Importance of Wetlands to Streamflow Generation

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Abstract

Hewlett (1961) proposed the variable-source-area concept of streamflow origin in the mountains of North Carolina suggesting streamflow was produced from water leaving saturated areas near the channel. Dunne and Black confirmed this concept on the Sleepers River watershed in Vermont (1970). Areas near the river were saturated by subsurface or interflow from adjacent upland slopes. In turn, these saturated areas fed water directly to the channel. In the northern Lake States, wetlands and lakes make up 10 to 35% of the basin. These flat landscape components are surrounded by relatively steep (10-15% slope) glacial moraine uplands. We investigated the importance of wetlands to streamflow production on watershed two at the Marcell Experimental Forest in north central Minnesota. A hydrograph separation technique for the entire watershed yielded hydrographs for water both from the upland alone and from the wetland alone. Additionally, selected direct measurements of upland runoff and watershed streamflow confirmed the timing of hydrograph peaks for the separated watershed components. The wetland produced 50 to 70% of the annual streamflow even though the wetland comprised only 1/3rd of the basin. Storm peaks from the wetland were 5 to 10 times higher than storm peaks from the upland and occurred about 1 hour before upland runoff peaked. Saturated wetlands (and lake surfaces) are the primary source of streamflow in these glacial landscapes.

Keywords: source of streamflow, peatlands, uplands, subsurface flow, interflow, hydrograph separation

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Introduction

Overland flow to streams results when rain or snowmelt exceeds the infiltration capacity of soils (Horton 1933). However, the generation of surface runoff, basin-wide, was not the source of streamflow in North Carolina forests with an intact forest floor (Hewlett 1961). Instead, Hewlett found streamflow generated from saturated areas near slope bottoms and near channels. The extent of these saturated areas changed during the year and expanded during individual storms. Thus, Hewlett coined the theory of a variable-source-area for streamflow generation. Whipkey (1965) in Ohio measured the amount of subsurface flow in mineral soils and suggested subsurface flow was the source of water saturating lower-slope areas.

Dunne and Black (1970) directly measured the areas of subsurface flow and saturated, over-land flow in the Sleepers River watershed in Vermont. They clearly demonstrated the saturated areas near the stream produced overland flow during summer storms. They also measured significant areas of subsurface flow upslope of the near-stream, saturated areas. In the Susquehanna River basin in Pennsylvania, 50- to 100-year events produced saturated flow even from sloping subsurface flow areas (Yarnal et al. 1997). Pearce et al. (1986) and Bonell (1988) have extensively reviewed the history of the variable-source-area concept and modeling efforts aimed at the processes that generate runoff in forested headwater basins. None, however, have considered the role of wetlands, with annually saturated soils, as a source of streamflow.

Study Site

We examined 20 years of streamflow record from a mixed upland/wetland basin on the Marcell Experimental Forest in north central Minnesota (Lat. 47:31:52N, Long. 93:28:07W) to determine the significance of wetlands to streamflow generation. Watershed No. 2 is a forested headwater basin 9.72 ha in size with 2/3rds of the basin in mineral soils (aspen/birch forests) and 1/3rd of the basin in a centrally located black spruce, sphagnum moss, wetland (a bog in the fennoscandia terminology) (Figure 1). Figure 1 also shows the upland topography (1 m contours) and wetland topography (3 cm contours) and the location of instrumentation used in our evaluation of streamflow origin.

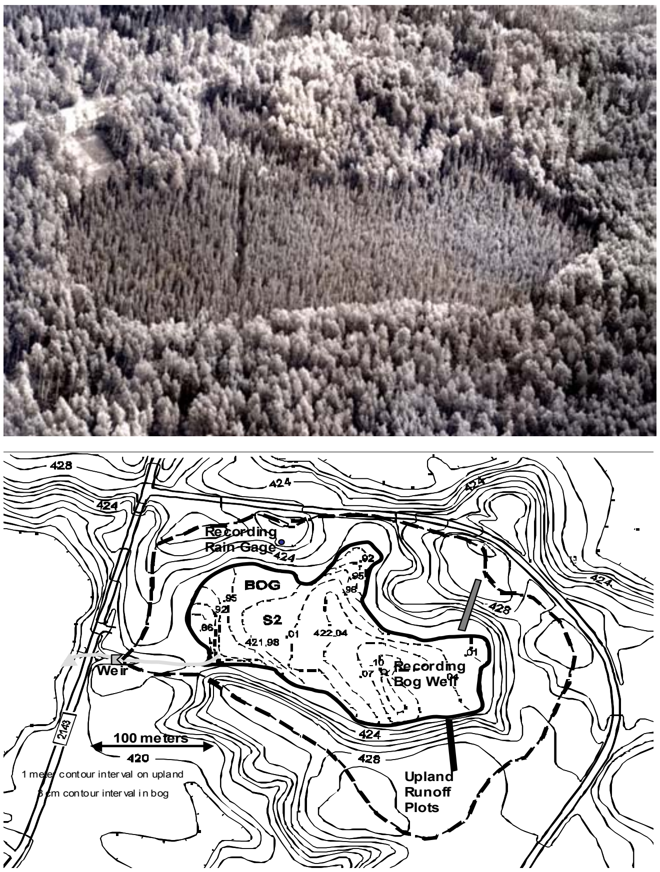

Figure 1. Aerial view of watershed S-2 on the Marcell Experimental Forest in north central Minnesota. The central area is a black spruce bog surrounded by an aspen/birch upland. In the lower map, upland contours are 1 meter and bog contours 3 cm. A recording rain gage, recording well (in the bog) and runoff plots with stage recorders in catch tanks, and the stream hydrograph at the weir were used to measure the timing and amount of streamflow originating from the upland and bog portions of the watershed.

Two sets of upland runoff plots are shown (Figure 1) one with a south aspect and one with a north aspect. At each site there are two upland runoff collection plots. One collects near-surface runoff through the forest floor (O horizons) usually very shallow flow over a frozen mineral soil. The other collects interflow or subsurface flow occurring as saturated flow in the mineral soil A and E horizons over a partially restrictive B2t horizon high in clay. The near-surface flow plots have a corrugated metal boundary, while the subsurface plots collect flow in a stainless steel well screen laid horizontally in a sand-filled trench dug into the surface of the B2t horizon about 30 cm below the surface. Contributions of the upland to total watershed streamflow are based on a hydrograph separation procedure.

Methods

The total watershed streamflow was separated into a bog-only and upland-only component using a hydrograph separation technique (Timmons et al. 1977). An analysis of total watershed hydrographs showed that logarithms of the total watershed recession leg slope were significantly higher (alpha = 0.001) during July and August than at other times. July and August recession legs represent flow periods from the bog only (water collections in upland runoff plot tanks were nil). The modal value for all July and August recession legs from 1961 through 1970 was a negative 0.21 log (base 10) of the total hydrograph recession leg in English units (cubic feet per second per day). Separation of the total stream hydrograph into an upland and wetland component is accomplished by applying the bog-only recession leg to total hydrograph peaks. On an annual basis, the bog-only recession leg is applied beginning with the first snowmelt-peak of the season in March. From that point on, the recession leg is drawn beneath the total hydrograph recession leg until another rising leg occurs. The rise (absolute amount) in the bog-only recession line is identical to the total streamflow rise measured at the weir.

The total hydrograph, rising-leg mimics the rise of the water table in the bog (from a recording well hydrograph) in timing and response. It is always identical to the streamflow weir hydrograph (see Figure 2). However, when the same amount of hydrograph rise is applied to the bog-only recession hydrograph, the peak flow is usually less than the total streamflow hydrograph rise because it begins at a lower "bog-only" value. The redrawn bog-only hydrograph beneath the total watershed hydrograph estimates water originating in only the bog wetland. Finally, the annual bog-only hydrograph (on a daily time step) is subtracted from the total watershed streamflow hydrograph to obtain daily estimates of upland-only contributions to watershed streamflow.

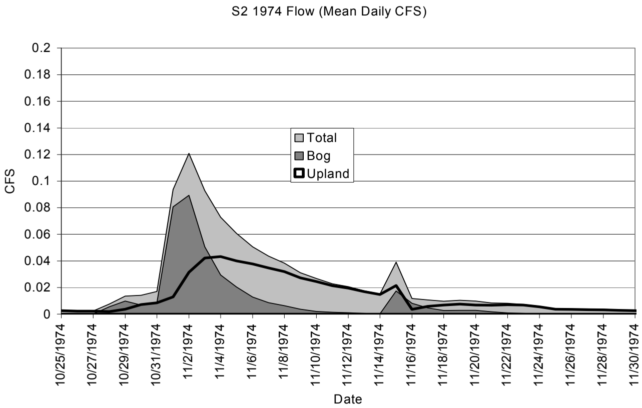

Figure 2. This one-month streamflow hydrograph for the S-2 watershed illustrates the importance of the bog wetland (dark gray) to the generation of total watershed streamflow (light gray) and the lesser importance of the mineral soil upland (black line).

In July of 1997, the upland runoff plot collection tanks were fitted with Belfort FW-I stage recorders and the data reduced to upland runoff hydrographs on an hourly time step with data read to the nearest half hour. Three July 1997 storms were analyzed at a half hour time step using the upland flow plots, bog water-table hydrograph, watershed streamflow weir hydrograph and a recording Belfort rain gage hyetograph to confirm the timing differences between upland and bog flow and the approximate total water yield from each watershed component.

A late October storm in 1974 illustrates the application of the bog-only recession leg (in dark gray) to the total watershed hydrograph (in light gay) (Figure 2). Subtraction of the dark gray from the light gray yields the upland-only, black hydrograph. The separations are based on a daily time step. Note that annual hydrographs are in cubic feet per second.

Results

Half hour upland and bog-only timing hydrographs

Three storms in July 1997 show the accumulated precipitation hyetograph, the bog well hydrograph, the total streamflow hydrograph, and two runoff-plot hydrographs for subsurface flow. On the larger, July 14 storm, the precipitation peaks at 8 AM along with the bog well and weir. In contrast the upland runoff plots peak at 9 and 10 AM for the south and north aspect respectively. A closer examination of the July 14 storm illustrates the detail of flow timing (Figure 3). The streamflow unit (cubic meters per minute) is 1000 times the unit for subsurface flow (liters per minute). However, the area of the upland 97,200 square meters is about 1000 times the area of one upland runoff plot (2 m x 49 m = 98 square meters). So the size of the hydrograph plots represent the approximate contributions to the total streamflow hydrograph.

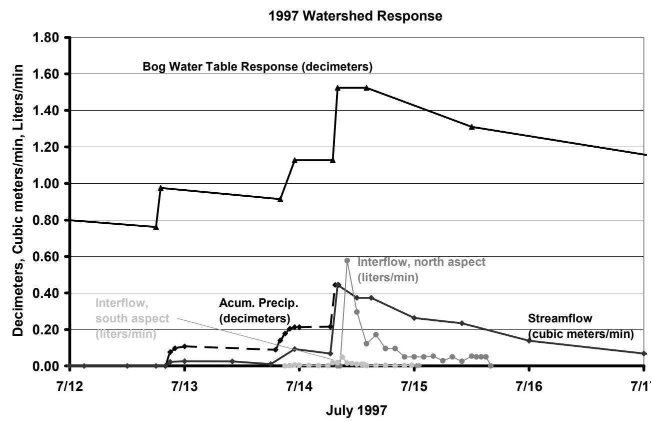

Figure 3. Direct measurements of precipitation on July 13 and 14, 1977, the upland runoff plot response and the rise of the water table in the bog show the bog responds first followed in an hour or two by the respective upland runoff plots.

The large differences between the north and south aspects reduce the combined upland runoff plot amounts to about a quarter of the total hydrograph for this particular storm. The subsurface flow for the south aspect is always less than interflow for the north aspect. Perhaps the south aspect always dries faster than the north aspect and thus has more soil water storage. Or differences in the undulation of the impeding B2t clay layer augments interflow collection on the north aspect and diverts interflow on the south aspect.

A comparison of the daily time step hydrograph separation with an hourly time step hydrograph for the same period is shown in Figure 4. The hourly hydrographs show as solid lines, from directly measured upland flow and confirm the delayed upland response compared with the bog well hydrograph and total watershed hydrograph. The annual hydrograph separation, using a daily time step, is shown with dashed lines and smoothes the hydrograph separation over several days. However, the area beneath both upland hydrograph curves (daily or hourly) is similar.

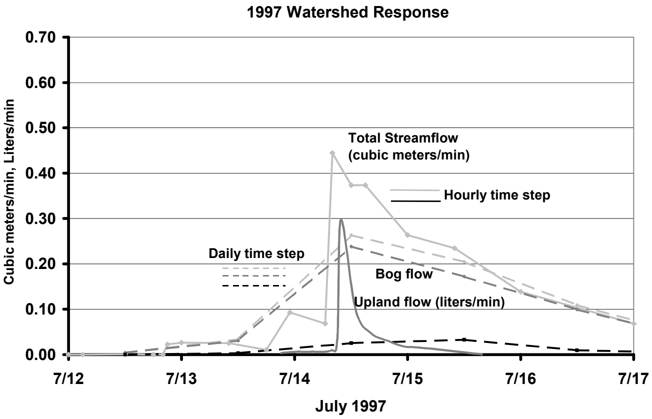

Figure 4. The July 14, 1977 storm shown with directly measured, hourly time step values for the upland runoff plots and total watershed stream flow (solid lines), and using a daily time step hydrograph separation technique for upland, bog, and total watershed streamflow (dashed lines). While the daily time step alters the actual timing, the area of total watershed and upland flow components are approximately equal for the daily and hourly time step hydrographs.

Examples of wetland-only response in annual hydrographs

The annual hydrograph separation for several years illustrates the role of the wetland (1/3rd of the basin) versus the upland (2/3rds of the basin) in producing the total watershed streamflow. Water years run from March 1 to February 28. In 1965, the first peak response is caused by melt of the snowpack followed by large rainstorms in May, June and late September. Throughout 1965, the bog responded first and peaked in flow rate 1 to 1.5 times the slower responding upland flow. This result occurs even though the upland is 2/3rds of the basin (Figure 5). Note the overall streamflow level on the Y-axis of each figure (cubic feet per second).

In 1968 peak flows were generally smaller, but the basin remained wet and responsive throughout most of the year. Again upland flow lagged peatland flow, but peak flow was more comparable between the two sources even though the bog-only portion contributed more and higher streamflow peaks (Figure 6).

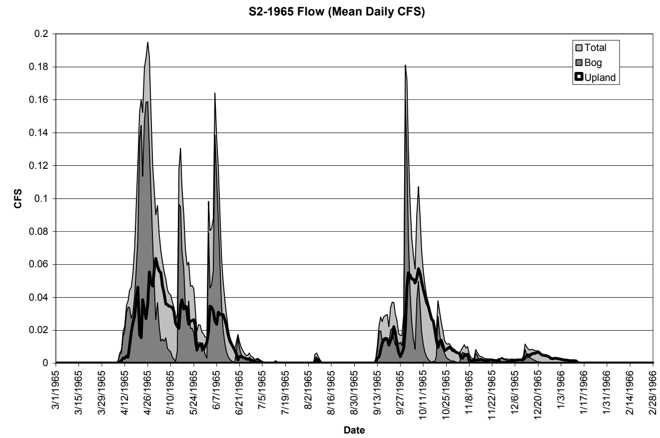

Figure 5. The 1965 hydrograph shows the bog always contributed first before the upland and had peak flows 1 to 1 ½ times the upland flow peak.

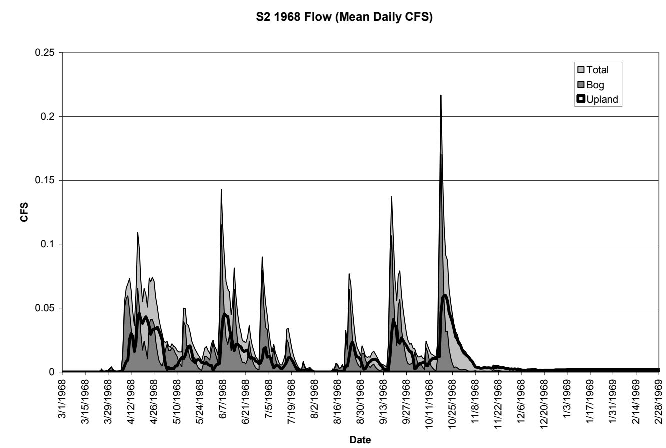

Figure 6. The 1968 hydrograph had lower streamflow than in 1965, but the bog portions again contributed first with greater peaks than the upland.

In 1966 the snowmelt and spring rain period was typical, but a dry summer stopped streamflow nearly 2 1/2 months. When a large August storm occurred, the bog responded first with a very high peak flow, 8 times the upland flow peak (Figure 7). The dry uplands provided significant soil water storage space before subsurface flow began.

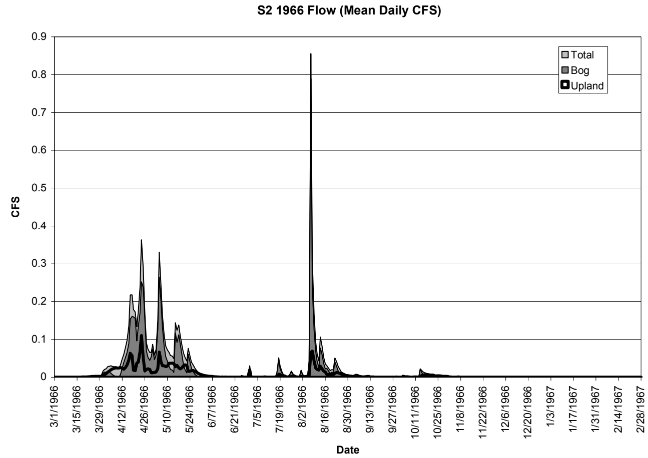

Figure 7. The 1966 hydrograph had a typical spring snowmelt period and a large summer storm when the bog responded first with a peak flow 8 times the upland peak flow.

1975 had a large snowpack and peak streamflow was high. In this spring, bog and upland contributed nearly identical spring flow volumes and nearly equal peak flows (Figure 8). A severe drought extended well into 1976 and meager snowmelt was mostly from the upland because the bog water table had dropped more than 1 meter during the drought (Figure 9).

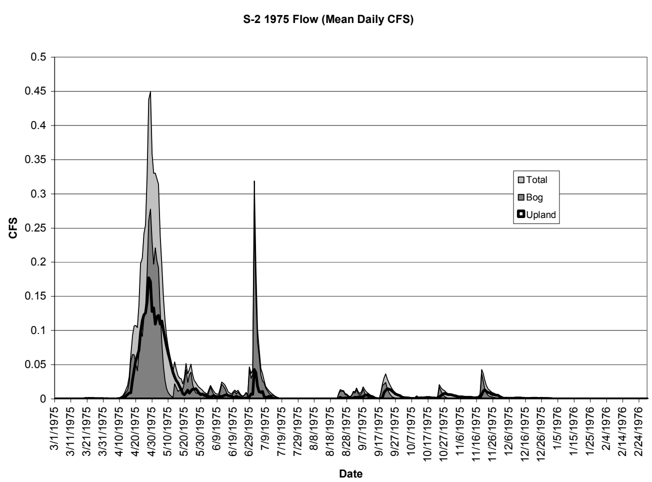

Figure 8. The 1975 hydrograph had a very large snowmelt when both the upland and bog become saturated and both had similar flow amounts and peak rates. A drought began in July of 1975 and extended through 1976.

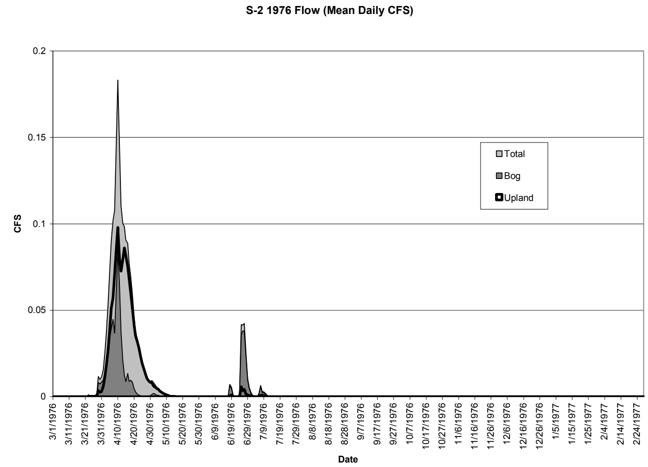

Figure 9. The 1976 hydrograph showed a small snowmelt peak, but the upland dominated because the bog water table had dropped over 1 meter during the drought.

In 1977, storage within the peat profile of the bog was quickly satisfied when spring rains broke the drought temporarily and bog-origin flow continued to dominate (Figure 10). In late September, when moderate storms, falling after leaf-fall, fully satisfied upland mineral soil water storage capacity, upland runoff gained in importance when interception on the bog black spruce was a significant factor in the peatland streamflow generation.

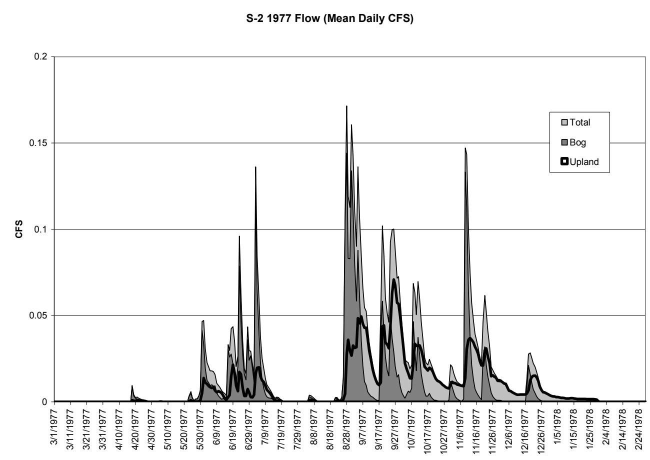

Figure 10. The 1977 hydrograph responded when spring snowmelt satisfied the large amount of soil water storage in both upland and peatland. Note however, the importance of upland streamflow in late September. Moderate storms falling after upland leaf-fall fully satisfied upland soil moisture storage, while spruce interception in the peatland reduced flow from

the peatland area. A very large, intense, convectional storm in July of 1979 (17 cm or 6.7 inches fell in less than 24 hours) immediately filled storage space in the bog, flooding the surface so only the tallest hummocks poked above water. The streamflow peak from the bog was 11 times that from the upland (Figure 11). The amount of soil water storage in the upland or wetland does affect storm response, but what is the relative importance of upland and wetland on an annual basis year after year?

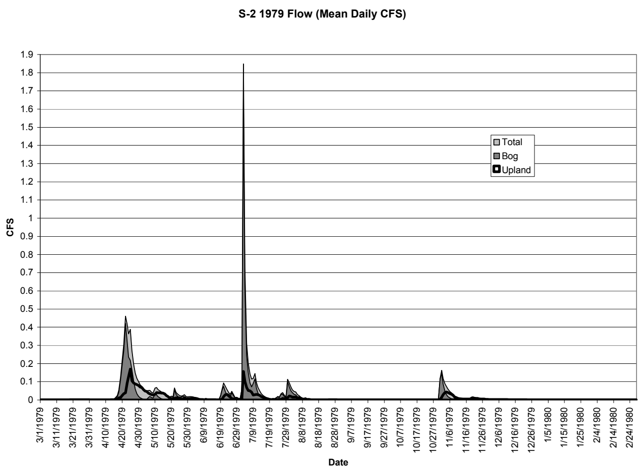

Figure 11. In 1979 a very large and intense July storm was produced mostly by bog only streamflow because the bog water table was still high, but upland soil moisture storage was high.

Average annual streamflow contributions

On average, the peatland produces 58% of the streamflow even though it occupies only 33% of the basin area. The peatland contributions range from 35 to 74% of the annual streamflow. The upland, on average, produces 42% of the streamflow even though it occupies 66% of the basin. During dry years in 1976 and less so in 1980, large amounts of soil water storage became available deep within the bog peat and the relative roles of the peatland and upland reverse (Figure 12).

The relationship of peatland and upland is obvious when annual streamflow contributions are plotted over water year precipitation (not shown). When plotted against water-year precipitation, the slope of the peatland streamflow response curve is 70% of the total streamflow response curve, and the upland streamflow response curve is 29% of the total. Thus the importance of each watershed component to total streamflow is the reverse of their relative areas.

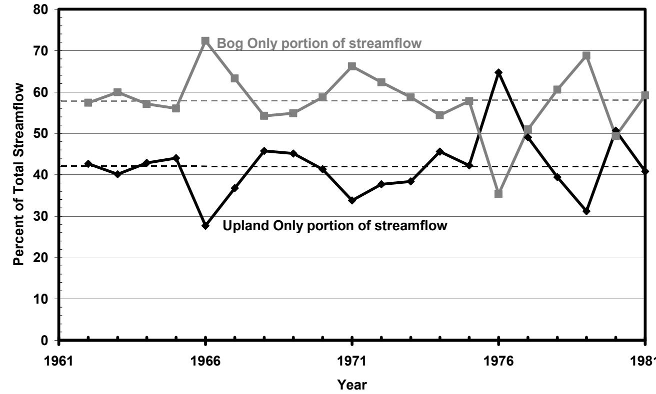

Figure 12. A twenty-year comparison of the annual amount of watershed streamflow originating from the upland (black line, average dashed) and the bog (gray line, average dashed).

Conclusions

Wetlands produce 50 to 70% of watershed streamflow even though they comprise only 1/3rd of the basin. Wetland storm peaks are 5 to 10 times greater than upland storm peaks, and upland storm peaks are delayed about an hour.

The data in this paper compares the relative contribution of upland and wetland to total watershed streamflow in a basin with moraine uplands (5 to 15% slopes) surrounding a flat wetland (black spruce bog). In this scenario the wetland is the primary producer of streamflow and primarily controls the magnitude of the storm peak. This arrangement of upland and wetland is common for Lake State pothole wetlands forming the beginning of stream systems.

Our comparison does not consider the peak streamflow response of landscapes dominated by wetlands versus landscapes dominated by steep-sloped uplands. Large landscapes with wetlands (and lakes) significantly reduce stormflow peaks at all recurrence intervals compared to landscapes with few wetlands and lakes (Conger 1971, Moore and Larson 1979, Ivanov 1981, Taylor and Pierson 1985, Roulet and Woo 1988, Johnston et al. 1990). Our evaluation of streamflow response to peak flows evaluates small basins without a groundwater, or base flow, component contributing to streamflow.
Our experience at the Marcell Experimental Forest with wetlands that do receive large groundwater inflow show similar peak flow responses on top of a substantial base flow component. Total streamflow from these groundwater-fed wetlands (fens) may be

ten times the streamflow from surfacewater-fed wetlands (bogs), yet peak flow responses are similar.

Further research looking at a longer record and examining the potential role of soil water storage can further define the role of wetlands in streamflow generation.

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