pitcher plants (and other carnivorous plants) are restricted to microhabitats with high sunlight and low nutrients (Givnish et al. , 1984). At higher nutrient concentrations, carnivorous plants are often replaced by superior competitors that can efficiently use soil nutrients (Ellison, 2003). Increased nitrogen deposition has been implicated in the local extinction of *Sphagnum* (Press et al., 1986), and in a shift from Calluna-dominated heathland to grassland (Heil and Diemont, 1983). Our results demonstrate that variation in abundance of *S. purpurea* within a bog is also sensitive to the concentration of macro and micronutrients $[Fe^{3+}]$, $[Na^{+}]$, $[Cl^{-}]$, and $[SO_4^{2-}]$ and distance to a rain-fed constant head source.

6. Conclusion

Molly Bog is precipitation dominated with limited regional groundwater influences The pH, EC, and [Ca^{2+}] are typical of true ombrotrophic bogs around the world, although a flow reversal during the wet season produces higher values of chemical constituents in isolated areas of Molly Bog. This flow reversal appears to influence surface vegetation, ion concentration, and pitcher plant density.

The detailed statistical well placement design in Molly Bog made it possible to identify effects of radial distance from an open pond, depth, and time on water gradient magnitudes, pH, EC, and [Ca^{2+}]. Distance and depth effects for water gradients, pH, EC, and [Ca^{2+}] are important from a restoration techniques. While the distance to a constant head source (i.e. blocked ditches in a cutover peatland) discussed by Schlotzhauer and Price (1999) may be important for maintaining continuous re-growth and moisture in a restored peatland, the ion water chemistry may have much more of an effect on the growth of rare plant species (i.e. pitcher plants).

Spatial variograms confirmed the effect of distance on pH, EC, and [Ca^{2+}] while temporal variograms and the use of geostatical kriging of pH confirmed the effects of distance, depth, and time on pore-water chemistry and was valuable in identifying locations of the flow reversal in Molly Bog. As depth from the surface increased, variogram time lags for pH increased drastically which is useful in estimating how often samples need to be taken to ensure independence below 1 m in Molly Bog.

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