Journal of the Minnesota Academy of Science

Volume 55 | Number 1 Article 19

1989

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Recommended Citation

Brooks, K. N., & Kreft, D. R. (1989). A Hydrologic Model for Minnesota Peatlands. *Journal of the Minnesota Academy of Science, Vol. 55 No.1*, 113-119.
Retrieved from https://digitalcommons.morris.umn.edu/jmas/vol55/iss1/19

A Hydrologic Model for Minnesota Peatlands

KENNETH N. BROOKS and DAWN R. KREFT

ABSTRACT—The Peatland Hydrologic Impact Model (PHIM) is a continuous simulation computer model developed over a twelve-year period to aid hydrologists in understanding the hydrologic functions of peatlands and upland-peatland watersheds. An initial conceptual model defined the research needed to create the working model. The research has become an iterative process of model design, field work, model refinement, model testing, and additional field work. The model is as physically-based as possible while relying on data input that is readily available to the natural resources community. It simulates streamflow response of peatlands, upland-peatland systems, mined peatlands, and a combination of these watershed units.

Introduction

The hydrologic role of wetlands has represented a complex puzzle to hydrologists and resource managers for some time (1). As with other wetlands, Minnesota's vast areas of peatlands were recognized as being closely associated with excesses of water. However, their role in water budgets, groundwater systems, and surface streamflow generation has not been well-understood. Are they areas that yield high amounts of water? Are they important groundwater recharge areas? Are they source areas of streamflow; do they sustain streamflow through dry seasons? Do peatlands reduce flooding? What are the consequences of eliminating or altering peatlands or portions of peatlands that are common in many headwater catchments in the northern Lake States? These are the types of questions that were being asked in the mid-1970s when large scale proposals to extract (mine) peat for energy alternatives were surfacing.

Research was initiated in 1977 to develop a better understanding of the hydrologic function of peatlands and to determine the hydrologic impacts of peatland development, particularly the mining of peat. Although hydrologic research had been conducted on peatland systems in north central Minnesota by the U.S. Forest Service (2, 3), the work focused on small peatlands as components of upland-peatland watersheds. Furthermore, there had been no hydrologic monitoring or research on the few existing peatland development areas in Minnesota or elsewhere in the northern Lake States.

Although long-term research on peatlands has been conducted in Europe, it could not be applied directly to conditions in Minnesota. Much of the European work dealt more with hydrologic processes and the effects of ditching peatlands to promote forest production. We found no literature that quantified the effects of peat mining on streamflow.

As a result, we were faced with the need to develop hydrologic studies that concentrated on the conditions in northern Minnesota. The ultimate aim of these studies was to predict the hydrologic effects of peatland development and to simulate the streamflow response from watersheds in the northern Lake States that characteristically contain peatland components. Literature searches indicated that there were no hydrologic computer models available to make such predictions. Existing models were not suited for wetlands (1), and even if one had been available, we had no field data with which to verify such a model.

Paired watershed experiments, the standard field method of determining the effects of land use on streamflow, could not be employed to determine peat mining effects. Answers were desired before long-term calibration and treatment periods could be carried out. As a result, a combination of plot studies, streamflow monitoring of mined and unmined peatlands, laboratory studies, and computer modeling studies were used to improve our understanding of the hydrologic functions of peatlands and to address questions of peat mining effects. This paper summarizes the accomplishments of this research program and indicates the present status of the hydrologic modeling work and continuing research on the hydrology of peatlands and upland-peatland watersheds. The model has important implications regarding our understanding of hydrologic processes affecting the quality of water in peatlands and downstream receiving waters, but the focus of this paper is on peatland hydrology rather than water quality.

Peat Hydrology Research Program

A modeling approach was used to design the research program and develop a framework to guide field work. The initial step was the development of a conceptual model for peatlands (4) that represented the status of knowledge concerning hydrologic processes and functions. During development, it became apparent that certain hydrologic processes could not be mathematically formulated with data available at the time and additional field work was needed. Of particular interest was the ability to simulate the streamflow response of a watershed made up of a mosaic of bogs, fens, and mineral soil uplands. Model components that could not be quantified and formulated for the initial, conceptual model represented areas in which research was needed. These deficiencies became the focus of subsequent research in the field, laboratory, and computer laboratory.

Following initial field and laboratory work, the Peatland Hydrologic Impact Model (PHIM) was developed and tested on a fen peatland and a mined peat bog (5, 6). Further

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analysis led to modifications in which the model was tested and verified on an upland-peatland watershed (7, 8). This effort revealed the need for further analysis and field work which improved and expanded the capability of the model to simulate the hydrologic response of upland mineral soil components and to simulate the effects of forest removal (9). As noted above, this research consisted of an iterative process of model design, field work, model refinement, model testing, further field work, analysis, further model testing, and so forth. As the model was being developed, three guidelines were used:

(1) the model should be capable of simulating the streamflow response of natural, undisturbed minerotrophic fen peatlands, ombrotrophic bogs, upland-peatland systems, mined peatlands, clearcut uplands, and a combination of these landscape units within upland watersheds;

(2) the model should be physically-based to the extent possible, so that the effects of peat mining and/or forest harvesting could be directly expressed in mathematical functions without having to "fit" or calibrate model parameters based on observed streamflow records; and

(3) the model should be useful in an operational setting and, therefore, should rely only upon climatic data and watershed characteristics that are normally available to natural resource managers.

The studies that resulted from the overall modeling work will not be described in detail here, but we will summarize the key results of these studies.

Water Budget of Peatlands

Much of the initial field work was designed to quantify components of the water budget for undisturbed and mined peatlands, and to develop rainfall- and snowmelt-runoff events for peatland systems that could be used to test and verify PHIM. Detailed water budgets were presented elsewhere for a small bog and a fen upland-peatland watershed near Marcell (3), the 3758 ha Toivola fen (10), the 65 ha mined fen near Cotton (11), the 155 ha mined Corona bog, and a nearby 58 ha unmined bog (12). Based on these water budgets we conclude:

(1) Groundwater fens exhibit less variable and more dependable streamflow than bogs.

(2) Evapotranspiration dominates the water budget of both bogs and fens and far exceeds annual streamflow from all peatlands; Verry[1] (1978) reported that evapotranspiration varies from 455 to 610 mm in contrast to annual precipitation of 760 mm in northern Minnesota.

(3) Mining of peat and the accompanying vegetation removal, ditching, and peat extraction in both bogs and fens appear to increase water yield over the short term. (We cannot state this with certainty because these were not paired watershed experiments.) Ratios of streamflow to precipitation averaged 0.25 and 0.17 for the mined and unmined peat bogs, respectively over a 2.5 year period (10); also, the initial ditching of the mined fen at Cotton resulted in large amounts of streamflow discharge (11).

(4) The greatest percentage of annual streamflow from natural peatlands occurs in spring, largely as a result of snowmelt. Streamflow is generally reduced during summer months because of high evapotranspiration.

Hydrologic Processes — Results and Status of Field Studies

Snow Accumulation and Melt

Snow accumulation and ablation are important hydrologic processes of peatlands in northern Minnesota. Bay (1969) observed that over 65 percent of annual runoff from peatlands is the result of snowmelt, even though only about 20 to 25 percent of the annual precipitation occurs as snow.

Field studies indicated that snow depths in disturbed sites (both for a mined peatland and a peatland that was cleared for cultivation) were less than snow depths in an undisturbed peatland (14). Likewise, the snowpack on disturbed sites was more variable, the result of wind conditions and drifting of snow. Much of the snowpack on mined peat fields is blown into drainage ditches and adjacent natural areas where wind velocities are reduced. Although snowpack ablation was not measured through the late spring seasons, observations over several field seasons indicated that snow remains longer in forested peatlands than in disturbed sites. The redistribution of snow into frozen channels of mined peatlands likely causes more efficient snowmelt runoff than would be expected from a more uniform melt over the typical hummock and hollow form of undisturbed peatlands. These observations point out the importance of soil and channel frost characteristics in determining snowmelt-runoff efficiency of mined peatlands.

Infiltration

The conceptual model emphasized infiltration as a key hydrologic process that could be modified by peat mining. Double ring infiltrometer measurements were made on unmined and mined peat surfaces. In addition, a detailed soil temperature-soil frost study was conducted to evaluate mining impacts on snowmelt-runoff processes. These field experiments indicated that mined peatlands had significantly lower final infiltration rates than natural, undisturbed peatland surfaces. Summertime infiltration rates averaged 32.8 cm/hr and 3.9 cm/hr for unmined and mined peat soil surfaces, respectively (15). During late winter and early spring months, mined peat fields contained nearly 100 percent concrete frost and exhibited minimal infiltration rates (less than 1 mm/hr) compared with unmined peatlands. No differences were observed between winter and summer infiltration rates in the unmined peatland. In general, infiltration rates of undisturbed peat surfaces are far in excess of rainfall intensities normally encountered in northern Minnesota. A subroutine for PHIM is currently being developed that will predict soil frost occurrence using a degree-day method for modeling snowmelt runoff from mined and unmined peatlands.

Hydraulic Characteristics of Peat Soils

The modeling work also pointed to the need for additional field work to better understand water flow through peat soils. As a result, studies were conducted to determine hydraulic characteristics of peat soils, estimate horizontal flow velocities, and determine the role of vertical components of flow in three different peatland types (16, 17).

The point dilution method was used to determine horizontal flow velocities through the acrotelm of four peatlands (17). By measuring hydraulic gradients in these peatlands, hydraulic conductivities (K) for different peat soil layers (and different levels of peat decomposition as expressed by the von Post method) were determined by solving for K using Darcy's Equation. Hydraulic gradients varied from 0.043 to 0.10 percent in unmined peatlands and the gradients were stable throughout the year. Peat bogs exhibited a steepening of the hydraulic gradient toward the lagg and averaged 0.10 percent for a raised bog and 0.053 percent for a perched bog in the S-2 watershed (a small perched peat bog near Marcell). An unmined fen averaged 0.043 percent while a mined fen exhibited a marked steepening of hydraulic gradients to over 22 percent near ditches.

Hydraulic conductivities decrease dramatically as the water table drops lower in the soil profile. At depths below 30-40 cm and von Post decomposition values of H5 or more, hydraulic conductivities drop to 0.01 cm/sec or less. Even though K values of the upper peat layers average more than 0.2 cm/sec, groundwater velocities are restricted by hydraulic gradients. The maximum groundwater velocities measured in the upper soil horizon were close to 0.5 cm/hr. Substantial horizontal flow from peatlands occurs only when the water table is at or above the soil surface or when the laggs of peat bogs become flooded and wedge storage develops (18). Nested piezometer and well records indicated that vertical flow does not appear to be a major component of flow within peatlands.

Flow Pathways in Peatlands

One concern that arose as a result of applying PHIM to the S-2 watershed related to the nature of the linkage between upland mineral soil components and the peat bog. Flow pathways are particularly complex where upland mineral soil systems come into contact with the organic soils of downslope wetlands. Our understanding of this linkage is incomplete.

Streamflow studies at S-2 have suggested that a portion of streamflow leaving the peatland is derived from upland subsurface flow (19). Water budget studies have indicated that the peatland also has significant deep percolation from the bottom of the peat mass through several layers of unsaturated sands and into the regional water table (20). However, several studies have indicated that the vertical hydraulic conductivity in deep peats is too low to yield the volume of deep percolation being estimated (16). These inconsistencies in flow rates and volumes confuse the conceptual framework used for linking uplands and peatlands.

It is presently hypothesized that a portion of the subsurface flow occurring in the A horizon of the upland mineral soil is the source of deep percolation beneath the peatland. Accumulating peat deposits (over 8,000 to 10,000 years) may have covered the mineral A horizon through which a significant amount of flow occurs. This narrow layer could be a conduit that carries upland water beneath the peat and contributes to deep percolation.

Work is currently underway to document the soil physical properties at the buried mineral (upland) and organic (peatland) interface. Measurements of hydraulic gradients and mineral and organic soil properties will enable us to estimate flow rates through the various soil layers within the lagg. This information will then be used to characterize the pathway of water flow at the interface between uplands and peatlands.

Once flow pathways are characterized and flow rates quantified for different precipitation and snowmelt events, algorithms in PHIM will be developed. Streamflow data simulated with the model will be compared with observed streamflow records to determine if the model has been improved. Data used in testing of the model would be independent of the data used in the model development.

Stormflow Response of Peatlands

The stormflow response of mined and unmined peatlands indicates that the percentage of rainfall that results in runoff is greater for mined peatlands than unmined (Table 1). This response is expected given the observed changes in infiltration and evapotranspiration. However, of major importance is the effect of ditches in the mined sites. Leibfried and Berglund (21) found that the perimeter ditch surrounding a mined peatland near Cotton lowered the water table up to a distance of 80 m into an adjacent, unmined area. The net effect of ditching is an increase in the area that contributes to streamflow. In the above example, the contributing watershed area increased by 53.6 ha, in contrast to the original mined area of 65 ha. Furthermore, ditching within the mined area provides a more extensive and efficient conveyance system for stormflow than found in undisturbed peatlands. Water table and piezometer data for a 3,758 ha undisturbed fen peatland indicated that only areas in close proximity to the outlet of the watershed contribute to streamflow during the summer months (15). The effects of the increased contributing area with mining may be just as dramatic for streamflow during the drier late summer flows. It is conceivable that dry season flows may be enhanced.

Modeling Tests and Results

The main purpose of developing a hydrologic computer model is to take advantage of knowledge gained from field and other experiments so that predictions can be made for other areas or to investigate how watersheds respond to unusual rainfall or snowmelt events. For example, if several sites are proposed for a horticultural peat operation, the hydrologic implications of disturbing the sites can be evaluated with the model. Decisions can then be made regarding leasing, development constraints, rehabilitation measures, and needed flow control structures.

Before any model can be applied operationally, it must be tested or verified with data independent from those used in model development. The following is a summary of the basic formulation of PHIM and the results of applying PHIM to four peatlands.

PHIM is a set of submodels that simulate streamflow from undisturbed peatlands, mined peatlands, and upland mineral soil systems (Figure 1). Channel routing and reservoir routing submodels are included to simulate the effects of ditches and settling (detention) ponds. The Peat and Mine submodels treat peat soil systems differently, as illustrated in Figure 1. Uplands are modeled using a more complex soil layered flow regime (9, 22).

Initially PHIM was successfully applied to a mined bog and an unmined fen (5, 6), as indicated in Table 2. Subsequently, PHIM was applied to a peatland-upland watershed and good agreement was found between simulated and observed streamflow (7, 8). Improvements were made on the upland submodel and the model was shown to be capable of predicting the effects of clearcutting upland aspen forests (9) as shown in Table 3. Examples of simulated and observed hydrographs resulting from these applications are shown in Figure 2. Currently, the model is being tested on a 65 ha

Table 1. Stormflow response of mined and unmined peatlands in northern Minnesota (12).

Watershed	Area (ha)	Response factor[a]		Peak discharge ($m^3\ sec^{-1}\ km^{-2}$)		Time to peak (h)[b]		Number of events
		$\bar{x}$	s	$\bar{x}$	s	$\bar{s}$	s	
Unmined fen	3,758	0.029	0.026	0.0145	0.0096	12.3	5.2	14
Mined fen	65[c]	0.065[d]	-	-	-	4.5	-	35
Unmined bog	58	0.009	0.004	0.0149	0.0006	6.9	3.1	7
Mined bog	155	0.015	0.009	0.0151	0.0047	5.7	4.0	7

Notes: [a] Response factor = ratio: mm stormflow/mm rainfall.

[b] Time to peak = time from centroid of rainfall to peak discharge.

[c] Mined area = 65 ha, but because of the ditching around its perimeter, the actual drainage area was increased by 53.6 ha because of flow contributions from adjacent peatlands that were diverted to the ditch (21).

[d] Actually the median value was reported by MDNR (11) for rainstorms ranging from 1.3 to 48.1 mm.

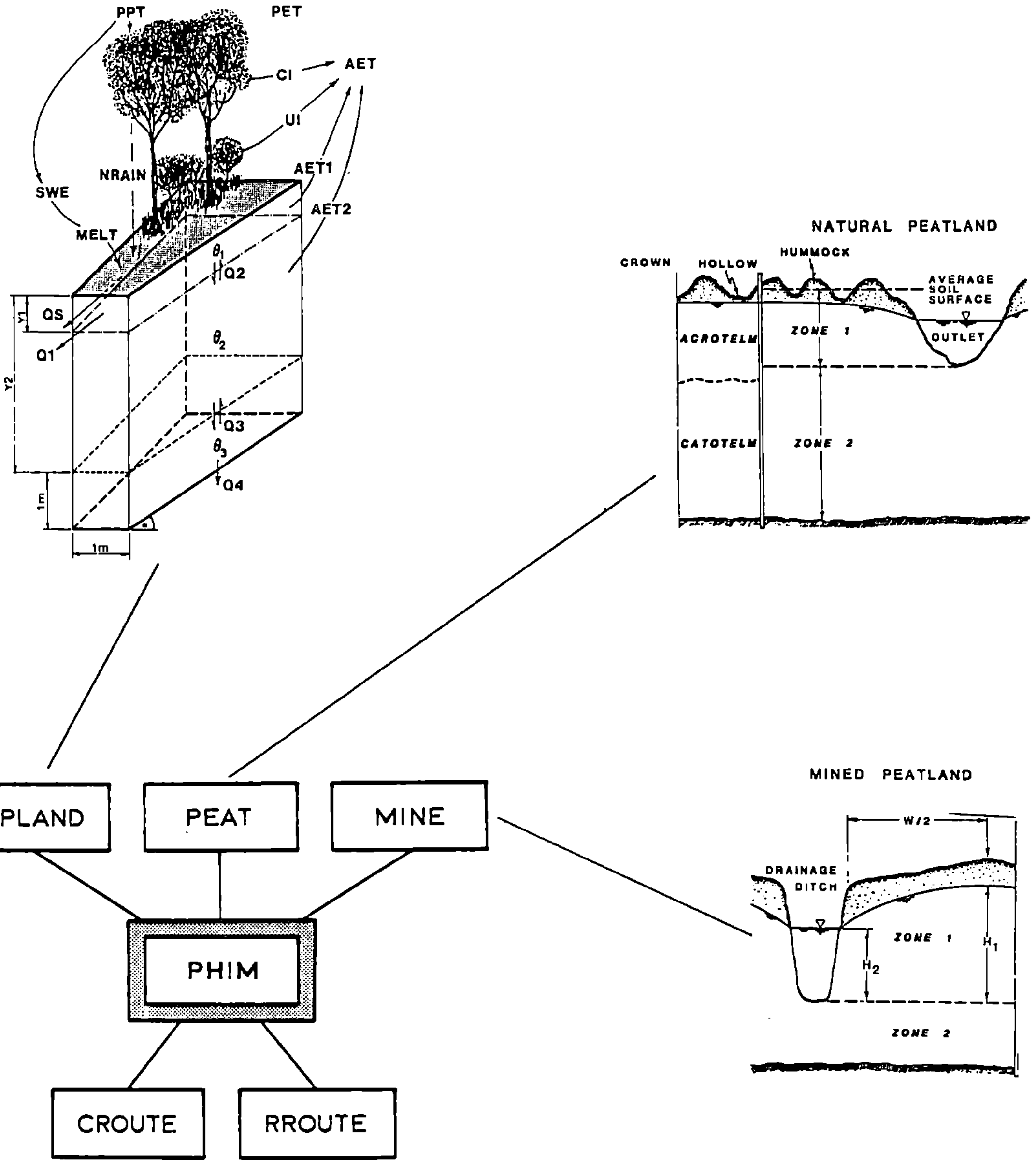

Figure 1. The Peatland Hydrologic Impact Model (PHIM) and the formulation of the upland, peatland, and mined submodels (9).

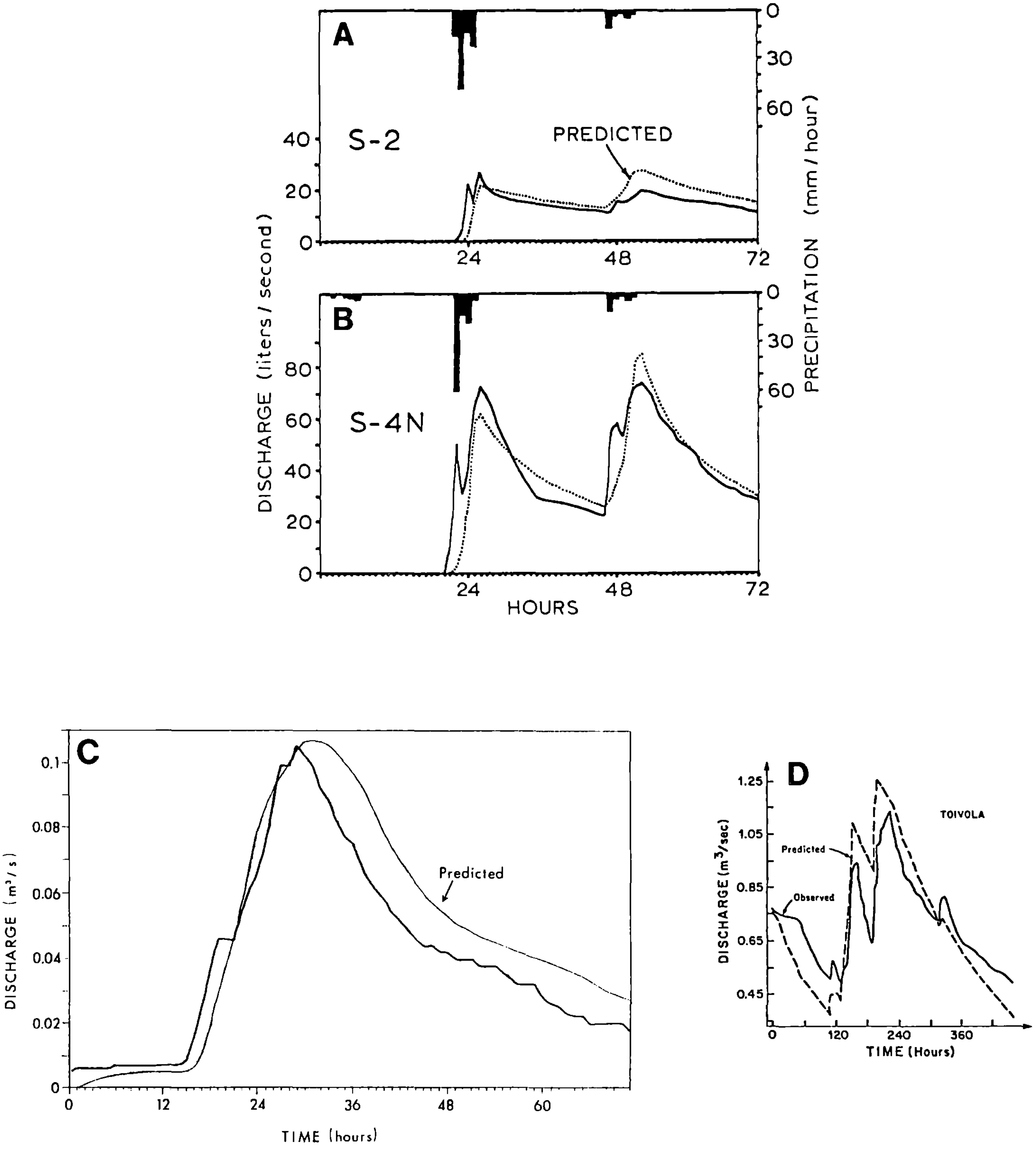

Figure 2. Examples of computer simulation results of applying PHIM to four watersheds: (A) an upland-peatland, (B) an upland-peatland in which the upland aspen was clearcut, (C) a mined peatland, and (D) an undisturbed fen. Dashed lines are simulated values and solid lines are observed streamflow.

Table 2. Summary of stormflow simulations with the Peatland Hydrologic Impact Model (PHIM) for an unmined fen (Toivola) and a mined bog (Corona) in northern Minnesota (8).

Site	Ratio of Predicted Observed* Stormflow Volume	 Peak Discharge	 Combined**
Toivola (Natural Peatland)			
Calibration (n = 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 = 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 3. Summary statistics for annual streamflow simulations (1962-87), for the control watershed (S-2) and a partially clearcut watershed (S-4N), Marcell Experimental Forest (9).

Watershed	Number of years	Mean ratio: $\frac{\text{Predicted Q}}{\text{Observed Q}}$	One Standard Deviation	Pred./Obs. Regression Slope	SE of* Estim. (mm)	r^2
S-2						
Calibration	12	0.97	0.12	0.95	22.5	0.85
Verification	14	1.00	0.12	0.99	20.8	0.86
S-4N						
Calibration	4	1.13	0.18	1.10	34.5	0.63
Verification	22	0.98	0.19	0.93	31.4	0.69

* Predicted annual streamflow = β_1. Observed annual streamflow; β_0 = 0.

mined fen near Cotton, Minnesota (see Figure 2c). Initial results are promising and following this phase the model will have been tested on five different watersheds. The next step will involve the development of user friendly software to facilitate use of the model by practitioners and students of forest and peatland hydrology.

Conclusions

The Peatland Hydrologic Impact Model (PHIM) is a continuous simulation computer model that has provided: (1) a framework and guide for a long-term, comprehensive research program on peatland hydrology and (2) an analytical tool to investigate and better understand the hydrologic functions of peatlands and peatland-upland watersheds. The model can be applied to estimate the effects of peat mining and upland forest harvesting on streamflow. Because a modeling approach was taken initially, field work has been more focused and has improved our understanding of hydrologic functions and the response of peatland and upland forested watersheds. As our knowledge of hydrology improves, the model will be improved to reflect new advances. Conversely, as the model is applied in the field, new questions can be asked — and the types of improvements needed by practitioners can be articulated. This type of feedback system helps us maintain a cohesive and goal-oriented peatland and forest hydrology research program and one that should benefit water resources management in Minnesota and the northern Lake States region.

Acknowledgements

This paper summarizes the work of many as evidenced by the literature cited. The cooperation and support of the Minnesota Department of Natural Resources, Division of Minerals, and the U.S. Forest Service, North Central Experiment Station, Grand Rapids, were instrumental in this research program. Without this support, the continuity of this research would not have been realized. This research was supported by the University of Minnesota Agricultural Experiment Station (published here as Experiment Station Publication No. 17,152), the Minnesota Water Resources Research Center, and by the Department of Forest Resources, University of Minnesota.

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