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The Peatland Hydrologic Impact Model: Development and Testing

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Questions concerning the effects of drainage, peat mining and timber harvesting on streamflow response in the northern Lake States of the U.S.A. led to the development of the *P*eatland *H*ydrologic *I*mpact *M*odel (PHIM). PHIM is a generalized, deterministic, continuous simulation model, that is physically-based to the extent possible. Three independent landtype submodels represent watershed conditions common in the region. The appropriate land-type submodel(s), either natural peatland (NWATBAL), mined peatland (MWATBAL), or mineral soil upland (UWATBAL) are configured by the model user to represent the watershed. The submodels were applied to test the model on the streamflow response from three different peatland watersheds. Stormflow events were simulated for a 3,758 ha natural peatland and a 155 ha mined peatland. Annual water yield simulations for a 9.72 ha upland-peatland watershed produced a mean ratio of predicted/observed streamflow of 1.01 ± 0.08 for six test years. The model is generalized so that it should be adaptable to similar physiographic regions with minor modifications.

Introduction

The development of predictive models, based on regional hydrologic data, has been identified as an urgent research need in wetland hydrology (Carter 1986). Six million hectares of peatland (wetland) have formed in the Lake States region of the U.S.A. (Fig. 1) since the last period of glaciation (Boelter and Verry 1977). Increased demand for peat may lead to extensive drainage and mining in headwater

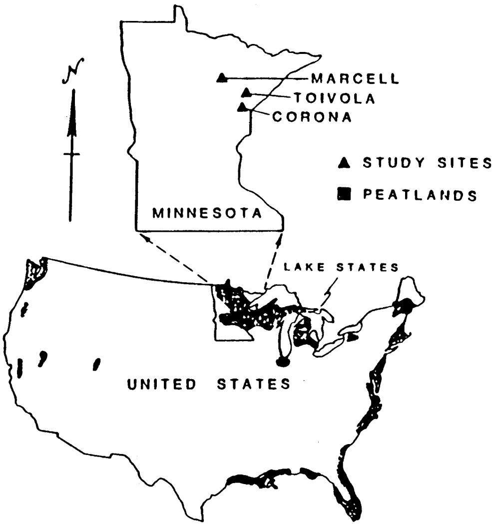

Fig. 1. Peatlands of the conterminous United States and study site locations (MDNR 1978)

areas. Timber harvesting, usually clearcutting, may also occur in the peatland or upland portions of the same watersheds. In the Lake States, land managers need a generalized method to quantify the hydrologic consequences of more intensive and widespread use of peatlands, and forest resources. This was the impetus for the development of the *P*eatland *H*ydrologic *I*mpact *M*odel (PHIM) (Guertin 1984; Guertin and Brooks 1985).

PHIM is a deterministic, continuous simulation model designed to predict changes in stormflow, low flow and water yield caused by changes in a watershed such as: 1) peatland drainage, 2) peat extraction (mining) for fuel or horticultural uses, 3) timber harvesting, or 4) a combination of these land uses within a catchment. The model can be used to formulate land management plans that minimize adverse impacts on the quantity and timing of streamflow.

Model Description

A conceptual model was developed by Brooks and Predmore (1978) to help identify gaps in the existing knowledge of peatland hydrology. This information was used to guide extensive field research on five watersheds in northern Minnesota (Brooks, Clausen, Guertin, and Stiles 1982; Clausen and Brooks 1983a, 1983b) that, coupled with an extensive literature review, led to the development of PHIM (Guertin 1984; Guertin and Brooks 1985). The ultimate objective of this continu-

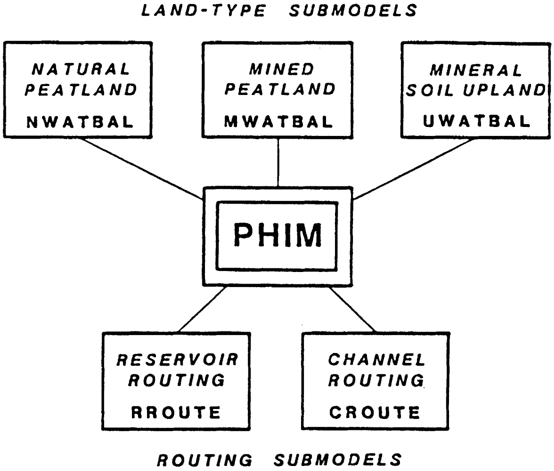

Fig. 2. The *P*eatland *H*ydrologic *I*mpact *M*odel (PHIM)

ing project is a generalized, physically-based model for operational use and research in the Lake States.

PHIM is physically-based to the extent possible with input limited to climatic data (precipitation, maximum and minimum daily air temperature) and descriptive information (e.g., vegetation type, canopy cover, soil depth) commonly available to hydrologists. Three independent land-type submodels represent a range of watershed conditions commonly found in the northern Lake States region (Fig. 2). The appropriate land-type submodel(s), either natural peatland (NWATBAL), mined peatland (MWATBAL), or mineral soil upland (UWATBAL) are configured by the model user to represent the integrated streamflow response of a watershed. The following sections describe these submodels in detail.

Natural Peatland Submodel (NWATBAL)

The streamflow response of a peatland area that has not been extensively drained, or mined is simulated with NWATBAL. Two soil zones are used to predict storage and outflow from natural peatlands (Fig. 3). Zone 1, roughly synonymous with the acrotelm or active layer of the peat soil (Ingram 1978; Verry 1984a), extends from the bottom of the outlet channel to the average soil surface (the mid-point of the average hummock and average hollow elevations). Zone 2, roughly synonymous with the catotelm or inert layer of the peat soil (Ingram 1978; Verry 1984a), extends from the bottom of the outlet channel to the underlying mineral substratum. The water storage characteristics for the peat at saturation, field capacity (10 kPa), and wilting point (1,500 kPa) can be estimated from a soil profile description with prediction equations developed by Boelter (1969).

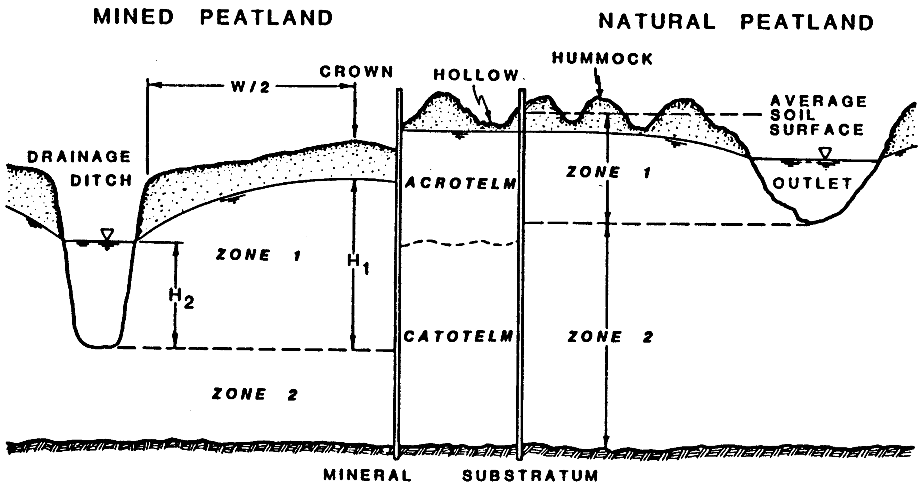

Fig. 3. PHIM soil zones for natural and mined peatlands.

Soil water storage in zone 1 of the peatland at time *t* is

$$S1_t = S1_{t-1} + (NPPT_t + MELT_t + QU_t + QGW_t - P1_{t-1} - AET_{t-1})\Delta t \qquad (1)$$

where

$S1$ – soil water storage in zone 1 (cm)
$NPPT$ – net precipitation (cm/time)
$MELT$ – snowmelt (cm/time)
QU – upland inflow, if any (cm/time)
QGW – regional groundwater inflow, if any (cm/time)
$P1$ – percolation loss at the base of zone 1 (cm/time)
AET – actual evapotranspiration (cm/time)
Δt – 1 hour or 1 day (the computation interval)
t – end of the time step
t-1 – beginning of the time step.

The estimation of the water budget variables in Eq. (1) is described below.

Interception losses are estimated as a function of vegetation type and canopy cover for the overstory (> 3 m), tall (1-3 m) and low (< 1 m) shrubs, and sphagnum moss (*Sphagnum* spp.). Intercepted rainfall is evaporated at the potential rate, as estimated with Hamon's potential evapotranspiration (PET) equation (Hamon 1961), sequentially from the tallest vegetation to the peat surface. Recommended maximum interception capacities for common peatland cover types are provided in the model documentation (after Verry 1976). Interception losses are only computed for precipitation classified as rain by a rain-freeze threshold temperature.

The interception storage for sphagnum moss (IMOSS) is calculated with the equation

$$IMOSS = MICM\,(MA)\,(YU) \tag{2}$$

where

$IMOSS$ – interception storage for sphagnum moss (cm)
$MICM$ – maximum interception capacity for sphagnum moss, 0.08 cm water/cm moss (Verry 1984b)
MA – area of sphagnum/area of peatland
YU – thickness of the unsaturated sphagnum moss between the capillary fringe and the average soil surface (cm).

A capillary fringe of 20 cm above the free water surface is used for natural peatlands (Romanov 1961; Boelter 1964).

Sphagnum interception storage is apparently related to rainfall intensity. Bay (1967) found that the increase in water table elevation was much less for low intensity storms than for high intensity storms of equal volume. The effect of rainfall intensity on the relative efficiency (IE) of sphagnum interception storage is represented by

$$IE = \frac{C}{PPT} \tag{3}$$

where

C – a calibrated coefficient (cm/time)
PPT – gross precipitation ($GPPT$) – canopy interception storage (CIS) (cm/time).

Net precipitation (NPPT) is computed by

$$NPPT = GPPT - CIS - (IMOSS(IE)) \tag{4}$$

Snowmelt is calculated with the Temperature Index Method (USACE 1960). Snow accumulation is predicted with a mean daily air temperature of 0 °C as the default rain-freeze threshold. Infiltration is assumed to be instantaneous for an undisturbed peat soil (Boelter 1965). Inflow from adjacent areas of mineral soil is computed with the upland submodel, UWATBAL. Regional groundwater inflow must be specified by the user.

When zone 2 is saturated, percolation from zone 1 ($P1$) is approximated by the saturated hydraulic conductivity (K_s) at the zone boundary. This can be estimated directly from the von Post classification of the peat soil (Gafni 1986), or with prediction equations using unrubbed fiber content (Boelter 1969). If the water table recedes into zone 2, percolation from zone 1 is calculated as a function of soil water storage (S1) with an equation developed by Huggins and Monke (1968). Deep seepage loss from the base of zone 2 is approximated by the K_s of the peat

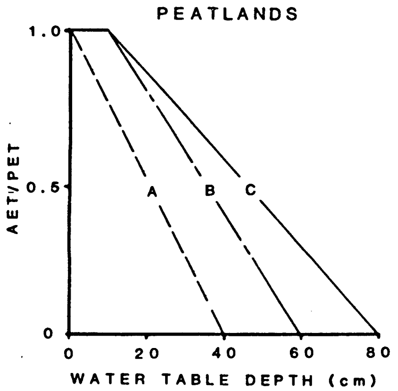

Fig. 4a. *E*vapo*t*ranspiration *R*atio (*ETR*) functions for peatlands: A for >25 percent sphagnum moss (adapted from Romanov 1962), B for mined areas, C for sedges and <25 percent sphagnum (Juusela, *et al.* 1970). Water table depth is referenced to the average soil surface.

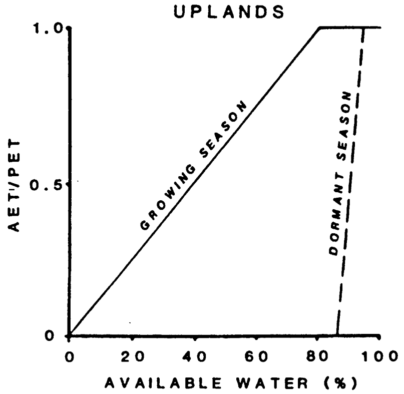

Fig. 4b. *E*vapo*t*ranspiration *R*atio (*ETR*) functions for mineral soil uplands during the growing and dormant seasons.

soil or mineral soil (Rawls and Brakensiek 1985) at the interface, whichever is limiting.

Actual evapotranspiration (*AET*) is estimated with *ETR* (*e*vapo*t*ranspiration *r*atio) functions (Fig. 4a). Curve A in Fig. 4a, adapted from Romanov (1962), applies to areas with greater than 25 percent sphagnum moss. Curve C represents areas of fine-leaved sedges (*Carex* spp.), with less than 25 percent sphagnum moss (Juusela, Kaunisto, and Mustonen 1970). Actual evaporation from the bare soil in mined areas is estimated with Curve B (Juusela *et al.* 1970). The depth of the water table is referenced to the average soil surface.

Streamflow from the peatland is predicted with the water balance estimate of storage (Eq. (1)) coupled with an iterative reservoir routing procedure (USACE 1972). The nearly flat topography, low drainage density, and short-term detention storage of natural peatlands produce a streamflow response comparable to that of an unregulated reservoir (Fig. 5). The numbers in parentheses in the following discussion refer to the labelled water surface elevations in Fig. 5.

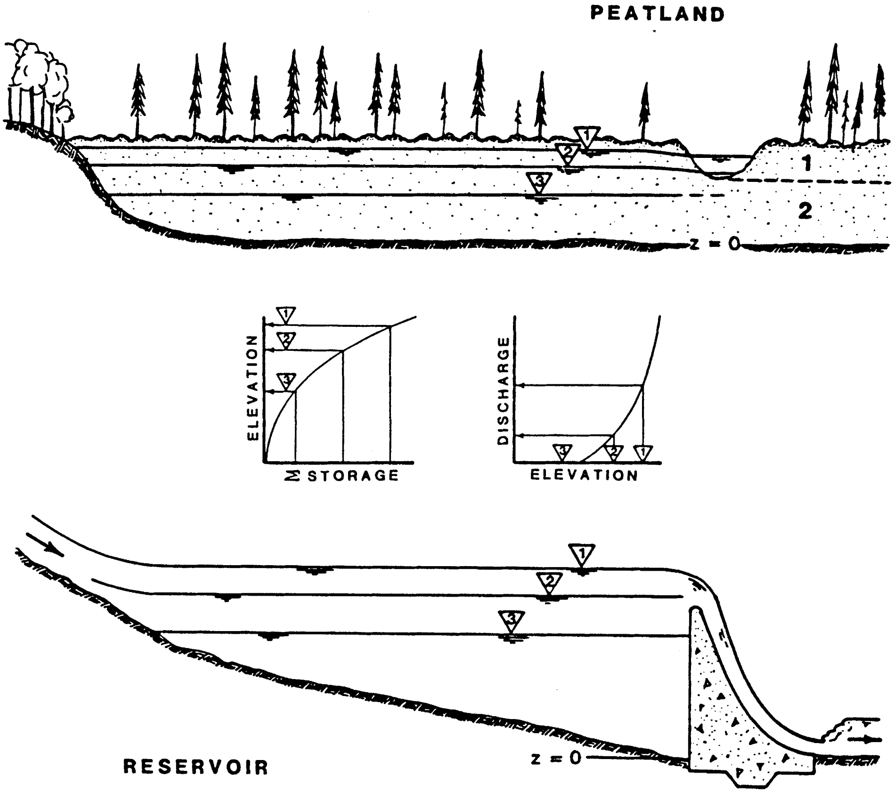

Fig. 5. Reservoir (storage) routing adapted for natural peatlands.

The water table in peatlands is near, or in some cases above, the surface during the early spring (1). Snowmelt and early-season rainfall quickly contribute to runoff during this period (Boelter and Verry 1977). Near the end of the growing season after extended periods of high evapotranspiration demand, the water table recedes into less conductive peat layers (2). The combination of increased available storage and increased resistance to lateral flow in more decomposed peat layers dampens the streamflow response to even high rates of precipitation (Bay 1969; Verry and Boelter 1975). When the water table recedes below the outlet elevation, streamflow ceases (3).

The dimensionless routing functions in Fig. 5 represent water table elevation versus cumulative detention storage, and discharge versus water table elevation for natural peatlands. These functions are currently developed from the peat profile description, and simultaneous observations of water table elevation and discharge.

The form of the elevation-storage function for a conventional reservoir describes the nonlinear changes in flooded area for incremental changes in pool depth. The pore size distribution and water storage characteristics of peat, namely the proportion of retention versus detention storage, are also nonlinear for incremental changes in water table elevation. This corresponds to the increased degree of decomposition moving downward in the peat profile (Boelter and Verry 1977).

The exponential form of a reservoir discharge-elevation function reflects the decreased resistance to flow for incremental increases in flow depth (H) over the weir; discharge is proportional to $H^{3/2}$ (Linsley, Kohler, and Paulhus 1982). In a natural peatland, increases in the hydraulic gradient and K_s that coincide with increases in water table elevation also reduce resistance to flow (Gafni 1986). These straightfoward analogies are the basis of the reservoir routing method used in PHIM.

Mined Peatland Submodel (MWATBAL)

Peat mining transforms a poorly drained natural peatland into a system of well drained fields, devoid of vegetation. A mining operation (milled peat process) usually includes: 1) forest vegetation and groundcover removal, 2) ditching to drain the surface peat and improve trafficability for field equipment, 3) raking and grading of the field surface, and 4) peat extraction (about 1 cm per harvesting cycle) with specialized equipment (e.g., a pneumatic harvester or sod peat extruder). The simulation of infiltration and overland flow, unnecessary for natural peatlands, becomes an important consideration for mined areas.

Two soil zones are used to simulate storage and outflow from a mined area (Fig. 3). Zone 1 extends from the field surface to the bottom of the drainage ditch. Zone 2 extends from the bottom of the ditch to the underlying mineral soil.

Infiltration rate is estimated with Holtan's (1961) equation. The effect of soil frost on infiltration during the snowmelt period is estimated empirically by calculating a thaw rate (cm/day) as a function of melting degree-days (MDD, mean daily air temperature – base temperature). When a snowpack is present, the available energy represented by MDD is first used to estimate snowmelt. Any residual energy is used to thaw the soil frost. Based on field observations it is assumed that soil frost is continuous and impermeable until the unfrozen zone reaches three-fourths of the maximum depth of frost penetration.

Overland flow from the mined area is simulated as a function of rainfall or snowmelt excess and available depression storage. Depression storage may be negligible for uniformly graded fields with a high crown, or sizeable for nearly level fields with a berm (up to 20 cm high) left at the ditch bank by mining equipment. The rate of overland flow is calculated with the equation

$$QO = c(SO)^{x} \tag{5}$$

where

QO – overland flow (m^3/sec)

SO – rainfall or snowmelt excess – available depression storage (m)
c, x – constants.

The constants c and x in Eq. (4) can be estimated with Manning's equation,

$$QO = \frac{s^{1/2}}{n} (2L)(SO)^{5/3} \tag{6}$$

where

s – field slope perpendicular to the ditch (m/m)
n – Manning's roughness coefficient
L – long-axis field length (m).

The cross-sectional area of flow is $2L$ (SO); the hydraulic radius can be approximated by SO for overland flow. Therefore, from Eq. (5), $c = (2L\ s^{1/2})/n$ and $x = 5/3$.

The remaining water stored on the field surface is evaporated at the potential rate. Evaporation from the peat soil is estimated as a function of the residual *PET* draft with an *ETR* curve developed by Juusela *et al.* (1970), curve B in Fig. 4a.

Saturated subsurface flow (Fig. 3) is calculated with the Dupuit-Forchheimer equation for an unconfined aquifer (Fetter 1980)

$$QSS \equiv \frac{K_s (H_1^2 - H_2^2)\ 2L}{W/2} \tag{7}$$

where

QSS – saturated subsurface flow (m^3/sec)
Ks – saturated hydraulic conductivity (m/sec)
H_1 – thickness of the saturated zone above bed elevation of the ditch at the center of the field (m)
H_2 – average flow depth in the ditch (m)
W – total field width (m).

Subsurface flow is assumed to be perpendicular to the drainage ditch with a flow length equal to one half of the total field width. The Dupuit-Forchheimer approximation assumes that (1) the hydraulic gradient (dh/dx) is equal to the average slope of the water table, and (2) the flow lines are horizontal. Subsurface flow in mined areas (Gafni and Brooks 1986; Liebfried and Berglund 1986) satisfies the condition specified by Bear (1972), $(dh/dx) << 1$, for the applicability of the Dupuit-Forchheimer equation.

The subsurface and overland flow calculated for a time step are combined and routed through the adjacent drainage ditch for each field. The flows from field ditches are combined at the perimeter ditch and routed to the outlet of the mined site. Channel routing can be performed with two submodels, either CROUTE using the four-point kinematic wave method (Brakensiek 1966), or RROUTE using storage routing (USACE 1972). RROUTE can also simulate flow through lakes, ponds, or sedimentation basins.

Mineral Soil Upland Submodel (UWATBAL)

In the upland submodel (UWATBAL), the root zone and a deep storage zone are used to simulate storage and outflow. The thickness of the root zone is determined by the maximum depth of water extraction by forest cover. Within the root zone, a shallow subsurface flow layer is used to predict upland contribution to streamflow during major rain or snowmelt events.

The calculation of *AET* begins with the depletion of canopy and understory interception storage at the potential rate. Growing season and dormant season ETR functions are used to estimate AET (Fig. 4b). These functions were developed with soil moisture records from the USDA Forest Service Marcell Experimental Forest.

The infiltration capacities of forest soils in the northern Lake States region are rarely exceeded by rainfall or snowmelt inputs. Infiltration is assumed to be instantaneous for undisturbed sites.

Shallow subsurface flow usually occurs through the highly permeable A and B horizons above an impeding layer, such as a horizon with a high clay content (e.g., the *B2t*) or a fragipan (Verry, Lewis, and Brooks 1983; Verry and Timmons 1982). The depth of the impeding horizon defines the thickness of the shallow subsurface flow layer. A Darcy approximation, with the hydraulic conductivity of the mineral soil or the adjacent peat (whichever is limiting), is used to estimate the lateral flow rate from the lower root zone and shallow subsurface flow layer.

The deep storage zone is conceptually a reservoir, supplied by percolation from the root zone that is estimated with the Huggins and Monke (1968) equation. The soil water content of this zone is assumed to remain at, or above field capacity (10 kPa). Gravitational water in the deep storage zone is apportioned between deep seepage loss to the regional groundwater system and baseflow with flow rate estimates. The deep seepage rate for a given watershed can be determined through water budget analyses (Verry and Timmons 1982).

The lateral flow rate from the deep storage zone is governed by the K_s of the parent material or the adjacent peat soil, whichever is limiting. The total outflow from an upland area can be added to soil water storage in an adjacent peatland (QU in Eq. (3)) or directly to a channel reach.

Model Calibration and Testing

Data from three watersheds in northern Minnesota (Fig. 1) were used to verify *PHIM*. Stormflow simulations were performed for a 3,758 ha natural peatland, Toivola, and a 155 ha mined peatland near Corona (Guertin 1984). Long-term

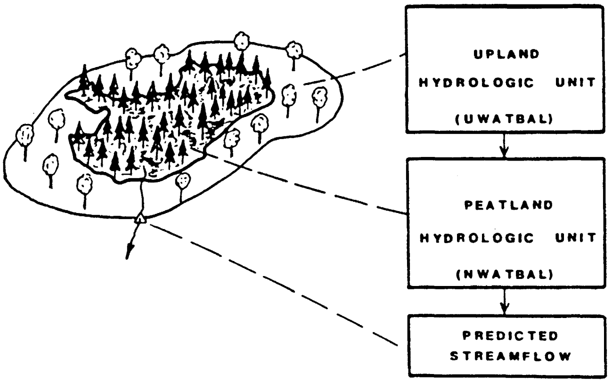

Fig. 6. PHIM configuration for the Marcell upland-peatland site.

water yield tests were based on daily simulations for a 9.72 ha upland-peatland watershed near Marcell (Barten 1985). The three land-type submodels could be tested for a range of climatic conditions with data from these watersheds.

Site Descriptions

The Toivola site is an undisturbed transitional peatland with an average slope of 1.3 m/km. The predominantly hemic peat (1/3 to 2/3 fiber) has an average depth of 3.7 m, ranging from 1.2 to 4.9 m and is underlain by fine sand and silt. Nearly 90 percent of the watershed is forested with black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch). Sphagnum moss and heath shrubs (*Ericaceae* spp.) are found over the entire area. Toivola contains small areas of mineral soil, totaling two percent of the watershed area. For stormflow simulations these areas were neglected. Toivola was represented as a single hydrologic unit with the natural peatland submodel, NWATBAL.

The Corona site has been mined since 1958 for horticultural peat with the milled peat method. Drainage ditches, averaging 1.8 m deep, are irregularly spaced at 60 to 100 m intervals. The mined areas are relatively level, often bordered by berms at the ditch bank. The peat deposit has an average depth of 4.6 m, ranging from 1.5 to 10.7 m. The soil grades from fibric peat (> 2/3 fiber) derived from sphagnum moss on the surface, to hemic reed-sedge peat, over a clay and sand substratum. Wood fragments are found throughout the peat profile. Stormflow from the Corona site was simulated with the mined peatland submodel, MWATBAL.

The Marcell site, watershed S-2 on the USDA Forest Service Marcell Experimental Forest, contains a 3.24 ha raised bog encircled by a 6.48 ha mineral soil upland (Fig. 6) (Verry and Timmons 1982). The bog water table is perched above the regional groundwater system (Bay 1969).

The raised bog has an average slope of 1.35 m/km, with characteristic hummock and hollow microtopography (Verry 1984a). The peat deposit, approximately 4 meters deep in the center of the bog, is underlain by 30 cm of marl and silty clay loam (glacial flour), over deep sands, glacial till and pre-cambrian bedrock. The bog vegetation consists of: a 117-year-old black spruce overstory, an understory of heath shrubs, with fine-leaved sedges and sphagnum moss at the surface. The bog periphery, or lagg, is occupied by a dense strip of speckled alder (*Alnus rugosa* (Du Roi) Spreng.) (Verry and Timmons 1982).

The upland section of Marcell is moderately well to well-drained clay loam till (Verry 1969), with an average land slope of 100 m/km (Verry and Timmons 1982). The upland vegetation consists of a mature, 58-year-old mixed stand of quaking aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) with a dense understory formed by hazel shrubs (*Corylus* spp.), ferns and herbaceous cover. Fig. 6 illustrates the model configuration for Marcell.

Climate

Northern Minnesota has a strongly continental climate. At the Marcell Experimental Forest the average annual air temperature is 4°C, with recorded extremes of −46 and 40°C. Average January and July temperatures are −14 and 19°C, respectively (Verry 1984a). Average annual precipitation at Marcell is 760 mm with approximately 75 percent falling as rain from mid-April to early-November, and 25 percent as snow during the remainder of the year (Verry and Timmons 1982). Annual streamflow averages 170 mm, beginning in April and ending in late-December during most years (Verry 1980). This corresponds to the thaw and freeze of the outlet channel.

Data Compilation

Hourly data for rainfall events at Toivola and Corona during 1978-1980 were used for stormflow simulations. The storms were classified as large (> 10 mm) and small events for each site. One-half of each size class was randomly selected for model calibration; the remaining storms were reserved for model testing. Site descriptive information for Toivola and Corona had been collected during a previous study (Brooks *et al.* 1982).

Eleven years of daily hydrometeorological data (1970-1980) from Marcell were used for annual water yield simulations. This period includes two years with above average streamflow and two dry years. Five years were randomly selected for model calibration; the remaining years were reserved for model testing. Site descriptive information, such as peat and mineral soil profiles, forest cover, and snowmelt rates, was obtained from previous studies of Marcell (Bay 1969; Verry 1984a, 1976, 1969; Verry and Timmons 1982).

Calibration

Calibration was limited to model coefficients or parameters that cannot be directly measured, or have yet to be characterized by a physically-based function. Site characteristics such as deep seepage loss, maximum interception capacities, and snowmelt coefficients that had been determined by previous studies (Haverly, Wolford, and Brooks 1978; Verry and Timmons 1982; Verry 1976) were not changed during the calibration process. A systematic trial and error process is used to calibrate PHIM.

PHIM required minimal calibration to produce acceptable simulations. The C parameter in Eq. (3) for the relative efficiency of sphagnum interception storage, and the slope of the ETR function required adjustment for Toivola and the peatland area at Marcell. The adjusted ETR function (Curve A) is shown in Fig. 4a. The reservoir routing functions for Toivola and Marcell were developed by regression analysis of recording well and streamflow data.

The rate of shallow subsurface flow from the uplands at Marcell was increased from 15 cm/day to 40 cm/day to match upland flow volumes predicted with a hydrograph separation technique reported by Verry and Timmons (1982). The roughness coefficient (Manning's n) for the drainage ditches, and the average K_s for the peat soil were adjusted for the Corona site.

Results and Discussion

The results of stormflow simulations for Toivola and Corona are summarized in Table 1. The mean ratios of predicted/observed stormflow volume, peak discharge, and a combination of both hydrograph characteristics are listed for the calibration and test storms. Table 2 summarizes the annual water yield simulations for calibration and test years at Marcell. The mean ratio of predicted to observed annual water yield for the calibration years was 0.93 ± 0.11. The mean ratio for the test years was 1.01 ± 0.08. Figs. 7 and 8 illustrate the overall performance of PHIM with predicted and observed sets of hydrographs for Toivola, Corona, and Marcell.

Toivola

Stormflow volume and peak discharge were consistently underestimated for calibration and test storms at Toivola. In light of the long-term simulation results at Marcell, it appears that these prediction errors are related to the inaccurate representation of mean basin precipitation rather than a consistent bias in the model formulation.

Precipitation data for the Toivola watershed were collected with a single station, located in an exposed area. The requirement of year-round accessibility necessi-

Table 1 – Summary of Stormflow Simulations for Toivola and Corona

	Ratio of Predicted Observed*		
Site	Stormflow Volume	Peak Discharge	Combined**
Toivola (Natural Peatland)			
Calibration ($n \equiv 6$)	0.91 (0.10)	0.80 (0.22)	0.86 (0.15)
Test ($n = 6$)	0.86 (0.16)	0.84 (0.22)	0.85 (0.18)
Corona (Mined Peatland)			
Calibration ($n \equiv 5$)	0.96 (0.10)	0.86 (0.35)	0.91 (0.22)
Test ($n = 4$)	0.91 (0.08)	0.65 (0.09)	0.78 (0,07)

* Ratio (1 Standard Deviation)

** Combined Ratio ≡ (Volume Ratio/2) + (Peak Flow Ratio/2)
Pooled standard deviation (Cundy and Brooks 1981)

Table 2 – Summary of Annual Water Yield Simulation for Marcell

Year	Observed Water Yield (mm)	Predicted Water Yield (mm)	*Predicted* Observed
Calibration			
1970	163	144	0.89
1973	154	160	1.06
1977	167	161	0.96
1978	229	222	0.97
1979	285	215	0.76
Test			
1971	174	191	1.09
1972	181	181	0.99
1974	181	176	0.98
1975	215	188	0.87
1976	57	63	1.10
1980	87	89	1.02

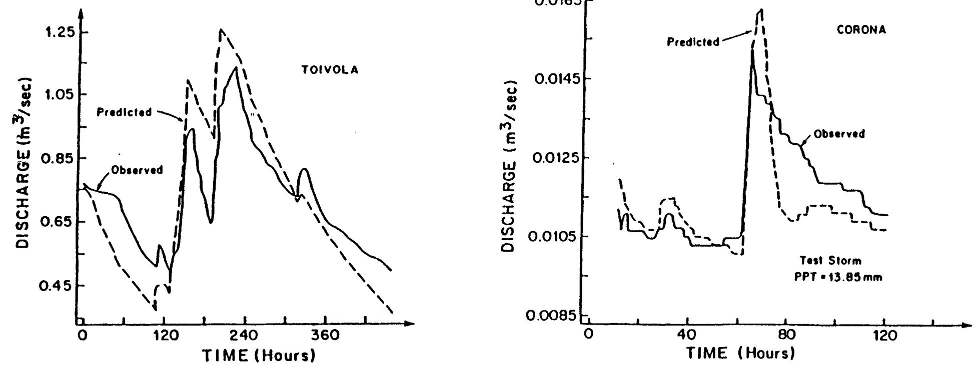

Fig. 7. Predicted and observed hydrographs for test stormflow simulations for Toivola (natural peatland) and Corona (mined peatland).

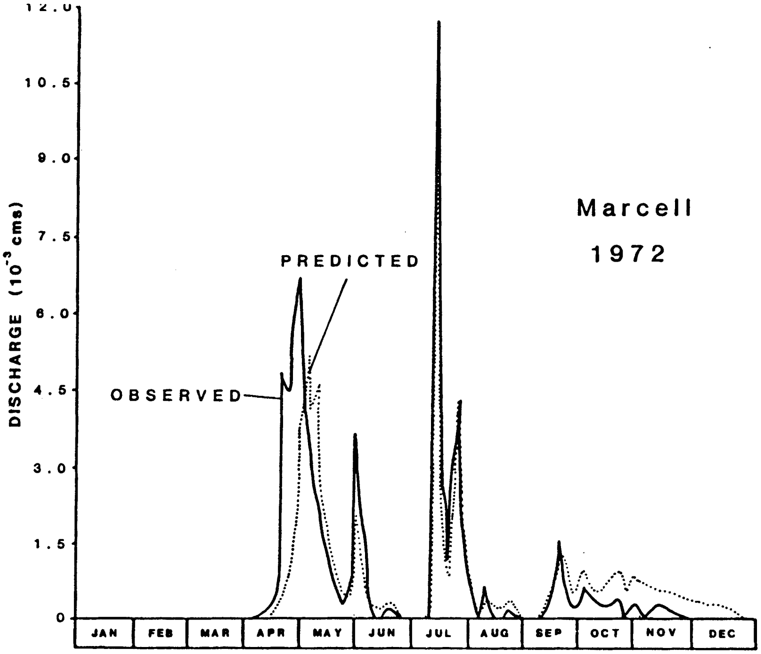

Fig. 8. Predicted and observed hydrographs for test annual water yield simulations for Marcell (upland-peatland watershed).

tated the use of this site. It is likely that this gauge location underestimated precipitation for the 3,758 ha watershed.

Corona

The variability in the size, slope, and surface configuration of the mined fields at Corona are likely sources of prediction error. Several fields have a concave surface capable of storing large quantities of water before producing overland flow. In contrast, some fields are likely to produce overland flow before it is predicted for the "average" field used for calculations in PHIM.

Inadequate construction and maintenance of the ditch system prevent accurate representation of site conditions at Corona with average ditch dimensions. Many ditches have adverse bed slopes, or are partially obstructed by sediment and debris. These sections store, rather than convey water for many runoff events.

Marcell

The volume and timing of predicted streamflow from mid-June to early-November was consistently accurate for calibration and test years (Fig. 8). The model identified the beginning and end of low flow periods within 1 to 6 days. The seasonal contribution of upland runoff to watershed outflow compared favorably to the percentage contributions determined by hydrograph separation (Verry and Timmons 1982).

Prediction errors in the volume and timing of streamflow were most prevalent during spring melt (March and April) and the late-fall period (November). The formation of channel ice, and soil frost in the peatland, typically causes the cessation of streamflow from headwater catchments in December or January.

Snowmelt in the deciduous stand of the upland occurs earlier, and at a more rapid rate than in the conifer shaded peatland. Excess water flows through the partially thawed mineral soil into the peatland. Most of this excess continues to flow over ice layers in the peat soil, producing a rapid streamflow response at the watershed outlet. A portion of the upland runoff may refreeze over ice layers in the peat. The development of a physically-based predictor for soil frost and channel ice may improve the timing of predicted streamflow during these periods. The addition of a soil temperature index and a snowpack cold content function (USACE 1960) may improve predictions of snowpack formation and snowmelt.

Model Application

The hydrologic impacts of watershed alterations such as peat mining or timber harvesting can be simulated with PHIM. The mined peatland submodel (MWATBAL) is used to simulate streamflow changes caused by drainage and peat extraction. The user specifies the: 1) size and location of the mined area within the watershed, 2) dimensions of the fields and drainage ditches, and 3) physical properties of the peat. The latter is needed to estimate infiltration, overland flow, and subsurface flow. Streamflow from the remainder of the watershed is predicted with the appropriate land-type submodel.

The effect of vegetation changes can be simulated with either NWATBAL or UWATBAL. The canopy coverage, maximum interception capacity, and snowmelt rate can be specified for the new cover type. The form of the *ETR* function (Fig. 4) can also be altered to represent changes in available water capacity and the physiological characteristics of the new vegetation type.

PHIM can be applied to ungaged sites by using verified estimates of fitted parameters from a similar gaged watershed, or from mean values in the region. The fitted C parameter (Eq. (3)) and the *ETR* function should not vary substantially between peatland watersheds with similar vegetation types. Although the absolute quantity and timing of streamflow cannot be predicted with certainty, reasonable estimates should be expected. The relative changes produced by watershed alterations in ungaged areas can be estimated as described above.

Conclusions

Annual water yield and stormflow events from the peatland and upland-peatland watershed types common in the Lake States can be simulated with the *P*eatland *H*ydrologic *I*mpact *M*odel. PHIM can be used to predict the effects of peat mining and vegetation changes on streamflow. Since the model requires minimal calibration, it could also be used to estimate streamflow from ungaged areas and relative changes due to watershed alterations.

Although hydrologists are routinely asked to evaluate the impacts of watershed disturbance, these assessments are often constrained by limited hydrometeorological data, descriptive information, and time. PHIM provides a means of predicting potential increases in flooding, and other changes in the streamflow regime of headwater areas. Coupled with a river basin model, such as SSARR (USACE 1972), regional impacts could also be examined. Accurate site-specific predictions can greatly enhance the hydrologist's contribution to multiple resource management and planning.

The valuation of wetlands is often linked to their perceived functions (Carter 1986), such as flood detention, with a qualitative estimate, rather than a direct assessment of their hydrologic effects. A verified model such as PHIM, can be used to quantify the value of wetlands for natural conditions and a variety of land management alternatives.

Tests of PHIM with long-term data sets from experimental watersheds, and subsequent model refinements will continue. This will eventually allow the routine prediction of hydrologic impacts for timber harvesting, wetland drainage, and peat mining throughout the northern Lake States. Land managers can then consider the cumulative effects of a variety of land uses proposed for a given watershed.

Notation

AET – actual evapotranspiration (cm/time)
c – $[(2L)(s^{1/2})]/n$
C – a calibrated coefficient (cm/time)
CIS – total canopy interception storage (cm)
$GPPT$ – gross precipitation (cm/time)
H_1 – thickness of the saturated zone at the center of the field (m)
H_2 – average flow depth in the ditch (m)
IE – relative efficiency of sphagnum interception
$IMOSS$ – interception storage for sphagnum moss (cm)
Ks – saturated hydraulic conductivity (m/sec)
L – long-axis field length (m).
MA – area of sphagnum/area of peatland
$MELT$ – snowmelt (cm/time)
$MICM$ – maximum interception capacity for sphagnum moss, 0.08 cm water/cm moss (Verry 1984b)
n – Manning's roughness coefficient
$NPPT$ – net precipitation (cm/time)
$P1$ – percolation loss at the base of zone 1 (cm/time)
PPT – gross precipitation – canopy interception storage (cm/time).
QGW – regional groundwater inflow (cm/time)
QO – overland flow (m^3/sec)
OSS – saturated subsurface flow (m^3/sec)
QU – upland inflow (cm/time)
$S1$ – soil water storage in zone 1 (cm)
SO – rainfall or snowmelt excess – available depression storage (m)
s – field slope perpendicular to the ditch (m/m)
Δt – 1 hour or 1 day (the computation interval)
t – end of the time step
t-1 – beginning of the time step.
W – total field width (m).
x – 5/3
YU – thickness of the unsaturated sphagnum moss between the capillary fringe and the average soil surface (cm).

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