

Preliminary Hydrogeologic Study of Cedar Swamp Bog,
High Point State Park, NJ

by

Melissa N. G. Rozenwald

for submission to
Department of Earth and Environmental Sciences,
Lehigh University
May, 1995

*in partial fulfillment of the requirements for
departmental honors and the College Scholars Program*

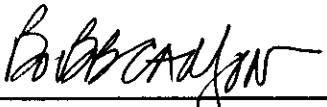
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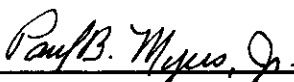
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Dr. Bobb Carson



Dr. Paul B. Myers

INTRODUCTION

Bogs are wetlands composed of deep layers of peat and a surface layer of living vegetation. Peat, which is 95% water (Cross, 1989), consists of partly rotted plant matter, animal remains, pollen, and dust. It accumulates over thousands of years and results from the lack of organic decomposition in a waterlogged, predominantly anaerobic environment. Due to the extremely wet, stagnant, and acidic conditions characterized by these ecosystems, microbial respiration is inhibited by the lack of oxygen. In other words, the "organic matter accumulates faster than the microbial respiration can dispose of it, creating organic peat soils" (Etherington, 1983). The acid water is maintained by the absence of an outside source of bases (Glaser, 1992) and by the cation exchange capacity (CEC) of the Sphagnum mosses, which are characteristic of bogs. The CEC is the ability of the mosses to absorb cations from the rainwater and release hydrogen ions back into the bog water, making the acidic environment even less suitable for the growth of micro-organisms.

By definition, a bog is an ombrogenous system; that is, water and nutrients are derived from precipitation, independent of groundwater. The water table remains near the bog surface above the saturated layers of the anaerobic catotelm. Fluctuations in the water table define the aerobic surface layer or acrotelm, where most of the limited biological activities take place.

CEDAR SWAMP BOG

Located in the northwest corner of New Jersey in the Ridge and Valley Province, High Point State Park (elevation $\leq 549\text{m}$) lies along Kittatiny Mountain and extends to the New York State line (Fig. 1). Within the park is the Cedar Swamp Bog which holds the distinction of being the highest altitude (approx. 457m) Atlantic White Cedar Swamp Bog in the world (Laderman et al., 1987).

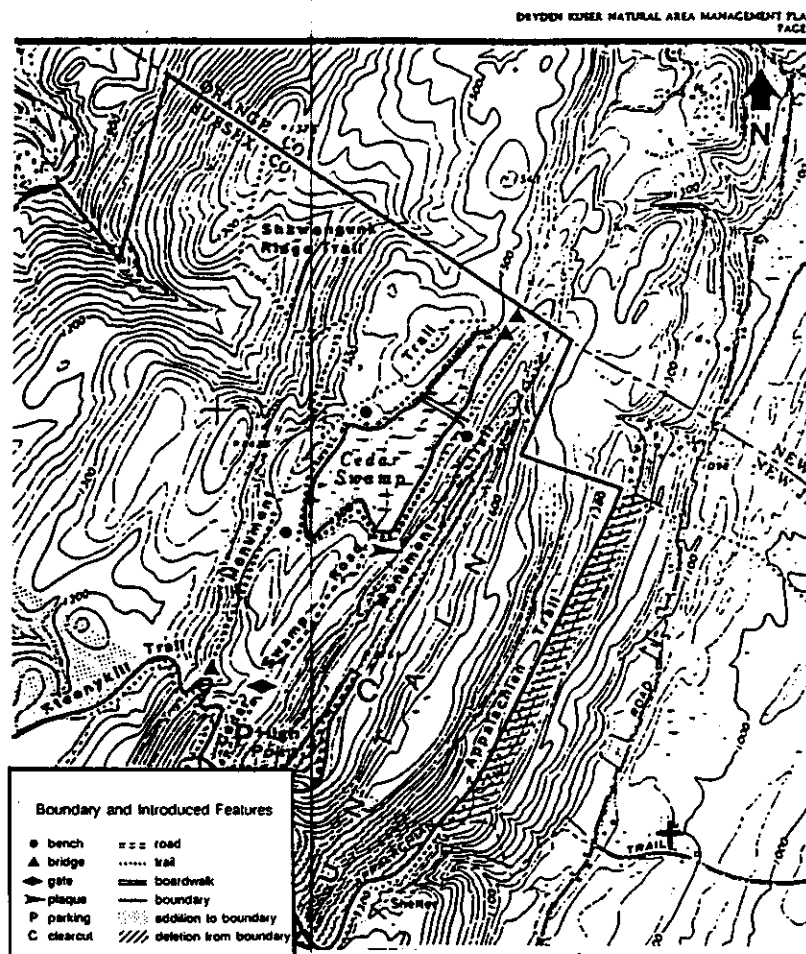


Figure 1: The Cedar Swamp Bog at High Point State Park, NJ is highlighted. The climatological data station (elevation 310m) is marked as a cross to the southeast of the bog.

ABSTRACT

This study provides a preliminary estimate of several hydrologic variables associated with Cedar Swamp Bog, High Point State Park, Sussex, NJ. Precipitation at the site varies seasonally, with lows occurring during the late fall and winter. Evapotranspiration was determined using Thornthwaite's equation for potential evapotranspiration. During the growing season, approximately April 15 - October 15, estimated evapotranspiration is 90% of the annual evapotranspiration, the remaining evapotranspiration occurring during the non-growing season. During this latter season, however, discharge, which was measured with a weir, constituted about 72% of the annual discharge. Change in storage and groundwater influx are considered negligible due to the hydraulic equilibrium maintained by a stream that discharges from the Bog and the low permeability of the Shawangunk Conglomerate bedrock.

This project seeks to provide a preliminary water budget of the Cedar Swamp Bog to establish its modern hydrogeology and specifically to investigate the temporal relationship between the evapotranspiration rates and the precipitation, outflow, and change in groundwater storage.

BACKGROUND

Kittatiny Mountain is underlain by the Silurian Shawangunk conglomerate and High Falls sandstone whereas the adjacent valleys are underlain by limestones and shales (NJDEP, 1995). Northwest of the highest elevations along the ridge, the slope is steep and then moderates to a plateau at 457m, where the Cedar Swamp is found (Figure 1). The Shawangunk conglomerate, which underlies the Cedar Swamp, is "primarily quartzite with small white quartz and slate pebbles embedded in a siliceous matrix" (Niering, 1953). The Shawangunk conglomerate has very low groundwater transmissivities, yielding on average less than five gallons per minute (Carswell, 1979). This characteristic reflects the low interstitial permeability and porosity of the Shawangunk Formation that result from secondary quartz cementation.

The Swamp was once a thirty-acre glacial lake formed at the end of the Wisconsin glacialiation, about 15,000 years ago (Gruzlovic, 1994). Till deposited by the retreating glaciers dammed the northern end of the valley, forming the lake. Over the

centuries, the lake filled with organic matter to form a semi-solid quaking bog (Plates 1 and 2).

The Cedar Swamp, which is now covered with a mixed conifer and deciduous forest, is in a late stage of bog succession. Sediments in a single core collected by Niering (1953) consist of 2.4 to 3.1m of clay, covered by 3.1 to 4.6m of gyttja (organomineral lacustrine deposit). Above the gyttja are 1.2m of sedge and sphagnum peat, above which is 1.8m of woody peat.

Out of the northeast end of the Bog, a small stream flows through a relatively level area before the water course cascades more steeply downhill into New York (Figure 1). According to notes in a management proposal (NJDEP, 1995), the stream was observed three times in 1993. In July and August, the stream had a low flow and later in October of the same year, it had a steady quick flow. The stream, which flows throughout the year, originates west of the summit of Kittatiny Ridge and eventually flows to the Hudson River as part of the Walkill watershed. From July, 1994 through March, 1995, the Cedar Swamp Bog has been observed at irregular intervals. After prolonged precipitation events, an intermittent stream feeds into the south end of the Cedar Swamp from a southwest direction and the water level in the Cedar Swamp rises (Plate 3). There is an intermittent pond located at the head of this stream.



Plate 1: The interior of the Bog during August, 1994. The Sphagnum drapes the drier hummocks as well as being submerged in the pools of water. Rhododendrum is very populous here as can be seen by the numerous branches.



Plate 2: Pools of acidic water with emergent bog vegetation in July, 1994, including the characteristic Sphagnum visible on the left side.

There have been no hydrologic studies made to date for this Atlantic White Cedar Swamp Bog. Previous research included plant community studies (Niering, 1953) as well as plant species lists prepared for the New Jersey Department of Environmental Protection (NJDEP, 1986; Anderson, 1991). Other previous botanic research can be found in the NJDEP management proposal (NJDEP, 1995).



Plate 3: The intermittent stream which flows into the Bog after prolonged precipitation events from the intermittent pond elevated above the Bog at the south end. This picture was taken looking SW from the Cedar Swamp Bog in March, 1995.

METHODS

The water budget equation for the catchment is:

$$P = ET + Q + G \pm \Delta S \quad (1)$$

where, ET is evapotranspiration, P is precipitation, Q is streamflow, G is groundwater flow, and ΔS is change in storage.

The term ' P ' was evaluated as follows: The catchment area was calculated using a topographic map. The watershed area was traced from the map and superimposed on a 0.5cm grid. The area of the watershed was assessed by relating the area of the squares to the same area on the topographic map. The number of squares lying inside the traced area were then counted to evaluate the catchment area ($1.94 \times 10^6 \text{m}^2$). For the squares lying on the perimeter, half of the square or more had to be inside the catchment border to be considered part of the catchment.

Precipitation readings were carried out by N. Stefano, who is certified by the National Oceanic and Atmospheric Administration (NOAA) to measure daily climatological data. This weather station, located approximately one mile southeast of the Bog, lies on the east side of Kittatiny ridge. The weather patterns at this location (elevation 310m) may vary somewhat from the those in and

around the Bog. The largest factor is most likely the difference in elevation between the data station and the study area. The Cedar Swamp Bog is probably cooler and may collect more precipitation, however, this study assumes unimportant differences in the rainfall between these two locations due to their proximity. The annual average precipitation readings (January, 1992 - March, 1995) are used to evaluate the volume of water available annually to the Swamp catchment area.

The term 'Q' was evaluated as follows: Stream flow was measured by a 90 degree, v-notch weir placed in the discharge stream (Plates 4 and 5). Discharge was evaluated using the formula

$$(Q = 2.5 H^{2.5}); \quad (2)$$

where, Q is the discharge (ft^3/s), H is the head of the backwater in feet above the weir crest (Fetter, 1994; Figure 2).

Daily precipitation measurements were used to make correlations between precipitation events and weir measurements. Annual variations in the discharge are unclear since the weir was not measured on a daily basis for a year. In order to evaluate a hypothetical annual discharge, the discharge was extrapolated from the precipitation and evapotranspiration data. An estimated daily discharge was derived from the annual estimate and compared to the actual daily weir measurements. These data were then used to

evaluate the deviation in outflow from the theoretical average. A non-growing season daily discharge is also evaluated and compared with the weir measurements.

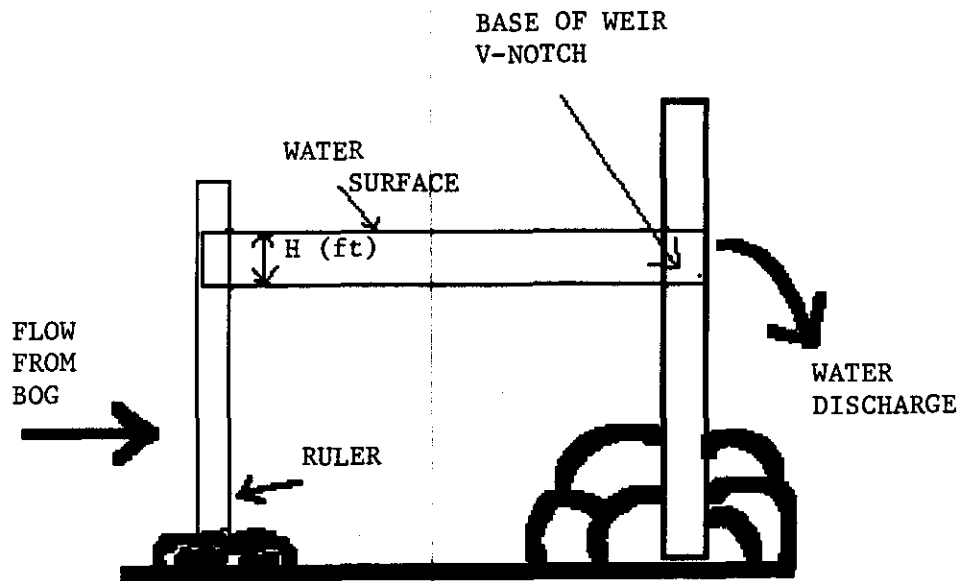


Figure 2: A diagram of the weir used to measure discharge.

The term 'Delta S' (change in storage) was evaluated as follows: "The very thinness of the acrotelm to which the water table movement is confined implies that most mires have a limited capacity either to store or release water in the short term" (Ingram, 1983). Because the acrotelm is thin, the water table movement is confined to a relatively small volume of space in relation to the total volume of the bog. Since storage is a function of the water table elevation, the change in storage is also very small. Most of the changes in water storage in bogs occur in the aerobic layer. Due to the reduced hydraulic



Plates 4 and 5: The 90 degree, v-notch weir was placed at the north end of the Bog to measure discharge. It was constructed of treated, exterior plywood and was stabilized with posts, rope, sandbags, and rocks.

conductivity from the surface of the acrotelm to its base, bog water level is regulated by increased flow at high water levels and decreased flow at low levels (Damman and French, 1987). As a result, bog water levels deviate little from average levels and reach peaks for brief periods only.

No water level measurements were carried out in the wetland, so the change in storage cannot be quantified. There are short term, small-scale changes in storage (< 1 day) after rain events or extended dry periods as the elevation of the Swamp is not constant. However, annual changes in storage are considered negligible as the stream at the north end of the Bog keeps the Bog in hydraulic equilibrium.

The term 'G' was evaluated as follows: Groundwater loss and input were considered insignificant due to the low permeability of the underlying Shawangunk Conglomerate bedrock. Furthermore, it has been assumed by various hydrologists (e.g. Sander, 1976; Boelter and Verry, 1977), that discharge of groundwater through thick layers of humified peat is negligible because of its very low hydraulic conductivity. It can be assumed, in this model, that groundwater moves slowly within the Shawangunk's restricted fracture system and that a minimal amount of groundwater enters the Bog system via secondary cracks and fissures in the Shawangunk bedrock. The Shawangunk has virtually no intergranular porosity, and the silica cementation virtually requires that secondary

fissures are the primary mode of water transport. Thus, G is taken to be very small, and can be approximated by 0.

The term 'ET' was evaluated as follows: Annual evapotranspiration data were evaluated using Turc's (Gray et al., 1970) and Thornthwaite's (Veihmeyer, 1964) empirical formulae for potential evapotranspiration based on precipitation and temperature. Potential evapotranspiration (PET), which is the maximum ET due to the absence of limiting conditions, is an appropriate estimation of actual evapotranspiration for this Bog ecosystem. This assertion can be made due to the availability of water for evaporation and transpiration all year long.

Thornthwaite's equation, which is used for the analysis of the water budget, is evaluated by calculating monthly heat indices based on the monthly mean temperatures and summing these for an annual heat index. PET was estimated with Thornthwaite's equation and then adjusted (Table 8) for variation in the number of days in a month and the effect of latitude on the number of hours in a day that support evapotranspiration. Thornthwaite has proposed values for these adjustments. Since the Bog is located at approximately 42 degrees north latitude, I used the tabulated adjustments for 40 degrees latitude. Interpolation between 40 and 45 degrees N latitude is unnecessary due to small differences between the adjustment factors.

The reduced water budget equation to be evaluated is:

$$ET = P - Q - \Delta S. \quad (3)$$

RESULTS

According to precipitation data from January, 1992 through December, 1994 (Fig. 3), rainfall patterns vary monthly, with a high in June (approx. 170mm) and low in February (approx. 70mm). Seasonally, the months of October through February show the least precipitation (approx. 430mm), whereas March through September have much greater rainfall (approx. 920mm), except for unexpected lows in May and July.

The average total annual precipitation for the three years is 1353mm; 1992 totalled 1310mm, 1993 totalled 1267mm, 1994 totalled 1481mm (Table 4). The average total volume of water available annually to the catchment, which has an area of $1.94 * 10^6 \text{m}^2$, is $2,625,260 \text{m}^3 \pm 2.2 * 10^5 \text{m}^3$.

TURC'S EQUATION VS. THORNTHEWAITE'S EQUATION FOR EVAPOTRANSPIRATION

Potential evapotranspiration values for the Bog were empirically derived, based on either temperature or temperature and precipitation. Turc's empirical formula, based on both precipitation and temperature, was used to estimate an annual average evapotranspiration value of 512mm. Monthly values were estimated using the equation for month-long time periods (Fig. 5).

Like precipitation, evapotranspiration is greatest in June and least in February. It must be noted that the sum of the monthly values of Turc's evapotranspiration is far greater than the annual estimation of evapotranspiration (Table 6), based on the same format. Turc's equation is not acceptable for the monthly ET estimated, as the sum of these short-term ET estimates is greater than the ET evaluated for the total annual period.

Also, ET from Turc's equation for the growing season, which is approximately April 15 to October 15 (Niering, personal communication), has a value (596mm) 116 percent of the total year's ET (512mm; Table 7). According to the Turc equation, evapotranspiration exceeds precipitation in the Bog from April through November.

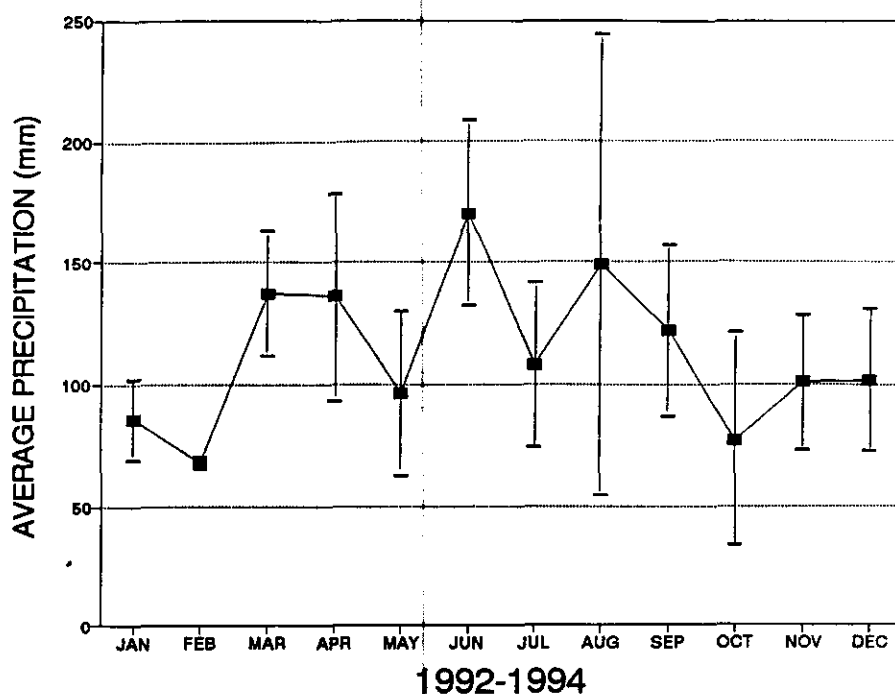


Figure 3: The average monthly precipitation for three consecutive years measured at 310m, 146m below the elevation of the Cedar Swamp. The error bars represent one standard deviation from the mean.

HIGH POINT STATE PARK
PRECIPITATION MEASUREMENTS
JAN. 1992 - DEC. 1994

(1020 ft.)

YEAR	1992.0	1993	1994		AVG. (in.)	AVG. (mm)	STD (in)	STD (mm)
JAN	2.95	2.88	4.29		3.37	85.7	0.65	16.48
FEB	2.55	2.77	2.72		2.68	68.1	0.09	2.39
MAR	4.05	5.67	6.5		5.41	137.3	1.02	25.84
APR	3.59	7.61	4.89		5.36	136.2	1.67	42.54
MAY	5.37	2.15	3.84		3.79	96.2	1.32	33.40
JUN	6.51	4.98	8.65		6.71	170.5	1.51	38.23
JUL	6.11	3.17	3.47		4.25	108.0	1.32	33.55
AUG	4.33	2.3	11.01		5.88	149.4	3.72	94.51
SEP	3.41	6.67	4.34		4.81	122.1	1.37	34.83
OCT	1.91	5.47	1.74		3.04	77.2	1.72	43.68
NOV	5.27	2.6	4.05		3.97	100.9	1.09	27.72
DEC	5.56	3.63	2.82		4.00	101.7	1.15	29.19
TOTAL	51.61	49.9	58.32		53.28	1353.2		

Table 4: Actual and average rainfall (inches) for each month from 1992 - 1994, as well as annual averages, and standard deviations.

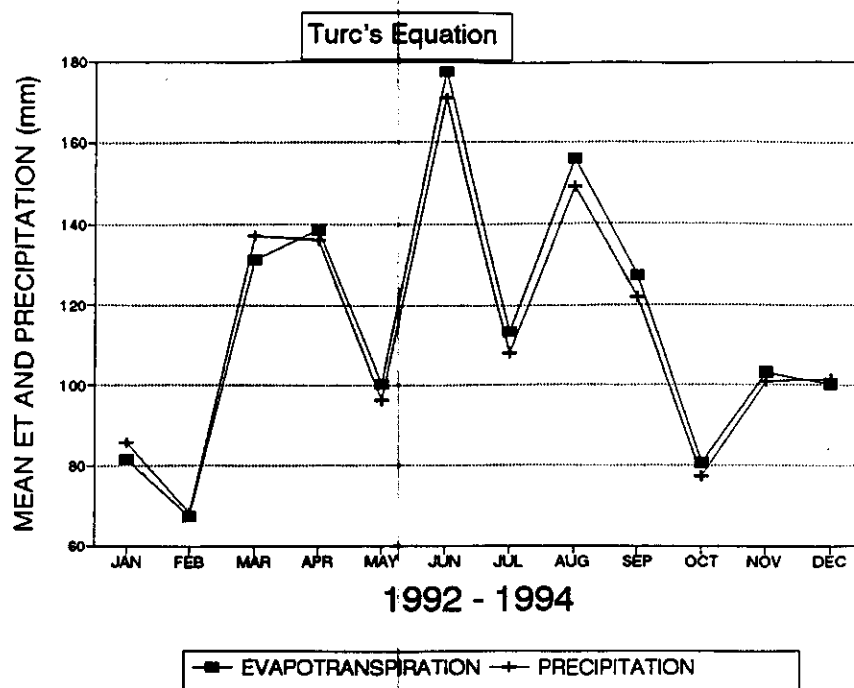


Figure 5: Monthly ET values according to Turc's equation. See Fig. 3 for error bars on precipitation.

MONTHLY EVAPOTRANSPIRATION
TURC'S FORMULA

(1992-1994)

MONTHS	PRECIP.	EVAP. CAP.	TEMP.	EVAPOTR. (mm)
JAN	85.7	189.1	-4.28	81.5
FEB	68.1	193.8	-4.04	67.4
MAR	137.3	315.3	0.61	131.6
APR	136.2	543.9	8.52	138.8
MAY	96.2	780.2	13.87	100.5
JUN	170.5	1107.7	18.87	177.4
JUL	108.0	1332.7	21.48	113.4
AUG	149.4	1189.1	19.87	156.1
SEP	122.1	878.2	15.57	127.3
OCT	77.2	576.1	9.39	80.6
NOV	100.9	431.3	5.00	103.3
DEC	101.7	283.8	-0.65	100.3

Total ET: 1378.2

Table 6: ET evaluated for each month using Turc's equation, as well as the sum of these monthly values, which represents the annual ET.

ATLANTIC WHITE CEDAR SWAMP BOG
 GROWING SEASON = APRIL 15 - OCTOBER 15
 NON-GROWING SEASON = OCTOBER 16 - APRIL 14

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GROWING SEASON - MEAN VALUES

MONTH	T (CELSIUS)	AVG. TEMP. (C):	15.8
		AVERAGE EVAP. CAP.:	889.3
APRIL 15 TO END	10.7		
MAY	13.9	TOTAL PRECIP. (mm):	763.4
JUNE	18.9		
JULY	21.5		
AUGUST	19.9		
SEPTEMBER	15.6		
OCTOBER 1 TO 15	9.9		
TOTAL ET DURING GROWING SEASON:		596.7	
TOTAL ET DURING YEAR:		512.9	
PERCENTAGE OF TOTAL ET DURING GROWING SEASON:		116.3	

Table 7: The growing season ET estimated by the Turc formula.

Thornthwaite's equation, based on temperature and empirically derived variables associated with latitude, provides an estimate of annual ET (621mm/yr) that is greater than Turc's long-term, non-additive, annual estimation (512mm/yr). Monthly values are evaluated by the Thornthwaite method and summed for a potential evapotranspiration total of 621mm (Table 8). The only month that evapotranspiration exceeds the precipitation is in July (Fig. 9). December, January, and February have values of zero due to the assumption in the Thornthwaite equation that in months where the average temperature is less than 0 degrees Celsius, no evapotranspiration takes place.

The Thornthwaite method estimates that 562mm of evapotranspiration takes place in the growing season, out of a total, annual evapotranspiration of 621mm, or 90.5 percent of the annual value (Table 10).

SHORT TERM RESPONSE TO RAIN EVENT

In order to evaluate the Cedar Swamp Bog's response to rain events, the weir was measured for seven consecutive days after a large rainfall event (52mm) on March 8, 1995. This event was followed by 2.5mm of rainfall on March 9. Discharge past the weir is plotted from March 9 until March 15 (Fig. 11). The discharge values are relative percentages due to leakage on the left side of the weir after March 8. The day with the greatest discharge, March 9, is considered 100 percent discharge and all other percentages are computed in relation to March 9.

	P (mm)	t (Celsius)	i	adjusted ET (mm)
JAN	85.7	-4.3	0.0	0.0
FEB	68.1	-4.0	0.0	0.0
MAR	137.3	0.6	0.0	1.9
APR	136.2	8.5	2.2	41.1
MAY	96.2	13.9	4.7	80.2
JUN	170.5	18.9	7.5	114.8
JUL	108.0	21.5	9.1	135.2
AUG	149.4	19.9	8.1	115.0
SEP	122.1	15.6	5.6	76.7
OCT	77.2	9.4	2.6	39.8
NOV	100.9	5.0	1.0	16.8
DEC	101.7	-0.6	0.0	0.0
TE (sum of i's):			40.8	
TOTAL ET (sum of adjusted ET's):				621.4
a = 1.1408				

$$ET = 1.6 (10/TE)^a$$

$$TE = \text{SUM OF } i's$$

$$i = (t/5)^{1.514} \quad (\text{for each month})$$

$$a = 6.75 \cdot 10^{-7} (TE)^3 - 7.71 \cdot 10^{-5} (TE)^2 + .01792 (TE) + 0.49239$$

Table 8: Estimated Thornthwaite value of ET for each month and annual average for the three years.

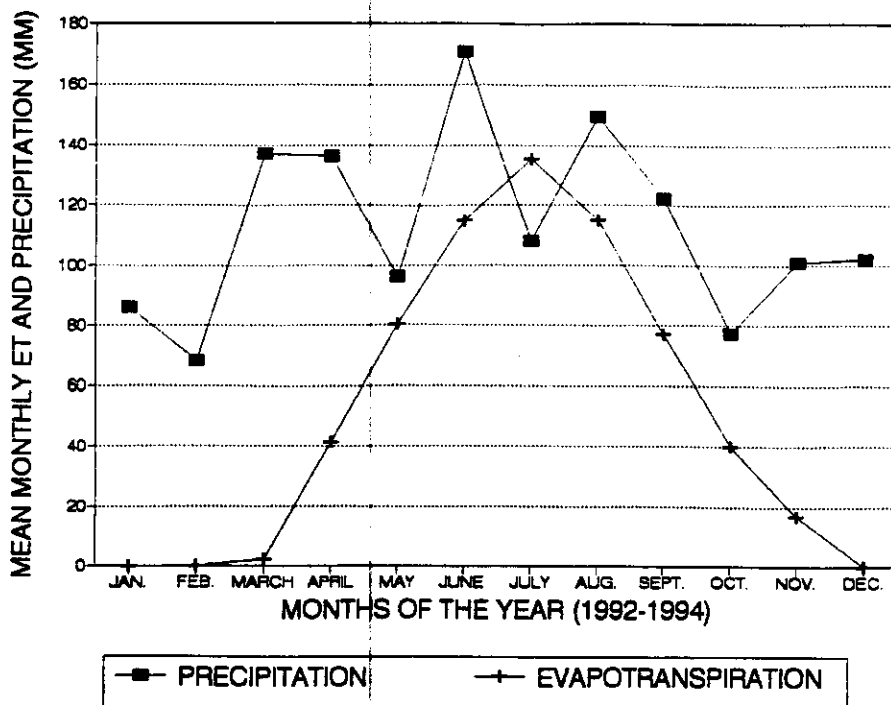


Figure 9: Thornthwaite's monthly ET compared to average monthly precipitation over the three year period.

HIGH POINT STATE PARK
GROWING SEASON
EVAPOTRANSPIRATION VALUES
THORNTHWAITE'S EMPIRICAL FORMULA
1992 - 1994

ATLANTIC WHITE CEDAR SWAMP BOG
GROWING SEASON = APRIL 15 - OCTOBER 15

MONTH	T (CELSIUS)		adjusted ET (mm)
APRIL 15 TO END			20.6
MAY	13.9	4.7	80.2
JUNE	18.9	7.5	114.8
JULY	21.5	9.1	135.2
AUGUST	19.9	8.1	115.0
SEPTEMBER	15.6	5.6	76.7
OCTOBER 1 TO 15			19.9

TOTAL GROWING SEASON ET: 562.3
TOTAL YEARLY ET: 621.4
PERCENTAGE OF TOTAL ET DURING GROWING SEASON: 90.5

Note: April 15 to end and Oct. 1 to 15: divided monthly ET by 2

Table 10: Growing season (April 15 - October 15) estimate of Thornthwaite ET.

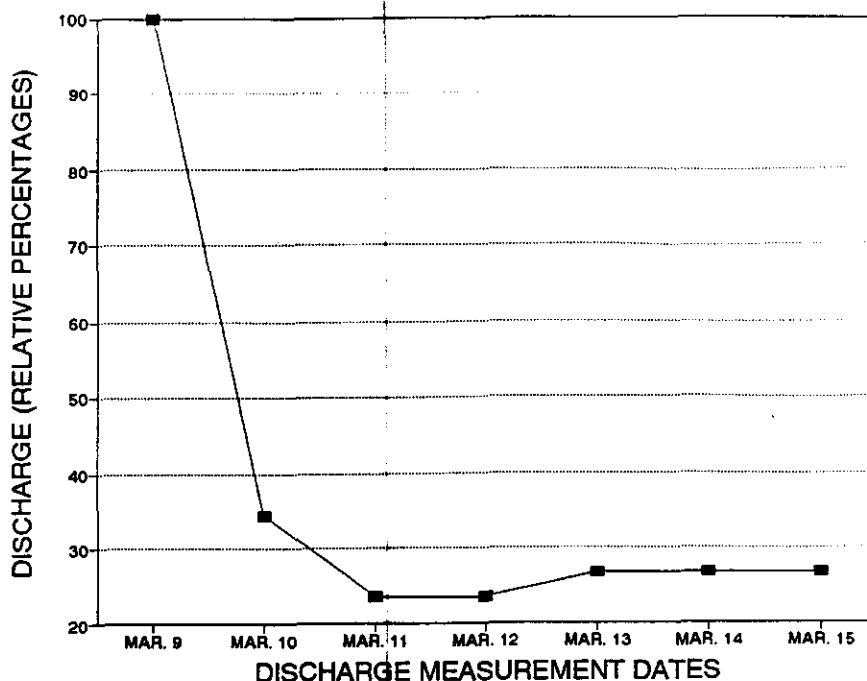


Figure 11: A plot of the discharge recession after the rainfall events of March 8 and 9, 1995.

STREAMFLOW - THEORETICAL VERSUS MEASURED

Average annual streamflow was calculated by subtracting the annual evapotranspiration value from the annual precipitation value. The resulting value (732mm) was converted into m/yr and then multiplied by the catchment area. The resultant rate of $1,420,000\text{m}^3/\text{yr}$ was then converted to m^3/s . The outcome was an average streamflow of $.045\text{m}^3/\text{s}$. This value is compared with measured values collected from November 23, 1994 to March 15, 1995 (Table 12, Fig. 13). This average discharge was exceeded only on March 9 and 10 after the large precipitation event. Low flow ($\leq .018\text{m}^3/\text{s}$) was measured during the winter from November, 1994 to February, 1995 (Plate 6).

$Q = P - ET$
 $Q = 731.778 \text{ mm/yr}$
 $Q = .045 \text{ m}^3/\text{s}$

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TIME PERIOD: 1994-1995

m^3/s	DATE
0.018	NOV. 23
0.011	DEC. 28
0.005	FEB. 5
0.000	FEB. 19
0.157	MAR. 9
0.054	MAR. 10
0.037	MAR. 11
0.037	MAR. 12
0.042	MAR. 13
0.042	MAR. 14
0.042	MAR. 15

$.045 \text{ m}^3/\text{s}$ CALCULATED AVERAGE

Table 12: Stream discharges of the small outflow creek which drains Cedar Swamp Bog measured during this study as well as the calculated average discharge.

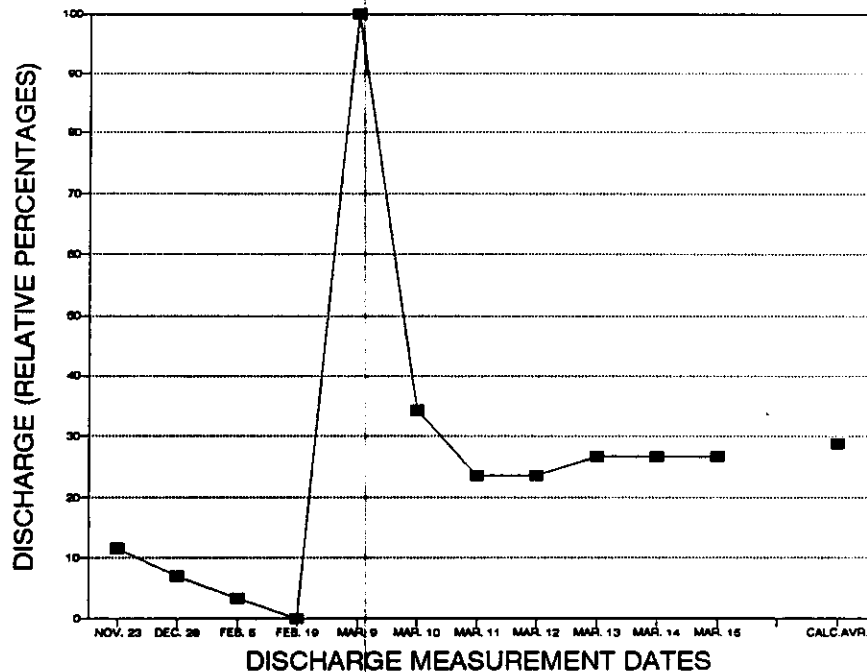


Figure 13: Discharge measurements of the outflow stream plotted as relative percentages. The lines connecting the first five discharge percentages are not all contiguous measurements.



Plate 6: The water flowing over the weir is hardly visible in February. H was 1/4 inch. Three inches of ice had to be broken through to make the measurement.

The growing season streamflow, accounted for by the difference between the growing season precipitation and evapotranspiration, is approximately $390,000\text{m}^3$, or $.04\text{m}^3/\text{s}$. This is 27% of the estimated annual total streamflow of $1,420,000\text{m}^3$, which is also $.04\text{m}^3/\text{s}$ (Fig. 14). Relative to the amount of water precipitated into the system, the non-growing season had a much higher percentage (approx. 90%) of water leaving via calculated streamflow, whereas during the growing season, the percentage of water leaving via calculated streamflow was approximately 26%. Estimated streamflow during the non-growing season is $.05\text{m}^3/\text{s}$. It is evident from these data that the volume of water leaving Cedar Swamp Bog in the form of streamflow varies greatly between seasons, however, the rate of discharge for both seasons remains around the value of $.04\text{m}^3/\text{s}$.

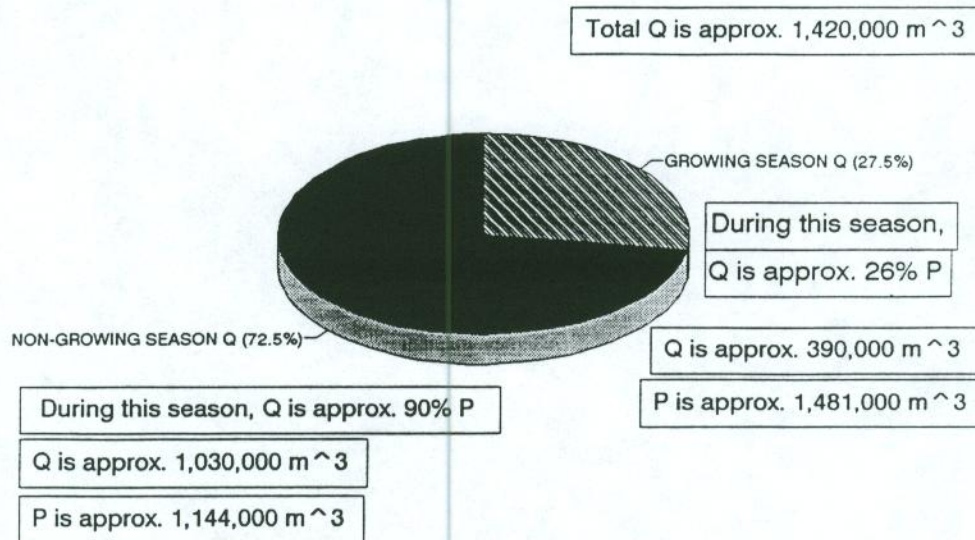


Figure 14: Growing season versus non-growing season stream discharge, Q, as established using Thornthwaite's equation for ET. P = precipitation volume which falls on the Cedar Swamp watershed.

DISCUSSION

ESTIMATES OF EVAPOTRANSPIRATION

The two estimates of annual evapotranspiration provide significantly different values: 512mm (Turc method), and 621mm (Thornthwaite method). Both formulae, however, estimate the Cedar Swamp watershed annual ET values at less than half the precipitation (1353mm).

Turc's equation gives an annual ET of 512mm. When this equation is used to obtain monthly values of ET, the results are contradictory. For example, most of the monthly values are greater than the precipitation for the same time period. As a result, there is no reasonable explanation for these values except that this equation is inapplicable to sub-annual time periods. Therefore, evapotranspiration estimates based on Turc's equation are not used in this study.

Thornthwaite's equation produces a higher annual ET value (621mm) and a more reasonable percentage of ET during the growing season than the values from Turc's method. According to Thornthwaite's equation, 90% of the ET occurs between April 15 and October 15. Such a value would be expected since actual evapotranspiration has the capacity to reach potential values when the plants are growing, there is more surface area from which to evapotranspire, and the water availability is extremely high due to the waterlogged conditions associated with a bog.

SEASONAL VARIATIONS IN PRECIPITATION AND STREAMFLOW

The three years of precipitation data (Table 4) show a seasonal trend, with high rainfall in late spring and summer (March - September) and low precipitation in fall and winter (October - February). Does streamflow vary from the Cedar Swamp comparably? Calculated streamflow discharge (Fig. 14) suggests that almost

three quarters of the water leaving the Bog as streamflow is lost in the non-growing season, approximately October 16 - April 14. The total discharge (Q) for the year is $1,420,000\text{m}^3$, obtained by subtracting the Thornthwaite evapotranspiration for the year from the annual precipitation.

To estimate the growing season discharge (Q), the calculated growing season ET was subtracted from the growing season precipitation. Volumetrically, the discharge for this season had a value of approximately $390,000\text{m}^3$, only 27% of the yearly Q. The estimated discharge rate for this season was $.04\text{m}^3/\text{s}$. Most of the water available to a bog at this time of the year is evapotranspired back to the atmosphere, reducing the volume of water to exit via the stream. According to Verry and Boelter (1979), peatlands do not sustain streamflow during dry summer months because the water is evapotranspired at maximum rates at the expense of streamflow. During the non-growing season, there is less precipitation, however, there is also much less evapotranspiration. Almost all of the precipitation, then, which falls on the watershed at this time of year, leaves as stream flow. This non-growing season Q (approx. $1,030,000\text{m}^3$) accounts for 72% of the estimated annual streamflow, at an average flow rate of $.05\text{m}^3/\text{s}$.

SEASONAL VARIATIONS IN EVAPOTRANSPIRATION

Peat acts as a storage tank because it is so absorbent and the water flow through it is poor. The acrotelm has a permeability that can exceed 10^{-1}m/s (Hobbs, 1986), however, the catotelm is less permeable than the acrotelm. In the case of sedge peat, such as the peat found in the Cedar Swamp Bog, the permeability may be approximated at 10^{-5}m/s (Hobbs, 1986). Hence, water availability generally permits vegetation growing on the peat to maintain increased evapotranspiration rates (Duever, 1988). Most of the water entering a bog leaves as vapor due to evapotranspiration. In fact, Ingram (1983) and Verry and Boelter (1979) have noted that actual evapotranspiration is approximately equal to potential evapotranspiration due to the availability of water almost year round.

Seasonal variations in evapotranspiration are due to many factors including solar radiation, wind speed, and vegetation types. Some of these factors have been accounted for in Thornthwaite's empirical formulas devised to estimate evapotranspiration, however this particular value in the water budget analysis is probably one of the most complicated due to the limited knowledge of evapotranspiration values at ecosystem levels.

The total ET for the year was calculated to be 621mm. This figure is the sum of the evapotranspiration values for each month except for December, January, and February, since these months had average temperatures of less than 0 degrees Celsius. It is assumed in the Thornthwaite equation that there is no evapotranspiration taking place when the temperature is below 0 degrees Celsius. The water should be in a solid state, with little or none of it able to be transpired or evaporated. Theoretically, this is the case, but there was free water available in February and December in this Bog (Plate 7). This equation, then, does not account for all evapotranspiration by assuming lack of liquid water availability during these three months.

The only month in which the Thornthwaite-derived evapotranspiration exceeded the precipitation was in July, at the peak of the ET curve. The amount of evapotranspiration that occurred during the growing season is a large percentage of the total annual ET. Of the 621mm of vapor evapotranspired throughout the year, 562mm (90%) occurs during the growing season. It is during this part of the year that there is increased rainfall and large amounts of actively evapotranspiring vegetation. It can only



Plate 7: Cedar Swamp Bog, February, 1995 - water available for ET.

be hypothesized that streamflow during this season is decreased due to the increased ET since no weir data are available for this season.

SHORT-TERM RESPONSE OF Q TO PRECIPITATION EVENT

The short-term response to a precipitation event early in March, 1995 was very rapid with maximum measured flow of $0.16 \text{ m}^3/\text{s}$. The next day, even with 2.5mm more rain, discharge declined to $0.05 \text{ m}^3/\text{s}$ and then to $0.04 \text{ m}^3/\text{s}$ after 48 hours. The recession curve for this response can be seen on Figure 11. The volume of water precipitated upon the watershed on March 8 and 9 was $106,900 \text{ m}^3$. Over the seven days discharge was measured following the

precipitation events, the volume leaving was $35,500\text{m}^3$ (the weir developed a leak during the March 8 event, so the discharge measurements are minimum values and valuable as relative rather than absolute measurements). What is evident from these data, however, is that stream discharge responses are rapid. The rapid increase and decrease in stream discharge are indicative of the capacity of the Cedar Swamp Bog, during that time period, to store water. Fig. 11 shows that the bog has reached its maximum water-retention capacity. More than $1/3$ of the water precipitated onto the catchment area was directed to the stream at the north end of the Bog as output.

The rapid initial response to a precipitation event is explained simply by bog water table fluctuations. According to Ingram (1983), precipitation elevates the water table, reducing temporary storage as it increases. Water is then discharged from the system, which in this case is the stream at the north end of the Bog.

Another factor in the rapid response of a bog to precipitation events are the hydraulic characteristics of the acrotelm and catotelm. The catotelm acts as a basal confining layer by restricting water flow or recharge to deeper levels (Glaser, 1987). This pattern is due to decomposition of the plants at these depths that decreases pore space and permeability. The surface peat, or acrotelm, drains quickly due to its relatively large pore space and

hydraulic conductivity. Thus, bogs tend to react very quickly to intense precipitation events, as shown in Figure 11.

The intermittent stream that flows into the south end of the bog is a function of the precipitation that occurs in the catchment. There is also the flux of groundwater in the system after precipitation events, which has not been measured. The influence of groundwater in the water budget remains unclear, although about 2/3 of the March 8/9 rainfall was retained for 7 days in the catchment area, presumably by elevation of the groundwater table.

THEORETICAL VERSUS ACTUAL DAILY DISCHARGE

Weir measurements of actual discharge did not exceed the calculated (annual) average discharge of $0.045\text{m}^3/\text{s}$ except on March 9 and 10, 1995, the two days following the large rainfall event. Of the months sampled for discharge rates (November, December, February, March - all of which fall into the category of the non-growing season), February had the lowest measured discharge value ($.0025\text{m}^3/\text{s}$) followed by December ($.01\text{m}^3/\text{s}$) and November ($.02\text{m}^3/\text{s}$). March values ($.06\text{m}^3/\text{s}$) are very close to the estimated annual average discharge of $.04\text{m}^3/\text{s}$ (Table 12).

Of the total estimated discharge for the year ($1,420,000\text{m}^3$), the discharge for the non-growing season is almost

three times the discharge for the growing season. The calculated average precipitation volume entering the system during this non-growing season is approximately $1,144,000\text{m}^3$, while the volume leaving as discharge is estimated at $1,030,000\text{m}^3$ (90% of the incoming precipitation). During the growing season, the incoming precipitation volume is $1,481,000\text{m}^3$. Volumetric stream discharge is estimated to be approximately 26 percent of this value, $390,000\text{m}^3$ (Fig. 14).

During the non-growing season, the spot-measurements of discharge averaged $0.04\text{m}^3/\text{s}$. The calculated average discharge during this season is $0.066\text{m}^3/\text{s}$. The fact that the estimated value differs from the actual value by approximately 50%, suggests that the water budget projected here is a reasonable approximation of conditions at Cedar Swamp Bog.

CONCLUSION

The flux of water coming into and leaving the Cedar Swamp Bog varies seasonally, however no simple relationship exists between precipitation and evapotranspiration. During the growing season (April 15 - October 15), evapotranspiration (approx. 562mm) constitutes approximately 90% of the annual ET and stream discharge is only about 27% of the annual discharge. The reverse is true for the non-growing season, when stream discharge constitutes about 72% of the yearly value, but ET is only approximately 8% of the annual

ET. The growing season is, then, a period of increased rainfall, a decreased Q/P ratio, and increased evapotranspiration. The non-growing season has decreased rainfall, an increased Q/P ratio, and decreased evapotranspiration.

There is no quick seepage into the bog, that is, precipitation is quickly directed to the output stream after precipitation events due to the inability of the Bog to store significant volumes of water. The relative contribution of groundwater to the discharge system is unknown.

Turc's equation for evapotranspiration is not useful for short-term, sub-annual, or month-long time periods. Thornthwaite's method is a good estimate of potential evapotranspiration for both month-long and annual approximations.

It is clear from the results that more work is necessary at Cedar Swamp Bog to establish a complete water budget. Remote daily measurements of water level, precipitation, and discharge are necessary. The time period for collection of data should be at least one year, although several years would provide a more accurate profile. These long-term variables are crucial to examining this ecosystem in depth.

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