

Simulating soil water dynamics in a cutover bog

G. W. Kennedy

Department of Earth Science, University of Waterloo, Waterloo, Ontario, Canada

J. S. Price

Department of Geography, University of Waterloo, Waterloo, Ontario, Canada

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[1] A simulation model flow in cutover peat systems (FLOCOPS) was developed to improve the current understanding of the hydrology of cutover peatlands and the water management programs designed to restore them. FLOCOPS considers temporal variability in peat bulk density, shrinkage character and θ - Ψ (soil moisture–pressure head) relationships, volume changes due to compression, and changes to saturated hydraulic conductivity (K_s) and saturated volumetric soil moisture (θ_s). FLOCOPS was evaluated by comparing simulated and observed 1998–1999 trends in elevation change (thickness of peat deposit), water table, θ , and Ψ . FLOCOPS effectively represented observed trends in elevation change, θ , and Ψ . A sensitivity analysis indicated that FLOCOPS was most sensitive to the retention, storage, and consolidation characteristics of the peat. Volume changes reduced hydrological variability, whereas low water retentivity and high water storage helped maintain high and stable θ , Ψ , and water table position. The sensitivity of the peat system's hydrology to changes in pore structure suggests that minimizing changes to the peat's characteristic pore structure during extraction and subsequent abandonment of the peatland will result in significantly more favorable hydrological conditions for bog restoration. *INDEX*

TERMS: 1829 Hydrology: Groundwater hydrology; 1832 Hydrology: Groundwater transport; 1866 Hydrology: Soil moisture; 1890 Hydrology: Wetlands; *KEYWORDS:* modeling, peat, peatland

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1. Introduction

[2] During bog restoration the survival of *Sphagnum* diaspores that are reintroduced to cutover peatlands relies on the availability of soil moisture near the peat surface [Price and Whitehead, 2001]. Nonvascular *Sphagnum* moss, the primary peat-forming vegetation, exerts relatively weak capillary pressure in its hyaline cells and interstitial spaces [Hayward and Clymo, 1982] to draw water from the soil and hence requires a high and stable supply of soil moisture not generally available in cutover peatlands [Price, 1997]. To plan appropriate restoration designs for *Sphagnum* reestablishment, it would be helpful to be able to predict seasonal patterns of water table (WT), volumetric moisture content (θ), and pressure (Ψ). Conventional models are ineffective at simulating the hydrology of cutover peatlands because they do not consider the important effects of soil shrinking and swelling [Nuttle et al., 1990; Chow et al., 1992; Price and Schlotzhauer, 1999] on the system's hydrological functioning. Price [2003] proposed that effective modeling of cutover peat systems will require dynamically variable hydraulic parameters, such that the peat's

hydraulic conductivity and water retention relationships (θ - Ψ) are expressed as an explicit function of strain or deformation.

[3] The conceptual model of the hydrology of cutover peatlands presented by Kennedy and Price [2004] illustrates the important linkages between short-term temporal variability in peat pore structure due to volume change and the system's hydrological behavior. Soil volume changes in fibric, cutover peats are essentially one-dimensional (vertical), caused by peat compression below the water table and shrinkage above it [Kennedy and Price, 2004]. Compression is the result of changes in effective stress caused by changes in water table position, whereas shrinkage is due to the contraction of the peat matrix as pore water suctions increase upon drying. Shrinkage and compression are important because they allow peat soils to maintain a higher water table (relative to the ground surface) and wetter moisture conditions than rigid soils. The reduction in peat pore volume results in decreased hydraulic conductivity (K) and greater water retention [see also Chow et al., 1992; Price, 2003]. The objectives of this research were (1) to develop a model to simulate peat deformation and its effect on the soil's hydraulic properties in both saturated and unsaturated conditions; (2) to evaluate the performance of the model through comparison of simulated WT, peat elevation change, and near-surface volumetric soil moisture (θ) and pressure

head (Ψ) with a set of field observations; and (3) to investigate the sensitivity of the model to peat volume change phenomena.

2. Modeling Approach

[4] *Kellner and Halldin* [2002] found that water transport and storage in a mire were basically one-dimensional (1-D) and suggested that a 1-D flow model designed to work in mineral soils could be adapted to simulate the unique hydrologic behavior of peats. *Kennedy and Price* [2004] used a 1-D conceptual model to represent post snowmelt water transport and the important linkages between peat volume change and the hydrology of a cutover bog in Lac-Saint-Jean (LSJ), Quebec (drainage ditches blocked). Most current applications of consolidation models involve the prediction of soil settlement due to an applied load. Several numerical flow models, e.g., ECOUL [*Garnier et al.*, 1997] and FLOCR 2.0 (Flow in Cracking Soils) [*Oostindie and Bronswijk*, 1992], can consider the transient shrinkage behavior of deformable clays but do not include a dynamic hydraulic parameter response linked to soil volume change. Because the model FLOCR can simulate 1-D shrinkage and flow in variably saturated media using actual meteorological input, it was suitable for adaptation to simulate the hydrology of cutover peats. A review of FLOCR is given by *Bronswijk* [1988, 1989]; a summary is given here.

2.1. Description of FLOCR Model

[5] FLOCR is a 1-D block-centered, finite difference, explicit numerical model for transient unsaturated vertical flow that can simulate water balance, cracking, and surface subsidence in clays [*Bronswijk*, 1988, 1989]. In addition to the moisture retention and hydraulic conductivity curves typically used in variably saturated flow models, FLOCR features the incorporation of the soil shrinkage characteristic (SSC) into model parameterization. The SSC is the empirical relationship between moisture ratio (volume of moisture/volume of solids) and void ratio (volume of voids/volume of solids), related by

$$\theta = \frac{v}{1+e}, \quad (1)$$

where v is the moisture ratio and e is the void ratio. Other required input includes the soil profile description, boundary conditions, soil material properties, and meteorological input.

[6] FLOCR calculates unsaturated vertical water flow in the same manner as in typical rigid soil models, relying on the Darcy equation for vertical flow:

$$v = -K \left(\frac{\partial \Psi}{\partial z} \right) + 1, \quad (2)$$

where v is the vertical flow velocity (cm d^{-1}), K is the vertical hydraulic conductivity, z is the depth (cm) (negative in downward direction), and Ψ is the pressure head (cm) (negative in unsaturated soil). First, Ψ is computed according to the moisture retention curve, relating the peat's assigned volumetric moisture content profile to values of capillary pressure [*Oostindie and Bronswijk*,

1992]. Using the computed values of Ψ , FLOCR calculates K of each variably saturated soil layer as a function of saturated hydraulic conductivity (K_S) and Ψ [from *Rijtema*, 1965]:

$$K(\Psi) = K_S \exp(\beta \Psi), \quad (3)$$

where $K(\Psi)$ is the unsaturated hydraulic conductivity (cm d^{-1}), K_S is the saturated hydraulic conductivity (cm d^{-1}), and β is the slope or gradient of the exponential relation (cm^{-1}).

[7] Then, vertical flow velocity through the soil profile within each time step is calculated using a 1-D integrated form of the Darcy equation (4) derived by *Wind* [1972] and *Wind and van Doorne* [1975] by differentiating (3) with respect to z , substituting in (2), and then solving the resulting linear equations to yield the expression

$$v_i = \frac{K_i - K_{i-1}}{\exp(\beta \Delta b_i) - 1} - K_{i-1}, \quad (4)$$

where v is the vertical flow velocity (cm d^{-1}) over the internodal distance Δb_i (cm) of consecutive soil layers (constant during one time interval) and i is the soil layer index. The flow calculation assumes that Ψ is a differentiable function of z and that the distances between nodal points are constant within each time interval but are adapted when the next time step starts. The change in a layer's moisture content is subsequently calculated in FLOCR by substituting the flow velocities in (4) into the continuity equation

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z}. \quad (5)$$

The change in a soil layer's moisture content over each time step is therefore

$$\Delta \theta_i = (v_i - v_{i-1}) \frac{\Delta t}{\Delta b_i}, \quad (6)$$

where Δt is the time step.

[8] Following the calculation of moisture content, FLOCR calculates volume change directly from the empirical soil shrinkage characteristic. The water content of each unsaturated soil layer is converted to a moisture ratio, and the void ratio corresponding to the calculated moisture ratio is interpolated from the SSC. The change in peat volume is converted to a change in thickness according to

$$\Delta z = z_1 - (V_2/V_1)z_1, \quad (7)$$

where V_1 and V_2 are the volume (cm^3) of the peat layer before and after shrinkage/swelling, respectively, and z_1 is the layer thickness before shrinkage or swelling (cm).

2.2. Scope of Required Changes to FLOCR Model

[9] Field studies of peat volume change phenomena [e.g., *Kennedy and Price*, 2004; *Price*, 2003] suggest that it is necessary to modify FLOCR to consider compression and transience in hydraulic properties. FLOCOPS (flow in cutover peat systems) was developed by adapting the FLOCR code, using Visual FORTRAN, according to the

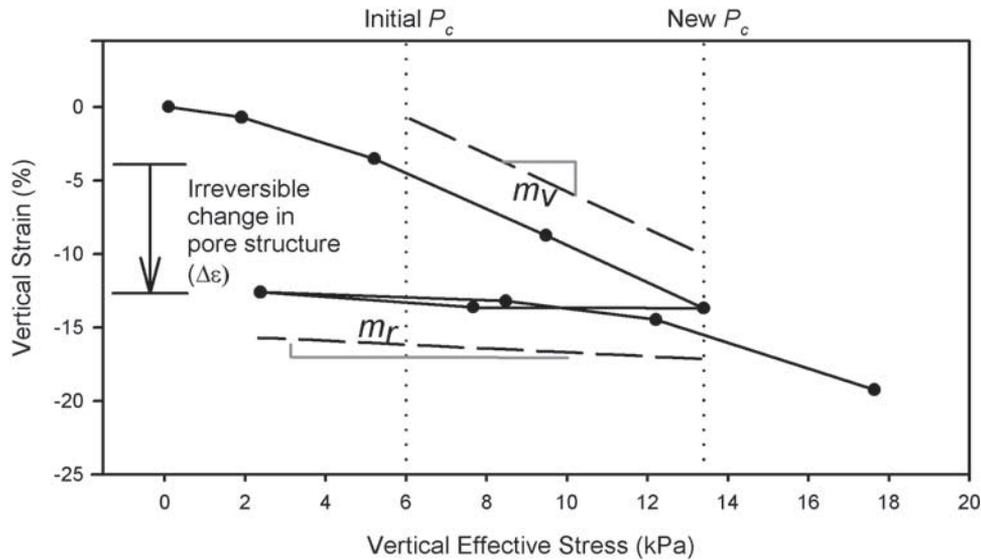


Figure 1. Consolidation plot of the Lac-Saint-Jean peat material [from Lang, 2002]. At effective stresses greater than the preconsolidation pressure (P_c), consolidation follows the virgin compression curve (m_v), whereas at stresses below the P_c , consolidation follows the recompression curve (m_r).

conceptual model of the cutover peat system presented by Kennedy and Price [2004]. FLOCOPS estimates compression according to Terzaghi's [1943] consolidation theory, which was reviewed by Kennedy and Price [2004] in relation to peat soils and is summarized here. Briefly, compression is attributed to changes in effective stress (σ') on saturated peat layers caused mostly by fluctuations in pore water pressure (u) and comprises primary consolidation (δ_p) and secondary compression (δ_s) components [Lang, 2002]. Effective stress is estimated as

$$\sigma' = \sigma - u, \quad (8)$$

where σ is the total normal stress and u is the pore water pressure. The consolidation rate depends on whether σ' exceeds the soil's preconsolidation pressure (P_c). A consolidation plot showing the stress-strain dynamics of saturated peat material from the Lac-Saint-Jean cutover bog, under loading and unloading conditions, is illustrated in Figure 1. Vertical strain (ϵ) is related to void ratio according to

$$\epsilon = \frac{\Delta e}{1 + e_0}, \quad (9)$$

where e_0 is the soil's initial void ratio. Soil volume changes at effective stresses below the peat material's P_c occur along the recompression curve (m_r), whereas volume changes at stresses above the peat's P_c occur along the virgin compression curve (m_v).

2.3. FLOCOPS: Unsaturated Zone

[10] The model's dynamics with respect to unsaturated peat layers is discussed first because the evaluation of stress and compression in the saturated zone is partly dependent on the weight of overlying unsaturated layers. FLOCOPS evaluates the effective stress profile of unsaturated peat layers after each time step. If the previous maximum stress,

or preconsolidation pressure, of a peat layer is not exceeded (i.e., $\sigma' < P_c$), then reversible shrinkage is simulated according to the soil's empirical SSC. Since drainage and extraction cause overconsolidation of the peat [see Lang, 2002], it is likely that most volume changes due to shrinkage are reversible. If an increase in σ' above the unsaturated peat layer's P_c occurs, however, there is an irreversible decrease in void ratio. Significant negative pressure caused by high evaporative demand [Price, 1997] may produce stresses exceeding the material's P_c near the peat surface, causing irreversible changes to the peat's void ratio and hence to hydraulic properties. Schlotzhauer and Price [1999] and Kennedy and Price [2004] attributed decreased peat compressibility and increased moisture retentivity over time to irreversible losses in peat pore volume. FLOCOPS estimates irreversible changes in void ratio in the unsaturated zone according to the stress-strain relationship of saturated peat (Figure 1) and simulates the effect of decreased void ratio on the peat's θ - Ψ , K_s , and shrinkage character.

2.3.1. Calculation of Effective Stress

[11] The effective stress experienced by an unsaturated soil layer (equation (6)) can be estimated as the (negative) pore water pressure (u) subtracted from the total stress (σ) due to vertical overburden, which varies with the bulk density and thickness of overlying peat [Kennedy and Price, 2004]. Hence estimation of the mean bulk density of overlying unsaturated peat layers (ρ_u) is necessary to evaluate the σ profile. The calculation of ρ_u over any specified depth interval considers changes in moisture content and dry bulk density (ρ_d), which increases as the soil dries and undergoes shrinkage, so that

$$\rho_u = \sum_{i=1}^n \left(\theta_{(i)} \rho_w + \rho_{d(i)} \frac{z_0(i)}{z(i)} \right) \frac{z(i)}{b}, \quad (10)$$

where ρ_u is the mean bulk density of the unsaturated peat over the specified depth interval (g cm^{-3}), ρ_w is the density

of water (1 g cm^{-3}), ρ_d is the dry bulk density of the peat based on its volume at saturation (no shrinkage) (g cm^{-3}), z_0 is the layer thickness at the start of the simulation (cm), z is the layer thickness (cm) of element i , b is the thickness of the specified unsaturated interval (cm), and n is the number of unsaturated layers. The subscript (i) denotes a layer element.

[12] The mean bulk density of overlying peat layers is calculated at each nodal depth in the unsaturated zone, permitting the evaluation of the complete unsaturated σ' profile. Effective stress is calculated by subtracting u (expressed as $\rho_w g \Psi$) from σ at the peat layer's midpoint or node:

$$\sigma'_i = \rho_u g (b_{(i)} - 0.5z_{(i)}) - \rho_w g \Psi_{(i)}, \quad (11)$$

where σ' is the effective stress (kPa), ρ_u is the mean bulk density of the overlying peat (g cm^{-3}), g is acceleration due to gravity (981 cm s^{-2}), $b_{(i)}$ is the distance from the peat surface to the bottom of the layer boundary (cm), and Ψ is the pressure head (cm), expressed as a negative value. In the mechanical evaluation of σ' in the unsaturated zone, Ψ is typically multiplied by a coefficient χ , known as the Bishop's parameter, which varies from 0 to 1 with increasing degree of saturation as a unique function of the soil [Bishop and Blight, 1963]. FLOCOPS assumes χ to be constant at 1, which may cause σ' to be overestimated when the soil is very dry.

2.3.2. Irreversible Peat Shrinkage

[13] Each layer of the soil profile is assigned a P_c value at the start of the simulation period, allowing the soil's previous loading history to be considered. The P_c is the critical stress value delimiting whether an irreversible decrease in peat volume due to shrinkage (in the unsaturated zone) occurs, thus causing a change to the soil layer's K_S and to θ - Ψ and SSC relationships. During a model simulation, if σ' in any given unsaturated layer exceeds the layer's assigned P_c value, an irreversible decrease in e_s (maximum void ratio) occurs, and the current σ' value is recorded as the layer's new P_c . The maximum void ratio is the void ratio of the peat layer at time (t) if it were rewetted to saturation.

[14] The magnitude of the change in e_s per unit change in σ' depends on the peat's coefficient of volume compressibility obtained graphically from Figure 1. The coefficient of volume compressibility, assumed to be constant over the range of stresses encountered in the field [Lang, 2002], is defined as the volume change per unit volume, per unit increase in effective stress,

$$m_v = \frac{1}{1 + e} \left(\frac{-\Delta e}{\Delta \sigma'} \right), \quad (12)$$

where m_v is the coefficient of volume compressibility along the virgin consolidation line ($\text{m}^2 \text{ kN}^{-1}$), Δe is the change in void ratio, and $\Delta \sigma'$ is the change in effective stress (kPa). Equation (12) can be rearranged to solve for the decrease in maximum void ratio (Δe_s) due to irreversible shrinkage,

$$\Delta e_s = -m_v \Delta \sigma' (1 + e_{s(t-1)}). \quad (13)$$

The subscript ($t - 1$) denotes the parameter value from the previous time step. The maximum void ratio is then adjusted according to

$$e_s = e_{s(t-1)} + \Delta e_s, \quad (14)$$

where e_s is the updated maximum void ratio. The soil layer's adjusted θ_s can then be calculated as

$$\theta_s = \frac{e_s}{1 + e_s}. \quad (15)$$

Consequently, when the threshold stress (P_c) of a particular soil layer is exceeded, the layer's θ_s will not recover 100% of its prior volume, even if it is completely rewetted to saturation.

2.3.3. Transient Moisture Retention Curve and Shrinkage Characteristic

[15] An irreversible decrease in pore volume due to significant capillary pressures near the peat surface will cause the layer to exhibit greater water retentivity and decreased peat compressibility (i.e., lower shrinkage capacity). On the basis of the updated value for θ_s a new moisture retention curve is generated using the Retention Code (RETC) program [van Genuchten *et al.*, 1991], which is run as an embedded subroutine of FLOCOPS. The RETC model can estimate unsaturated soil hydraulic functions from previously estimated soil hydraulic parameters, such as residual volumetric moisture content (θ_R) and θ_s , and the van Genuchten model's shape parameters (α , n , and m). Following irreversible shrinkage, FLOCOPS generates a new moisture retention curve using the updated θ_s value assigned to the soil layer and the input RETC shape parameters.

[16] It was found that seasonal changes in the peat's in situ θ - Ψ relationship [see Kennedy and Price, 2004; Schlotzhauer and Price, 1999] could be reasonably represented by varying the α shape parameter in the van Genuchten *et al.* [1991] model linearly with θ_s (keeping n and m constant) [Kennedy, 2002]. On the basis of these findings the following relationship is used in FLOCOPS to simulate the effect of a smaller pore diameter on the shape of the moisture retention curve (greater retentivity):

$$\alpha = [1 - H(\theta_{s(0)} - \theta_s)] \alpha_{(0)}, \quad (16)$$

where α is the shape parameter (cm^{-1}), $\alpha_{(0)}$ is the initial value for the retention curve's RETC shape parameter (cm^{-1}), θ_s is the updated saturated volumetric moisture content, $\theta_{s(0)}$ is the initial saturated volumetric moisture content, and H is an empirical constant.

[17] The soil shrinkage characteristic must also be modified to account for the irreversible decrease in e_s and hence in compressibility of the unsaturated peat layer. FLOCOPS uses a simple graphical technique to scale the layer's SSC to the new e_s value, as described in Figure 2 [Kennedy, 2002].

2.3.4. Transient Hydraulic Conductivity

[18] An irreversible decrease in the unsaturated peat layer's pore volume also causes a decrease in hydraulic conductivity. FLOCOPS uses the theoretical relationship

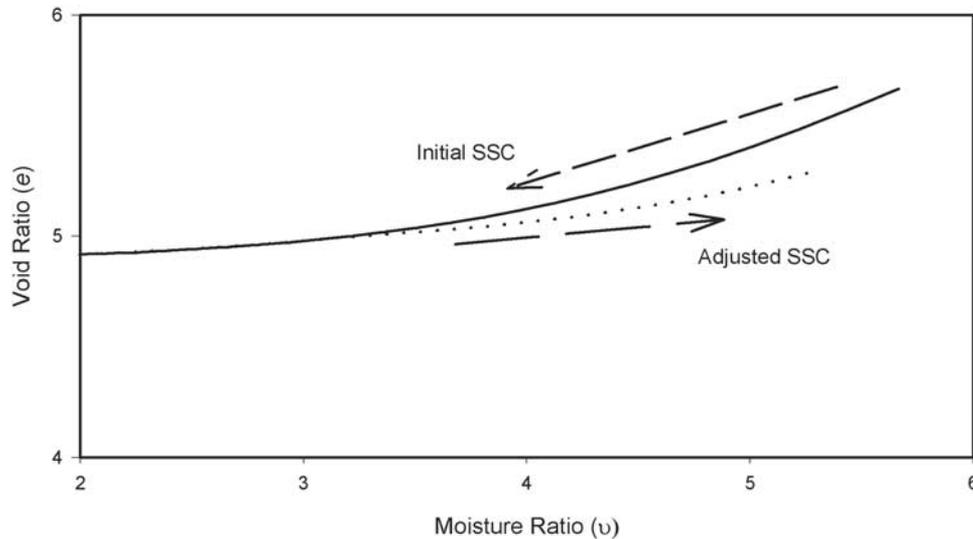


Figure 2. Transformation of a peat layer's soil shrinkage characteristic (SSC). If σ' does not exceed the peat layer's P_c , peat shrinkage and swelling will follow the initial SSC. If, however, σ' exceeds the layer's P_c , an irreversible decrease in void ratio at saturation is simulated, altering the shape of the SSC. The portion of the peat layer's SSC where e is greater than the layer's current void ratio is scaled to the new maximum void ratio, and peat swelling will follow the adjusted SSC upon rewetting.

between e and K_S expressed by *Narasimhan and Witherspoon* [1977] to estimate the decrease in K_S due to a peat layer's reduction in e_s ,

$$K_S = K_{S(t-1)} \exp \left[\frac{2.303(e_s - e_{s(t-1)})}{C_k} \right], \quad (17)$$

where $K_{S(t-1)}$ is the saturated hydraulic conductivity of the previous time step (cm d^{-1}) and C_k is the best-fitting straight line for the e versus $\log K_S$ relationship. FLOCOPS calculates K as a function of K_S according to (3).

2.4. FLOCOPS: Saturated Zone

[19] FLOCOPS was modified to consider compression of saturated peat layers and consequent changes to K_S and water storage (θ_s). In the saturated zone a peat layer's thickness is adjusted according to *Terzaghi's* [1943] 1-D consolidation theory, with changes in σ' acting upon the layer's upper boundary because of a change in hydraulic head causing a change in layer thickness.

2.4.1. Calculation of Effective Stress

[20] The effective stress at any depth in the saturated zone is calculated by subtracting the pore water pressure from the total stress due to the combined overburden of both unsaturated and saturated peat layers:

$$\sigma'_{(i)} = [\rho_u g(-WT)] + [g(\rho_s - \rho_w)(WT + b_{(i)} - 0.5z_{(i)})], \quad (18)$$

where σ' is the effective stress (kPa), WT is the depth to the water table relative to the peat surface (cm), ρ_u is the mean bulk density of the unsaturated zone (g cm^{-3}) calculated in (10), ρ_s is the mean bulk density of overlying saturated layers (g cm^{-3}), and $b_{(i)}$ is the distance from the peat surface to the bottom of the soil layer (cm). Saturated bulk density (ρ_s), which varies with peat pore structure, also

affects σ' and can be calculated over any specified depth interval as

$$\rho_s = \sum_{i=1}^n \left(\rho_0 \frac{z_0(i)}{z(i)} \right) \frac{z(i)}{b_{s(i)}}, \quad (19)$$

where z_0 is the layer thickness at the start of the simulation (cm), $b_{s(i)}$ is the saturated thickness over the specified depth interval (cm), and ρ_0 is the bulk density of saturated peat at the start of the simulation (g cm^{-3}).

2.4.2. Peat Compression

[21] An increase in hydraulic head will produce a decrease in σ' in the saturated zone, causing fully saturated layers to expand. Conversely, a decrease in hydraulic head will increase σ' , causing saturated peat layers to compress. Primary consolidation of each saturated layer is calculated as

$$\delta_{p(i)} = m_r \Delta \sigma' g z_{(i)}, \quad (20)$$

where δ_p is primary consolidation (cm), m_r is the coefficient of volume compressibility along the recompression line ($\text{m}^2 \text{kN}^{-1}$), and $\Delta \sigma'$ is the change in effective stress (kPa) acting on the soil layer's upper boundary. The coefficient of volume compressibility m_r is assumed to be constant over the range of stresses encountered in the field [Lang, 2002]. FLOCOPS assumes that primary consolidation is completely reversible because it is expected that the range of σ' values in the field due to water table variability will be less than the peat's P_c (i.e., heavy machinery has been used to remove peat), and consolidation of saturated peat will therefore follow only the recompression curve (m_r) (Figure 1). The approach to modeling consolidation also assumes that m_r is constant with depth and the reaction of z to σ' is instantaneous. *Narasimhan and Witherspoon* [1977] noted that the assumption of an instantaneous reaction of z to σ' is

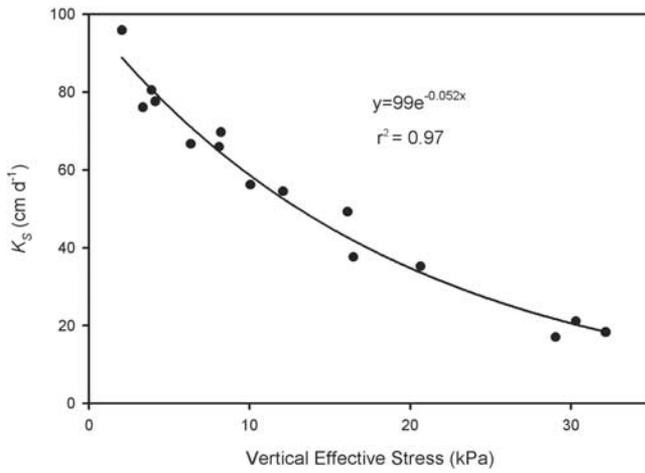


Figure 3. Saturated hydraulic conductivity-effective stress relation from constant head permeability testing of Lac-Saint-Jean peat from H92 [from *Lang, 2002*]. The slope of the equation ($C = -0.052 \text{ kPa}^{-1}$) was used in model parameterization.

valid in soils in which the time required for the dissipation of excess pore water pressure is small. The dissipation of excess pore water pressure was found to be rapid in consolidation tests of the high-permeability cutover peat material [*Lang, 2002*].

[22] Secondary compression, due to the gradual readjustment of the saturated peat matrix under load, occurs as a function of time and can be calculated for each saturated peat layer as

$$\delta_{s(i)} = C_{\text{sec}} \log \frac{d}{d_0} z_{(i)}, \quad (21)$$

where δ_s is secondary compression (cm), d is the number of days since the peat substrate thawed in the spring (marking the onset of $\sigma' > 0$), d_0 is the number of days between spring thaw and the start date of the simulation, and C_{sec} is the dimensionless secondary compression index. *Mesri and Godlewski [1977]* define the secondary compression index as the slope of the straight line portion of the strain versus log time relationship following primary consolidation. In FLOCOPS, volume changes due to δ_s are irreversible, and C_{sec} is assumed to be constant with depth. Since the range of σ' in the saturated zone is expected to be less than the peat's P_c [*Lang, 2002*], C_{sec} is also assumed to be constant over time [*Mesri et al., 1997*]. Hence the total change in saturated layer thickness can be expressed as the sum of primary consolidation and secondary compression components,

$$\Delta z_{(i)} = \delta_{p(i)} + \delta_{s(i)}, \quad (22)$$

where Δz is the total compression of the peat layer (cm).

2.4.3. Compression Storage

[23] A change in layer thickness produces a concomitant change in the saturated layer's storage and a moisture flux (v_c) between the saturated zone and overlying unsaturated layers [*Kennedy and Price, 2004*]. Since δ_p is assumed to be instantaneous, FLOCOPS also assumes that the moisture

flux due to excess pore water pressure is redistributed among unsaturated layers within one time interval. The total amount of moisture exchanged with unsaturated layers is equivalent to the change in saturated zone thickness (Δz_s). Thus, for each unsaturated layer, changes in θ due to v_c are calculated by

$$\Delta \theta_{(i)} = \frac{\Delta z_s}{nz_{(i)}}, \quad (23)$$

where Δz_s is the total compression of the saturated zone (cm) and n is the number of unsaturated layers.

2.4.4. Saturated Volumetric Moisture Content and Hydraulic Conductivity

[24] The saturated volumetric moisture content, and hence maximum void ratio (e_s), will also vary according to changes in saturated layer thickness:

$$\theta_{s(i)} = \frac{\theta_{s(i,t-1)} z_{(i,t-1)} + \Delta z_{(i)}}{z_{(i)}}, \quad (24)$$

where $\theta_{s(i,t-1)}$ is the layer's previous saturated volumetric water content, $z_{(i,t-1)}$ is the previous thickness of the soil layer (cm), and $\Delta z_{(i)}$ is the change in layer thickness (cm). A change in pore structure has hydraulic consequences with respect to K_s . Laboratory permeability tests of cutover peat material sampled from Lac-Saint-Jean showed that saturated hydraulic conductivity varied as an exponential function of applied or effective stress (Figure 3) [*Lang, 2002*]. This relationship is expressed in FLOCOPS as

$$K_s = K_0 \exp(C\sigma'), \quad (25)$$

where K_s is the saturated hydraulic conductivity (cm d^{-1}), K_0 is the initial saturated hydraulic conductivity (cm d^{-1}), σ' is the effective stress (kPa), and C is the empirical slope (or multiplier) in the K_s - σ' relation (kPa^{-1}).

3. Field and Laboratory Methods

[25] The field study was performed from 7 May to 13 August 1999 in a peatland near Sainte-Marguerite-Marie, in the LSJ region of Quebec, Canada ($48^\circ 47' \text{N}$, $72^\circ 10' \text{W}$). The study area is part of a 4315 ha bog-poor fen complex, classified as ombrogenous plateau-bog [*National Wetland Working Group, 1997*], which has developed over a terrace of permeable deltaic sands in the Lac-Saint-Jean lowland because of the presence of an underlying iron pan formation that limits seepage losses [*Price, 1997*]. The iron pan formation effectively isolates the bog from the regional aquifer system, limiting inputs of water and nutrients to direct precipitation only. A more detailed physical site description is provided by *Kennedy and Price [2004]*.

[26] The study focuses on a 7 year post cutover section (H92) of the LSJ bog [*Kennedy and Price, 2004*] because of the availability of field and laboratory results. Drainage and extraction operations commenced in 1990 at this site, and drainage ditches were blocked in 1992. The cutover portions of the bog were drained using a network of ditches

Table 1. FLOCOPS Parameterization Used During Model Evaluation

Parameter	Value
m_v	0.015 m ² kN ⁻¹
m_r	0.0035 m ² kN ⁻¹
C_{sec}	-0.0050
P_c	4.5 kPa
ρ_s	1.04 g cm ⁻³
ρ_d	0.1 g cm ⁻³
θ_S	0.81–0.85
H	20
b	180 cm
K_S	6.1–15.0 cm d ⁻¹
β	0.032 cm ⁻¹
C	-0.052 kPa ⁻¹
a	6.0
C_k	3.6
n	1.1
m	1.0
α	0.01

spaced 30 m apart, and the upper 35–60 cm (acrotelm) of the bog were removed using the Haku technique (block cutting with heavy machinery) [Money, 1995]. The residual peat deposit, which has undergone significant oxidation and compression due to drainage and extraction activities, consists of moderately decomposed peat with a mean dry bulk density of ~ 0.109 g cm⁻³. Comparatively, the mean dry bulk density of peat at an undisturbed section of the site is only 0.052 g cm⁻³. Peat thickness ranges from 1.66 to 1.70 m at the H92 site [Price, 2003]. LSJ peat material can be classified as fibric, with a von Post number of ≤ 4 , even at depth.

[27] The field setup is described by Kennedy and Price [2004] and follows a similar setup as reported by Price [2003] for 1998. Briefly, the site was instrumented to provide continuous measurements of meteorological variables, of water table, using a float potentiometer device, and of θ , using an array of Campbell Scientific™ CSI615 reflectometer probes, calibrated for peat and inserted at depths -5, -20, and -100 cm. Elevation change was recorded weekly by measuring the displacement of aluminum rods anchored at various depths within the peat profile relative to a stable datum. Pressure head was also measured weekly at depths -2, -5, -10, -20, and -50 cm with tensiometers. To assess the FLOCOPS model's performance, simulated results were compared to 1998 and 1999 measured values of elevation change, WT, θ , and Ψ at the H92 site. Sensitivity analyses were subsequently conducted to investigate the hydrological functioning of the cutover peat system.

3.1. FLOCOPS Parameterization

[28] The parameters used in the model are summarized in Table 1. They are also described in sections 3.2–3.6.

3.2. Soil Shrinkage Characteristic

[29] Kennedy and Price [2004] measured the peat's shrinkage characteristic by laboratory drying of resin-coated peat blocks sampled from the site [see also Brasher et al., 1966]. The peat's SSC followed an exponential relationship with normal ($\Delta v = \Delta e$), residual

($\Delta v < \Delta e$), and zero ($\Delta e \rightarrow 0$) shrinkage zones. The exponential relation is described by

$$e = \exp(av) + I, \quad (26)$$

where a is the slope of the $e(v)$ relation and I is an empirical constant. The laboratory SSC could not be directly applied to model parameterization because field θ_S (and e_s) values were lower than laboratory values [Schlotzhauer and Price, 1999; Lang, 2002], and the in situ peat shrinkage response was less pronounced than the laboratory response. In the field, peat material is confined within the structural arrangement of the soil matrix (1-D shrinkage) and cannot deform as freely as a peat sample in the laboratory (3-D shrinkage). The SSC relation was thus transformed so that the maximum void ratio matched in situ values of e_s , and the slope (a) of the exponential relation was decreased to fit the shrinkage response observed in the field (e.g., a 20% decrease in field θ resulted in 2.5 cm of peat shrinkage) [Kennedy and Price, 2004].

3.3. Peat Compressibility

[30] Lang [2002] measured the consolidation characteristics of peat from the H92 site using standard oedometer and Rowe consolidation cells at pressures consistent with those generated by seasonal changes in water table. The mean coefficient of volume compressibility was approximately 0.0035 and 0.015 m² kN⁻¹ along the recompression (m_r) and virgin consolidation (m_v) portions of the curve, respectively, in 1-D multi-increment loading and unloading consolidation tests [Lang, 2002] (Figure 1). The secondary compression index (C_{sec}) obtained from Rowe cell single loading tests was determined to be approximately -0.005. The mean P_c value was determined to be 4.5 kPa, and the dry and saturated bulk densities of the peat were estimated to be 0.1 and 1.04 g cm⁻³, respectively [Lang, 2002].

3.4. Peat Hydraulic Conductivity

[31] Lang [2002] performed Rowe cell constant head permeability tests following primary consolidation (for each load increment) to measure the saturated permeability of H92 peat. A pronounced difference between field and laboratory measurements of peat K_S , however, was found by Lang [2002] and has been reported by other researchers [Boelter, 1965; Päivänen, 1973; Schlotzhauer and Price, 1999; Baird et al., 2004]. Consequently, the average field estimate of K_S (15 cm d⁻¹) [Schlotzhauer and Price, 1999], measured at the H92 site using bail tests and the hydrostatic time lag method of Hvorslev [1951], was assigned to the model. The difference between field and laboratory K_S values has been attributed to increased anisotropy with respect to K_S in the field, leakage due to separation of the peat core and inner wall of the permeameter, peat compression and smearing around piezometer screens, the development of well skins, and greater gas-filled porosity in the field.

[32] Although laboratory K_S values were considerably higher than field values and could not be directly inserted into the model's parameterization, the slope (C) of the exponential K_S - σ' relation measured during the constant head permeability tests [Lang, 2002] was used in FLOCOPS to estimate the relationship between K_S and changes in void

Table 2. Simulated and Observed Mean Seasonal Values of Δb , WT, θ , and Ψ and Standard Deviation for 1998 and 1999^a

Parameter	Mean		Standard Deviation		r^2
	Simulated	Observed	Simulated	Observed	
1999					
Δb , cm	-1.0	-0.8	0.9	0.7	0.86
WT, cm	-25.7	-30.4	8.8	10.8	0.87
θ , %	72.5	71.5	5.2	4.3	0.85
Ψ , cm	-20.6	-13.8	9.4	7.6	0.73
1998					
Δb , cm	-3.3	-2.9	1.2	0.9	0.79
WT, cm	-36.2	-30.8	11.1	10.5	0.67
θ , %	70.0	71.2	5.1	5.0	0.88
Ψ , cm	-28.5	-36.2	15.7	21.2	0.94

^aCoefficients of determination (r^2) between simulated and observed results are also provided.

ratio due to compression (Figure 3 and equation (25)). In the unsaturated zone an irreversible decrease in e_s results in decreased K_S according to (17). On the basis of the results of the constant head permeability tests [from Lang, 2002] the slope (C_k) of the best fitting straight line for this relationship was 3.6.

[33] As discussed in section 2.1, FLOCOPS calculates unsaturated K as an exponential function of K_S and Ψ (equation (3)). Schlotzhauer and Price [1999] measured the peat's unsaturated hydraulic conductivity function (K - Ψ) using methods similar to those described by Hsieh and Enfield [1974]. Fitting an exponential relation to laboratory measurements of K and Ψ yielded a β value of 0.032.

3.5. Moisture Retention Curve

[34] The initial θ_S profile (and hence e_s) was assumed to decrease with depth, reflecting the more decomposed and smaller pore structure of peat at depth [Boelter, 1968; Hayward and Clymo, 1982; Schlotzhauer and Price, 1999]. The lower field-calibrated θ_S values compared to laboratory measurements [Lang, 2002] are likely due to air entrapment during peat rewetting and CH_4 production resulting in <100% saturation. The RETC model was used to generate moisture retention curves over the range of θ_S values assigned to the peat profile (0.81–0.85) by adjusting the parameters n , m , and α (Table 1) in the van Genuchten *et al.* [1991] function so that the curve would approximate actual field values of θ and Ψ . The use of field measurements of the peat's θ - Ψ relationship inherently considers the effect of peat volume changes on θ .

3.6. Boundary Fluxes and Model Domain

[35] Meteorological input consisted of daily rainfall distributed evenly into five separate periods for each day and evapotranspiration distributed evenly over two periods for each day (~9:30 A.M.–7:00 P.M. EST), which is in general agreement with the observed diurnal patterns of ET at LSJ [see also Price, 1996]. A no-flow bottom boundary and zero drainage were assigned to the model because of the presence of the underlying impermeable substrate and the blockage of drainage ditches. Water balance estimates generally confirm these assumptions [Price, 1996]. In order that FLOCOPS output would correspond with the depth of

field sensors (5 cm depth), the peat profile was discretized into 18 layers of 10 cm thickness (midpoint of 0–10 cm layer). A smaller spatial discretization (5 cm) was not found to significantly influence model output.

4. Results

4.1. Comparison of Simulated and Observed Results

[36] The results focus on the performance of the model at simulating θ and Ψ at 5 cm depth because the moisture content and pressure of shallow peat layers best indicate the availability of soil moisture to nonvascular *Sphagnum* [Price, 1997]. Using the set of parameters detailed in Table 1 and 1998–1999 rates of P and ET, the performance of the FLOCOPS model was evaluated by comparing simulated and observed patterns of elevation change, water table, volumetric moisture content (5 cm depth), and pressure head (5 cm depth). Manual elevation change measurements were regressed with water table position [Kennedy,

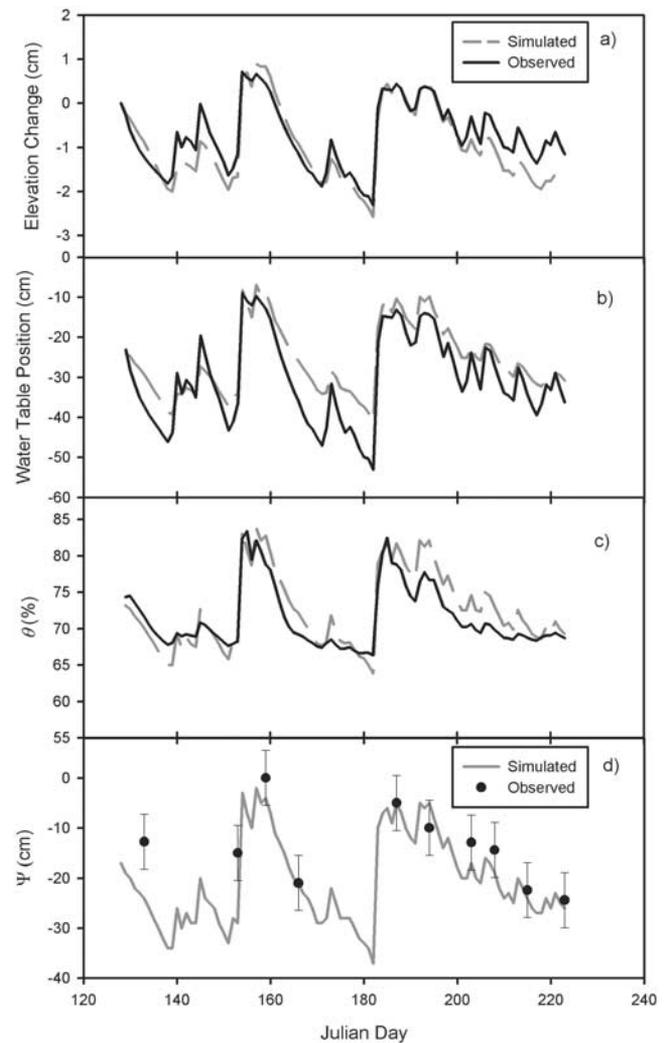


Figure 4. Simulated and observed patterns of (a) Δb , (b) WT, (c) θ (–5 cm), and (d) Ψ (–5 cm) in 1999. The standard deviation of 1998 measurements of Ψ (± 5.5 cm and $n = 62$), standardized to the mean of each set of measurements, was translocated to the 1999 data set and is shown as error bars.

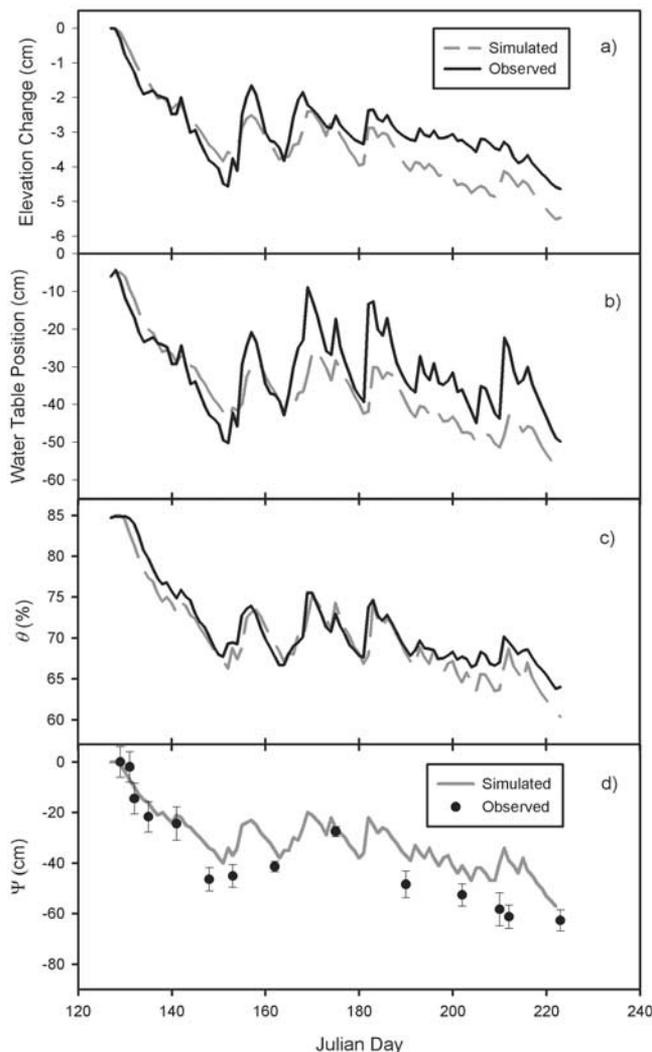


Figure 5. Simulated and observed patterns of (a) Δb , (b) WT, (c) θ (-5 cm), and (d) Ψ (-5 cm) in 1998. Error bars represent the standard deviation of measurements of Ψ between sampling locations.

2002] at the H92 site ($r^2 = 0.88$) to provide a continuous record of elevation change over the 1998–1999 seasons (Δb) and thus to facilitate comparison of observed data with simulated results. Table 2 compares the simulated and measured standard deviation and mean values of Δb , WT, θ , and Ψ for 1998–1999.

[37] The 1999 simulated and observed seasonal patterns of Δb , WT, θ , and Ψ (Figure 4) are reasonable, considering that the model's parameters were specified directly from field and laboratory testing and not optimized. Simulated WT was less variable (Table 2), and simulated Ψ was generally good but lower at the beginning of the 1999 study season compared to field values. To further evaluate the model's performance, FLOCOPS was applied to a set of field data from 1998 using the same hydraulic parameters. The 1998 simulation predicted patterns of θ and Ψ that were highly correlated (Table 2), whereas patterns of Δb and WT were not as well matched. The best fit between simulated and observed trends is during the drying period at the beginning of the 1998 study season (prior to J.D. 152).

Simulated Ψ was generally less negative than measured values in the 1998 simulation (Figure 5). FLOCOPS output also included seasonal trends in shrinkage, primary consolidation (δ_p), and secondary compression (δ_s) (Figure 6).

4.2. Sensitivity Analysis

[38] Using 1999 meteorological input, the peat's consolidation, retentivity, and water storage parameters (Table 1) were varied to investigate the model's sensitivity (Table 3). Field and laboratory results were used to determine appropriate ranges of parameter inputs for the analysis. Lang [2002] found that m_r could vary by as much as a factor of 3 within the peat profile, and field results from LSJ showed that older, more disturbed peats exhibit a more moderate shrinkage response [Kennedy and Price, 2004]. A 3 times increase in the coefficient of volume compressibility (m_r) enhanced primary consolidation (δ_p) (equation (20)), producing slightly drier soil conditions and reducing variability of WT, θ , and Ψ (Table 3). Decreasing the slope (a) of the exponential SSC (equation (26)) reduced the peat's volumetric response to a given change in moisture content. A reduction in peat shrinkage resulted in a more variable and drier moisture regime (Table 3). These findings are discussed in section 5.2.

[39] Simulated σ' in the unsaturated zone did not exceed the peat's assigned preconsolidation pressure (P_c) of 4.5 kPa, and therefore only reversible changes in pore structure in the unsaturated zone were simulated. Halving P_c to test the effect of irreversible changes in e_s still had minimal effect on simulated patterns of Δb , WT, θ , and Ψ . Increasing the slope (C) of the exponential K_s - σ' relation (equation (25)) by a factor of 10 resulted in only slightly drier and more variable moisture conditions at 5 cm depth (Table 3).

[40] Field results at LSJ have shown that the peat pore volume decreases with time since extraction, resulting in more negative Ψ at a given moisture content (steeper moisture retention curve) [Kennedy and Price, 2004]. Kennedy and Price [2004] found that pressure head at a given moisture content decreased seasonally by a factor of 1.5 in 1999 at the H92 site. The change from natural to disturbed peat is associated with an even greater increase in moisture retentivity. To investigate the effect of a steeper moisture retention curve on the simulated results, Ψ values in the peat θ - Ψ curves were multiplied by a factor of 2. Changing the moisture retention curve caused increased variability in simulated patterns of WT and Ψ (Table 3). Finally, decreasing θ_s by 0.08 (0.73–0.77) resulted in drier conditions and more variability with respect to simulated patterns of WT and Ψ (Table 3). The magnitude of this change in θ_s is reasonable compared to changes in θ_s due to the displacement of water by CH_4 production [Beckwith and Baird, 2001; Price, 2003] and due to the longer-term effect of peat subsidence on the pore volume of abandoned cutover bogs [Price, 1997].

5. Discussion

5.1. Model Performance

[41] Simulated trends of Δb , WT, θ , and Ψ generally followed the magnitude and variability of observed data but with some exceptions. The weakest performance was associated with WT and Ψ , evidenced by the lower r^2 between simulated and observed WT in 1998 and Ψ in 1999 (Table 2

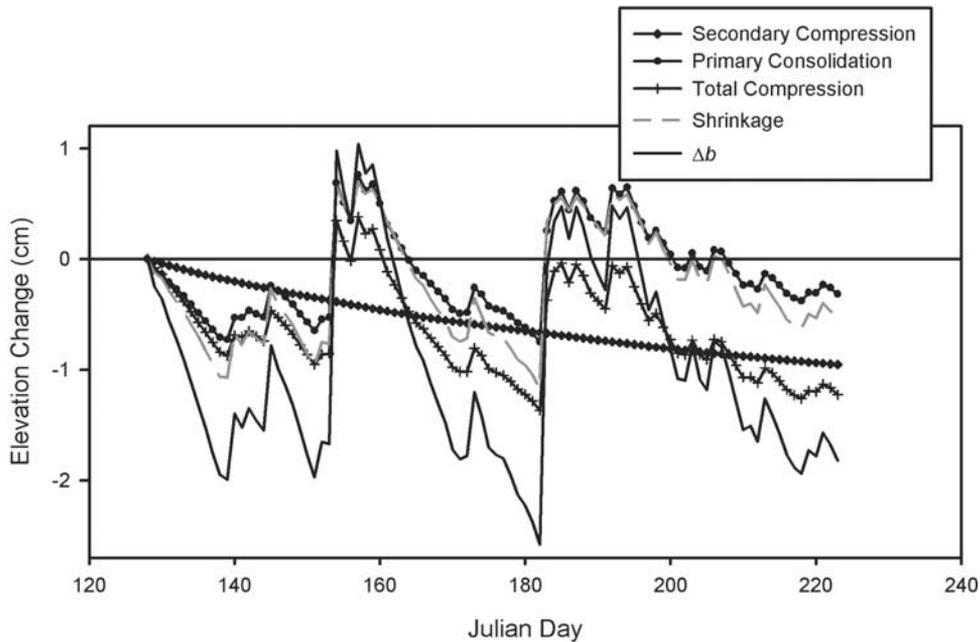


Figure 6. Simulated components of volume change in 1999. Total compression is the sum of primary and secondary compression components, whereas Δb is the sum of shrinkage and total compression.

and Figures 4–5). This may be attributable to either the quality of the field data, the model parameterization, or the model structure. Field values of Ψ in cutover peatlands have been shown to exhibit high spatial variability [Shantz, 2003], as illustrated in Figure 4 by the large standard deviation of each set of measurements. We now know that spatial sampling of Ψ should be more intensive [Shantz, 2003]. Although a close fit between simulated and observed Ψ is unlikely, simulated Ψ was generally within 1 standard deviation of measured values.

[42] The dampened WT response in both 1998 and 1999 was at least partly related to the use of daily P input from manual rain gauge measurements, resulting in lower water table variability. The lower simulated water table variability may also have resulted from inadequate parameterization of the depth variability of the peat's specific yield (S_y) (through θ_s parameter) or moisture retention curve. Better character-

ization of the depth variability of the peat's hydraulic properties (SSC , θ_s , K_S , and θ - Ψ) would improve the model's performance. For example, because FLOCOPS evaluates water table position as the sum of the vertical distance from the peat surface to the lowest unsaturated node (z_g) and the pressure head at this nodal depth,

$$WT = z_g + \Psi, \quad (27)$$

a steeper retention curve at depth (more exaggerated change in Ψ per change in θ) would increase water table variability and thereby improve the fit of observed and simulated results.

5.2. Sensitivity Analysis

[43] The sensitivity analysis was useful in evaluating the model/system response and indicates where model refinements or improved parameter estimation should be directed.

Table 3. Results of the Sensitivity Analysis, Summarizing the Effect of Key Parameter Changes on Simulated Mean θ at 5 cm Depth and Standard Deviation of θ

Parameter	Change	Change in Mean θ , % at 5 cm Depth	Change in Standard Deviation
m_r	= 0	-0.1	+1.4
	$\times 2$	-0.9	-1.3
	$\times 3$	-2.7	-1.4
C_{sec}	= 0	-1.6	-0.5
	$\times 2$	+1.8	+0.6
	$\times 3$	+2.8	+0.7
Soil shrinkage characteristic	$a = 5$	-1.5	+0.4
	$a = 7$	+2.8	-1.0
θ - Ψ	$\Psi \times 2$	-1.4	+1.2
	$\Psi \times 1/2$	-4.0	+1.8
θ_s^a	0.89–0.93	+9.0	-0.1
	0.73–0.77	-7.2	+0.1
C	$\times 10$	-0.4	+0.1
K_S	$\times 1/4$	+0.3	+1.4
	$\times 4$	-2.0	+2.4

^aInitial values are 0.81–0.85.

The model was sensitive to the peat's consolidation characteristics; increasing m_r resulted in a slightly lower mean seasonal θ at 5 cm depth (Table 3) because the moisture absorbed/stored in surface peat layers during the 3 June and 2 July storm events was efficiently transported, through compression flow (v_c), to deeper saturated peat layers, swelling in response to the sudden decrease in effective stress. From the point of view of restoration the expulsion of water from saturation storage under conditions of declining head (compression) in a more typical (drier) year replenishes moisture lost above the water table, causing smaller changes in θ and less WT variability. (Note in Table 3 that the standard deviation of θ decreases with increasing m_r .) Although changes in θ_S (porosity) due to peat compression were small (0.1–0.3%), the model results demonstrate that compression has an important role in regulating hydrological variability by decreasing the unsaturated moisture difference between wet and dry periods.

[44] Shrinkage (i.e., above the WT) was also important in regulating hydrological variability. Increasing the slope of SSC to enhance shrinkage resulted in a wetter and less variable surface moisture regime (Table 3) because shrinkage upon drying decreases the distance from the peat surface to the water table and allows residual water to be held in a smaller soil volume. In practice, shrinkage and compression would vary in the same direction when representing different peat types in a simulation, the combined effect (of more deformable peat) resulting in reduced variability and increased moisture content near the surface.

[45] The model simulated very small changes in the maximum void ratio (e_s) during the wet 1999 season [Kennedy and Price, 2004] and was not very sensitive to P_c . The small simulated changes in e_s in the unsaturated zone suggest that the assumption of $\chi = 1$ did not result in significant overestimation of irreversible volume changes. Increasing the secondary compression index (C_{sec}) to enhance secondary compression (equation (21)) resulted in greater irreversible losses in peat porosity in the saturated zone and was associated with increased variability in WT, θ , and Ψ (Table 3). Increasing C_{sec} also produced wetter surface moisture conditions because secondary compression of saturated peat layers caused more storage to be released to overlying unsaturated peat layers.

[46] A reduction in K_S due to compression results in less efficient transport of moisture to the peat surface to satisfy atmospheric demands, which restricts moisture losses during drying, but also causes more variable θ . FLOCOPS was not very sensitive to C , the slope of the K_S relation (25), partly because compression is assumed to be instantaneous, and therefore the peat layer's K_S does not control the rate of compression and associated flow in the saturated zone. The simulated changes in K_S due to peat compression were small compared to the range of K_S observed in the field, where K_S has been shown to vary by as much as 1 order of magnitude [Kennedy and Price, 2004]. It is possible that subsurface CH_4 accumulation due to methanogenesis may have a more important role in controlling the peat's saturated hydraulic conductivity [see Price, 2003; Beckwith and Baird, 2001]. It should also be noted that simulated changes in K_S were 1 order of magnitude lower than changes in unsaturated K .

[47] Assigning a steeper moisture retention curve to the model resulted in more negative and variable Ψ , caused by

the greater sensitivity of Ψ to changes in θ (Table 3). Similarly, mean WT was lower and more variable because of the increased variability in Ψ at the lowest unsaturated nodal depth (equation (27)). The modified θ - Ψ curve resulted in a slightly lower simulated mean θ at 5 cm depth because water transport to surface layers was limited by the lower K associated with more negative pressure head and the increased moisture retentivity of deeper unsaturated peat layers. This was partially offset by the increased retention of moisture being transmitted downward through the peat profile following a rain event.

[48] Decreasing θ_S has the effect of reducing S_y , thus increasing WT variability. Decreasing θ_S also has the effect of decreasing the peat's shrinkage capacity. Although reduced peat shrinkage was earlier associated with greater changes in θ , variability in moisture content did not change significantly because of the increased water retentivity of peat with lower θ_S and hence a smaller pore structure. These results have important implications for peatland managers. It suggests that cutover peat that has low water storage and high water retention characteristics is more likely to experience WT and Ψ values exceeding threshold tolerances for nonvascular *Sphagnum* [Price, 1997].

5.3. Model Refinements

[49] Better representation of complex peatland processes such as hysteresis in θ - Ψ relationships [Kellner and Halldin, 2002] and the effect of fluctuating biogenic gas levels on peat compressibility, permeability, and volume [Baird and Gaffney, 1995; Kellner et al., 2004] may improve the model's performance. Although consolidation of the high-permeability peat was rapid [Lang, 2002], consideration of the time dependency of δ_p and v_c may improve the model's accuracy and better represent flow due to changes in compression storage. The use of material coordinates to define unsaturated hydraulic properties as a function of moisture ratio, on the basis of the approach of Philip [1969], may be explored in future versions of the model.

[50] Further research and model development should be directed toward testing the relationship between irreversible volume change in the unsaturated zone and the peat's hydraulic and shrinkage character. The 1998 and 1999 simulated results were not especially sensitive to this aspect of the model's functioning, although testing the model under drier (greater water deficit) conditions is needed. Longer-term application of the model would require consideration of peat oxidation [Waddington et al., 2002] and soil freeze-thaw cycles as they relate to changes in peat pore structure.

6. Conclusions

[51] Testing of the FLOCOPS model indicated that patterns of Δb , θ , and Ψ could be simulated well enough to provide insight into the hydrological functioning of a cutover bog. The model performed best for Δb and θ but was somewhat less effective at representing WT variability. Discrepancies between simulated and observed results were primarily attributed to difficulties associated with the field and laboratory measurements of model parameters. Better characterization of the cutover peat system and better representation of complex physical peatland processes such as methanogenesis and hysteresis would improve the model's

performance. The development of a simulation model for cutover bogs has important implications for management of these sites. The model FLOCOPS can be used to assess the impacts of various extraction techniques and the efficacy of peat-rewetting scenarios. The model sensitivity analysis demonstrated the importance of preserving the characteristically high compressibility and porous structure of the peat to maintain sufficiently wet moisture conditions for *Sphagnum* recolonization. It is suggested that commencing bog restoration soon after abandonment and using extraction methods that minimize soil compaction will significantly improve bog restorability.

Notation

a	slope of the exponential e - θ relation.
b	thickness of peat deposit, cm.
b_s	saturated thickness of the peat deposit, cm.
C	slope of K_S - σ' relation, kPa^{-1} .
C_k	slope of best fitting straight line for the e versus $\log K_S$ relationship.
C_{sec}	secondary compression index.
e	void ratio.
e_s	maximum void ratio.
ET	evapotranspiration, mm.
g	acceleration due to gravity, cm s^{-2} .
H	constant used to estimate the change in α due to a change in θ_S .
i	used to denote an element of space in an array.
I	empirical constant in exponential soil shrinkage characteristic relationship.
K	hydraulic conductivity, cm d^{-1} .
K_S	saturated hydraulic conductivity, cm d^{-1} .
m	curve-fitting parameter in RETC model.
m_r	coefficient of volume compressibility (recompression), $\text{m}^2 \text{kN}^{-1}$.
m_v	coefficient of volume compressibility (virgin compression), $\text{m}^2 \text{kN}^{-1}$.
n	curve-fitting parameter in RETC model.
P	precipitation, mm.
P_c	preconsolidation pressure, kPa.
S_y	specific yield.
t	time, days.
u	pore water pressure, kPa.
v	vertical flow velocity, cm d^{-1} .
v_c	compression flow, cm d^{-1} .
WT	water table position, cm.
z	peat layer thickness, cm.
α	curve-fitting parameter in RETC model, cm^{-1} .
β	slope of the exponential unsaturated hydraulic conductivity function, cm^{-1} .
Δb	elevation change at -5 cm depth.
δ_p	primary consolidation, cm.
δ_s	secondary compression, cm.
Δz_s	change in thickness of saturated zone, cm.
θ	volumetric moisture content, %.
θ_R	residual water content.
θ_S	saturated volumetric moisture content.
ρ_d	dry bulk density, g cm^{-3} .
ρ_0	bulk density of saturated peat layers at start of simulation, g cm^{-3} .
ρ_s	bulk density of saturated peat layers, g cm^{-3} .

ρ_u	bulk density of unsaturated peat layers, g cm^{-3} .
ρ_w	density of water, g cm^{-3} .
v	moisture ratio.
χ	Bishop parameter.
Ψ	pressure head, cm.
ε	strain.
σ	total stress, kPa.
σ'	effective stress, kPa.

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G. W. Kennedy, Department of Earth Science, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1.

J. S. Price, Department of Geography, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1. (jsprice@watserv1.uwaterloo.ca)