STREAMFLOW RESPONSE FROM AN OMBROTROPHIC MIRE

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ABSTRACT

Streamflow response to a rainstorm exceeding a 100-year return interval is documented in relation to the peat profile and microtopography. The water table:discharge relation is corrected for specific yield and found to closely parallel the stage:discharge relationship for a level reservoir for flows up to a 25-year return interval. A faster water table:discharge relation occurs at higher flows when the mire develops wedge storage in the completely flooded, channel-like lagg around 2/3 of the mire perimeter. Flood frequency analysis was used to estimate a 25-year return interval peak flow of 350 liters per second per sq. km for a 10-hectare basin.

KEYWORDS

Peatlands; Wetlands; Mires; Hydrology; Floods; Design flows

INTRODUCTION

The behavior of streamflow from mires is a function of the amount and intensity of precipitation, antecedent conditions, the nature of the peat profile, the location of the peatland within the landscape, and topographic forms within the mire. This paper explores the response of an ombrotrophic mire to the maximum 24-hour rainstorm of record (July,1979).

Streamflow from mires is considered similar to flow from an unregulated reservoir that has lower flow peaks than open channels. We test that notion here by comparing actual peatland streamflow to flow from a level reservoir. In addition, we determined the 25-year return period peak streamflow rate and its relative water table elevation based on a 26-year streamflow frequency analysis. Finally, we suggest the use of hydrologic models to evaluate mire size, position within the entire basin, and storm size.

PEATLAND SETTING

We conducted this study at the Marcell Experimental Forest in north central Minnesota (USA), a glaciated region where mires are interspersed with mineral soil in a recessional moraine area. The study basin contains 9.72 ha with a central ombrotrophic mire of 3.24 ha that drains to an exit stream (Fig. 1). The peat has filled an ice-block depression to a depth of 7.5 m. A small Sphagnum dome (0-45cm) has developed over poor fen (45-200cm), intermediate fen (200-325cm), rich fen (325-605cm), and aquatic peats (605-745cm) (Pers. Com. Jan Jansens, Univ. of Minnesota). Contour lines of hollow elevations illustrate the 40 cm dome that has developed on the peatland (Fig. 1). The surface of the peatland is a typical hummock-hollow Sphagnum community with small Ericaceae shrubs. A 125 year-old black spruce (Picea mariana [Mill.] B.S.P.) forest covers the peatland. Sphagnum species are characterized by S. Angustifolium (Rucurvum) in the hollows and S. Magellanicum on the hummock sides and tops. Rare hummocks of S. Fuscum also exist. A band (3-5m wide) of speckled alder (Alnus rugosa [Du Roi] Spreng.) grows in the lagg.

The surrounding upland forest is aspen-birch (Populus tremuloides Michx. and Betula papyrifera Marsh.) growing on a glacial till with a sandy loam surface texture that grades to a clay loam at depth. Mineral soil upland slopes average about 10 percent. Shallow subsurface flow is produced from these mineral soils when water is impeded by the B horizon and saturates part or all of the A horizon (Timmons, et al.,1977).

The climate is strongly continental with wide and rapid temperature fluctuations, low winter precipitation, and normally ample summer rainfall. The area receives 775 mm of annual precipitation with 75% as rain from mid April to early November and the remainder as snow. The average annual temperature is +2 degrees C with extremes of -46 and +40 degrees C. Average January and July temperatures are -16 and +19 degrees C respectively. Each year about 65 rainstorms average 9 mm, and 3 or 4 storms exceed 25 mm each year.

METHODS

A recording float well with a diameter of 30 cm is located at the center of the Sphagnum dome (Fig. 1). Level surveys to establish the well's mean sea level elevation (error of closure +/-9mm) are performed several times annually. Streamflow from the mire and its surrounding mineral basin is measured at a 120 degree V-notch weir. The weir rating equation is: Cubic Feet Per Second = 4.43 * Stage(in feet) ** 2.449. For this paper, all flow units were converted to cubic meters per hour. We used the equation of flow from this weir to represent the flow from a level reservoir that does not have wedge storage in a moving flood wave.

Streamflow from the mire stops at nearly the same water table elevation each year. In 1979 this mean sea level elevation was 421.94 m at the mire center. This elevation was given a value of 0.00, and all water table elevations reported in this paper are relative to this point of streamflow stopping. It is also the elevation where weir (reservoir) flow stops.

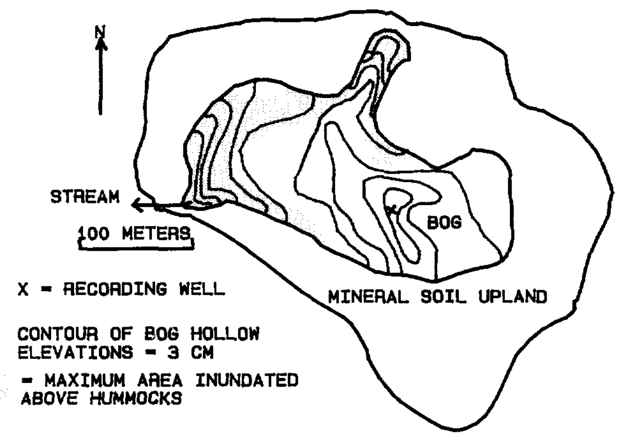

Fig. 1. Basin No. 2 showing contour lines of the bog dome and lagg.

A detailed level survey by Verry (1984) is illustrated in Fig.1. H-values on the von Post scale were determined and assigned to various horizons at the recording well site. Specific yield values determined by Boelter (1965) were assigned to peat horizons of similar von Post H-values. For elevations above the hollows, weighted specific yield values were calculated on the basis of inundated hummock horizons and flooded areas (given a value of 1). Relative hummock and hollow areas were described by Grigal (1985).

Precipitation was measured in two standard and one recording rain gage on the basin. A 27-yr annual series for 24-hr rainfall at the Marcell Experimental Forest ranges from 3.43 to 16.59 cm. The storm we analyzed for streamflow response occurred on 2 and 3 July 1979 during which 16.6 cm of rain fell in 24 hours (17-cm in 26 hours). This rain had a return interval well beyond 100 years for a point measurement (Hershfield, 1961). Another method to estimate rainfall frequency in the state of Minnesota is based on the area covered by a 15-cm, 24-hr rain as a percent of the entire state area (Kuehnast et al, 1988). These 15-cm rainfall areas typically cover 10 to 500 sq.km. The 16.6-cm storm we analyzed was also larger than the 15-cm, area-based, 24-hr rain in Minnesota that had a 91-yr return interval. Both are a rare events. A 72-year record at a station 40 km south has a record of only 11.3 cm in 24 hr.

A 27-yr annual series for peak streamflow rates was subjected to a frequency analysis using the Log-Pearson Type III extreme probability distribution (USWRC, 1976). Water table elevations at the recording well site were analyzed for frequency of occurrence (ice-free periods for 25 years) to illustrate the total range in the peat profile.

RESULTS

General water table occurrence in the peat profile

Seventy percent of the time, the water table resides in a zone extending 13 cm below the hollows, in peat horizons with a von Post H-value of 1 or 2. Twenty-five percent of the time, it resides in deeper and more decomposed horizons when there is no streamflow. The water table has dropped as much as 55 cm below the hollow elevation during prolonged drought. In most years, the water table drops no more than 18 cm below the hollows. Five percent of the time, the water table is above the hollow elevation in response to large rains (Fig. 2).

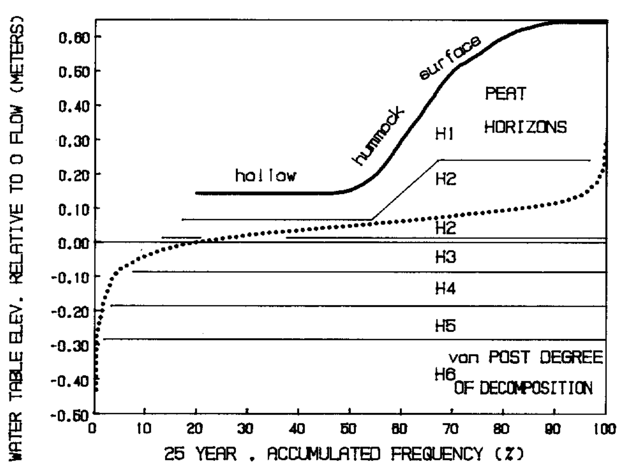

Fig. 2. The accumulated frequency of water table occurrence (dotted line) during ice-free periods. Elevations are relative to zero streamflow. Hummock-hollow cross section and peat horizons are superimposed.

Record rain and streamflow response

The rain and streamflow response for the 2 and 3 July 1979 storm is shown in Figure 3. The 17-cm rain produced a peak streamflow of 485 cubic m per hr and had an estimated return interval far beyond 100 years (Fig.4). It fell in two major segments with intensities of 8 mm per hr and 16 mm per hr, respectively.

During very large storms, the peatland looks like a reservoir surface punctured by tree boles and individual hummocks . Overland flow from the mineral soil was not directly observed; however, runoff plots on another basin caught worms and ants flushed from the saturated A horizon of the mineral soil. This indicates that saturated flow was occurring right at the soil surface, if not over it.

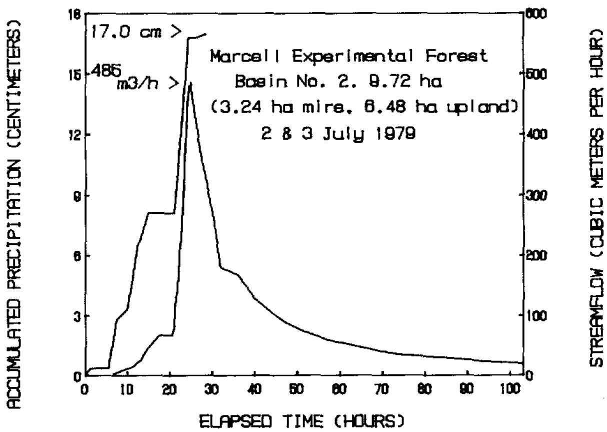

Fig. 3. Streamflow response and accumulated rainfall for the maximum storm of record (27 yrs.) at the Marcell Forest.

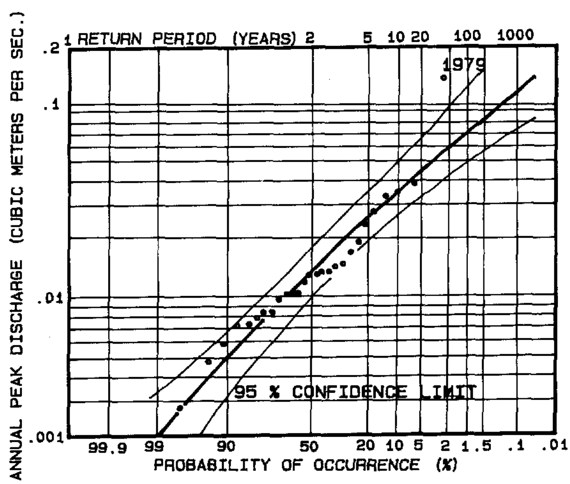

Fig. 4. Annual peak discharge from basin No. 2.

Water table response

The water table elevation where streamflow stops is 14.5 cm below the hollow. From there, in response to the storm, the water table rose about 7 cm to the top of the H-2 horizon before streamflow increased significantly. Increases in streamflow were still limited by some resistance to flow within the H-1 horizon of the peat below the hollows. When the water table rose above the hollow elevation, streamflow incréased rapidly, from 35 to 160 cubic m per hr with a water table rise of 8 cm. When the water table rose above the H-2 horizon within the hummocks, streamflow increased from 160 to 485 cubic m per hr in a vertical span of an additional 8 cm (Fig.5).

The water table rose rapidly twice without significant increases in streamflow (see points A and B in Fig. 5). These rapid rises were caused by the Lisse and Wieringermeer effects as described by Hooghoudt (1947). In the Lisse effect, "infiltrating rain acts as a tightly closing lid, which results in the water table rising to the level required to compensate for the pressure increase." (Heliotis and DeWitt, 1987). The Lisse effect is possible in heavy rainfall (4-15 mm per hr) (Heliotis and DeWitt, 1987). Rain fell during the July 1979 storm at 8-16 mm per hr.

In the Wieringermeer effect, the addition of rain water reduces the curvature of the menisci in the tension-saturated capillary fringe. The Wieringmeer effect is always followed by a rapid decline in water table elevation. This occurs at point C and A in Fig. 5.

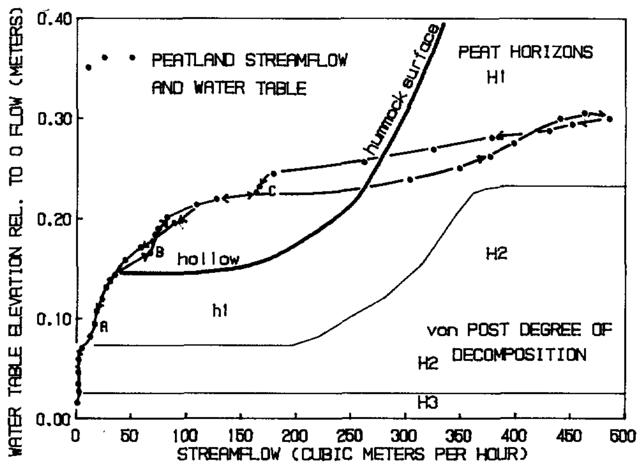

Fig. 5. Peatland streamflow and measured water table elevation. Hummock-hollow cross section and peat horizons are superimposed. Arrows indicate storm progression.

Comparison of peatland streamflow to a level reservoir

Water table response at the mire center is magnified by the specific yield of the peat. If the water table elevation is reduced to reflect only the specific yield, the elevation at a given streamflow rate from the mire is nearly identical with stage at the same discharge rate from a level reservoir, at least up to a discharge rate of 160 cubic meters per hr (Fig. 6). Below this rate, there is actually a small attenuation of flow below the level reservoir outflow rate (about 20 cubic m per hr) as the water table rises 5 cm above the hollow elevation (dots are higher than the solid line in Fig. 6). We attribute this resistance to flow to the presence of hummocks and trees.

Beyond the 160 cubic m per hr flow rate, streamflow increases significantly above that from a level reservoir. This occurs when channel-like flow begins in the lagg trapped between the upland and the Sphagnum dome. The large looping pattern of flow and stage (Fig.5) is caused by wedge storage when a channel (or relatively narrow reservoir) develops a moving wedge of water above a level datum (Linsley et al., 1982).

At the maximum flow rate, about 35% of the mire is covered with water completely above the hummocks, and in a channel-like lagg that directly intercepts mineral soil subsurface flow from about 2/3 of the mire perimeter. The remainder of the mire is dotted with hummock tops protruding above the water surface. It should be noted, that the hollow elevation in the lagg adjacent to the recording well is 8 cm lower than the hollow elevation at the recording well, and 29 cm lower at the stream outlet.

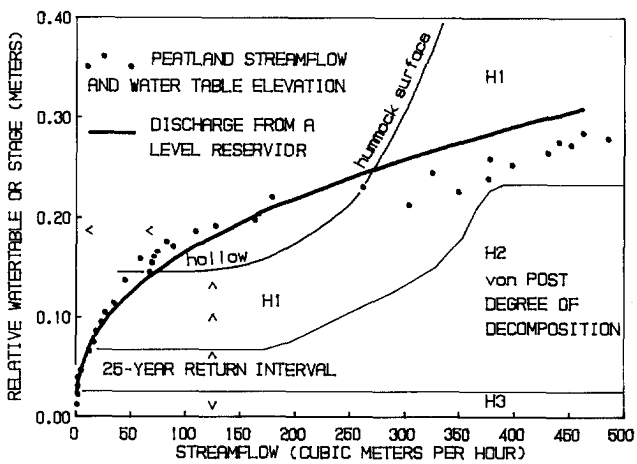

Fig. 6. Streamflow from a level reservoir (solid line) and measured from the mire (dots). Water table elevations for the mire have been corrected for specific yield.

Return period flow rates

The frequency curve for streamflow annual peaks was calculated using only 26 years of record. The 1979 point was considered an outlier (Fig.4). The estimate of peak streamflow rate for the 25-yr return period was 350 liters per second per sq. kilometer (l/s/km2) (or 32 cubic feet per second per sq. mile). Respective 95% confidence limits are +/-87 and +/- 8.

MODELING STREAMFLOW FROM PEATLAND

Our description of mire streamflow response to a very large storm points out the behavior of a particular mire in response to a particular storm. Many other combinations of mire size, mineral upland size, position of the mire within the entire basin, storm size, and intramire topography could result in a different response.

It is difficult to recommend area-based flow rates for a given return interval because we have information on only a few condition combinations. One way to extend our understanding of streamflow response is to combine long-term precipitation records from one station with a functional model of basin streamflow response in other areas. In addition the model could handle a spatial and size mix of mire and mineral soil upland. Such a model has been reported for a 3758 ha mire in Minnesota (Guertin et al., 1987). It is called PHIM (Peatland Hydrologic Inpact Model) and produces an hourly or daily water budget coupled with an iterative reservoir routing algorithm.

The model can handle channel-like flow within the mire if a water table :discharge relation is known (such as the dots in Fig.6). It could be improved by testing other water table:discharge relations from various intra-mire topographies.

CONCLUSIONS

Peatland streamflow responds to large storms almost the same way as streamflow from a level, unregulated, reservoir. The peat, hummock-hollow topography, and tree boles even reduce the streamflow rate slightly (approximately 20 cubic m per hr). This effect persists until the elevation of the 25-yr event, when the development of a channel-like flow system in the lagg area, and wedge storage increase flow rates above that of a level reservoir.

The 25-yr peak streamflow rate is given for a small basin (10 ha with 1/3 peatland and 2/3 mineral soil). Area-based peak rates lower than 350 l/s/km2 are likely to occur on larger basins. Seuna (1981) has measured rates of 317 and 204 l/s/km2 from 500-ha drained and undrained mires in Finland. Well-defined hydrologic relations in functional models, and long-term precipitation records can be used to verify these return periods in a variety of landscape configurations.

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