WATER LEVEL REGIMES IN A SWAMP

by

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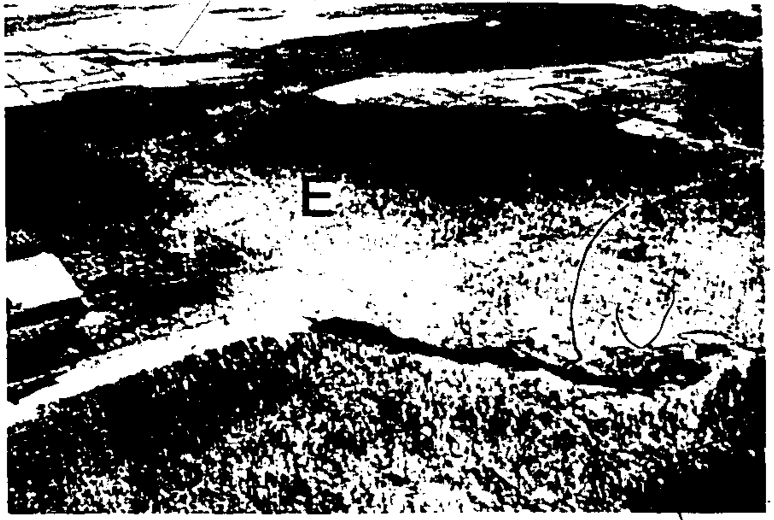

Frontispiece: Aerial view of part of Beverly Swamp.
The location of the major research sites is indicated in the overlay:

Northeast Site (NE)

Part of the North Site (N)

Confluence Site (C)

East Site (E)

South Site (S)

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ABSTRACT

This research studies the spatial and temporal variations of the watertable of Beverly Swamp (Southern Ontario), within the context of the hydrology of the area. Fieldwork was conducted from April to November, 1977, and it concentrated on the monitoring of water levels at selected sites in the swamp.

Results indicate that there is a strong interaction between streamflow and subsurface flow, which led to a classification of swamp water level regimes. In general, streams entering the swamp tend to impose their regime on the surrounding aquifer which thus experiences a "periodically effluent" regime, with periods of marked influent flow. The flow of the streams starting at the swamp, instead, depends on the watertable of the surrounding aquifer, which experiences a "predominantly effluent" regime.

The relationship between swamp water levels and outflow is analyzed in detail. At a seasonal scale, this relationship is non-linear, and at a reduced time scale it shows a series of hysteresis loops caused by two factors. The first is related to a translation time lag, and the second to different discharges resulting from a given watertable level.

Stream level, evaporation and rainfall data are then used in a numerical model which synthesizes the water level hydrographs at several sites in the swamp.

Finally, runoff regulation ability of the swamp is examined, and it is concluded that it is of small magnitude, noticeably only in small-volume, flashy inputs to the swamp.

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CHAPTER ONE

INTRODUCTION

Away to the Dismal Swamp he speeds;
His Path was rugged and sore;
Through tangled juniper, beds of reeds,
Through many a fen, where the serpent feeds,
And never man trod before.

Thomas Moore

1.1 Introduction

The Canadian Department of Fisheries and Forestry (1969) defined wetlands as areas of organic water-worked soils which are saturated periodically. In Canada, wetlands constitute a substantial portion of the land surface. In the Canadian National Atlas, Hare et al. (1975) estimated the coverage to be 8.2 percent, most of which occurs in the Canadian Shield and the sub-Arctic regions. With an increasing interest in the development of the north, there is a growing demand for information concerning wetlands.

The classification of wetlands suffers from a lack of precision. The Canadian Department of Fisheries and Forestry (1969) subdivided wetlands into marshes, swamps, fens and bogs. For the present study this classification will be adopted, a summary of which is presented in Table 1.1. This table's subdivisions show that, from marshes through swamps and fens to bogs, there is a progressive decrease in the pH and the O_2 content of the water, an increase in the amount of peat formed,

TABLE 1.1

Classification of Wetlands

Type of Wetland	Hydrology	Vegetation	Soils	Water Chemistry
Marsh	Periodically inundated with slowly moving or standing water.	Grassy, non-woody plants, not very consolidated.	Mineral or organic substratum with high mineral content. Little peat.	Neutral or alkline. High in O_2.
Swamp (Forested wetland)	Seasonally or semi-permanently inundated with slowly moving or standing water. Bottom soils always water-logged.	Trees (tall shrubs, hardwoods and conifers) and mosses, ferns and grasses.	Substratum of transported minerals or organic sediments. Not much peat but well decomposed.	Neutral or acid.
Fen	Watertable usually at surface level; some standing water in the spring. Restricted drainage.	Sedges and may be grasses, reeds, shrubs; perhaps trees.	Fair amounts of not very decomposed peat.	Not very acid. Low O_2. Low mineral supply.
Bog	High watertable, from the surface to slightly below, but no standing water except ponds.	Carpet of mosses. Possible tree or shrub cover.	Fair amounts of peat, formed in situ under closed drainage.	Inside water is acid, open water not so much. Low O_2.

After the Canadian Department of Fisheries and Forestry (1969).

and a high watertable of increasing duration. For swamps, a subdivision into "minerotrophic" and "transitional to bog" types corresponds to a decrease in the rate of water flow and the accompanying biochemical consequences due to such a decrease.

In another classification, Veatch and Humphrey (1966) recognized marshes by their herbaceous vegetation and swamps by the presence of trees. Heinselman (1970) classified peatlands according to type of flow: minerotrophic peatlands, which include swamps and fens, have a concave profile and therefore a confluent flow of mineral-rich water, while ombrotrophic peatlands or bogs have a convex profile and therefore a divergent flow of rainwater or snow meltwater of low pH and low nutrient content. Other classifications also exist, but they are all largely based upon hydrologic processes. This reflects the outstanding importance of these processes in the formation and continued existence of wetlands.

Wetland hydrology has received considerable attention in the U.S.S.R. and various countries of northern Europe (Symposium on Hydrology of Marsh-Ridden Areas, 1972), as well as in the north-central parts of the United States. In Canada, however, only a limited amount of research has been conducted (Goode et al., 1977; Radforth, 1977). In view of the extent of wetlands in Canada and of their ecological and socio-economical importance (Thomas, 1976), further research on wetland hydrology is required.

1.2 Objective

In the light of the mentioned considerations, this research will study the spatial and temporal variations of the watertable of a swamp. A numerical model will also be used to examine the relationship between the swamp watertable and the level of the streams in the swamp.

1.3 Literature Review

This review concentrates on three main aspects of wetland hydrology:

1. The hydrological effects of the active layer.
2. The effect of the storage characteristics on runoff.
3. The nature of the water balance.

Goode et al. (1977) considered this information on wetlands to be indispensable when considering the role of these landforms in water resources management.

The active layer, which is that zone within which the watertable fluctuates and peat forms, shows considerable spatial and (to a lesser extent) temporal variations in its hydrological characteristics, thus complicating hydrological measurements (Ingram, 1974). In a typical vertical profile, though, increased compaction and humification with depth lead to a definite vertical change in the hydrological properties of peat (Bay et al., 1964; Boelter, 1965; Goode et al., 1977). Thus, empirically, changes in the hydrologic properties of peat for a given plot can be expressed as functions of depth alone (Romanov, 1961; Goode et al., 1977).

From the water balance equation

$$\Delta z = \frac{\Delta S}{Sy} = \frac{P-E-R}{Sy} \tag{1.1}$$

where Δz is the water level change

ΔS is the storage change

Sy is the specific yield of the active layer

P is the precipitation

E is the evaporation

R is the runoff

and from Romanov's (1961) mentioned approximations

$$E = \alpha Rn \tag{1.2}$$

$$\alpha = f(z) \tag{1.3}$$

$$R = g(z) \tag{1.4}$$

$$Sy = h(z) \tag{1.5}$$

where Rn is the net radiation

and z is the water level

This latter author developed the following equation

$$\Delta z = \frac{P - f(z)\,Rn - g(z)}{h(z)} \tag{1.6}$$

Thus, the water level can be considered to be the only non-meteorologic factor determining the magnitude of its own changes. Also, equation (1.6) suggests the possibility of deriving an empirical relationships between water level and outflow from wetlands (Goode et al., 1977).

With the presented considerations in mind, Bay et al. (1964) indicated that only surface horizons are hydrologically important in peat. In them, hydraulic conductivity and specific yield are critical in determining the magnitude and the timing of outflow (Boelter, 1965).

Although some authors have tried to find long-term hydrological effects for which wetlands are responsible, it seems that only a slight reduction in the total runoff of wetlands (and especially of swamps) can be found to affect the seasonal water balance (Chebotarev, 1962). Moreover, the hydrological effects of wetlands should not be looked for at that scale; Bay (1969) and others have shown that in swamps, the storage capacity is small and, therefore, their major effect will be the attenuation of short-term inputs such as flash floods. Peat storage capacity is greatest when the watertable is low.

This regulating capacity of swamps and its implications are generally not adequately understood, although they have been investigated by many authors such as Sokolovskii (1968), Bay et al. (1964), Bay (1967b, 1969), Balek et al. (1973), and Goode et al. (1977).

Young et al. (1968) also claim that because the regulating capacity depends on the water level, a rational-formula type of runoff prediction equation is inadequate for wetlands unless a storage capacity term (as a function of water level) is included. This stresses again the hydrological importance of water levels in wetlands, and in swamps in particular.

The hydrologic regime of swamps ranges from continental to oceanic (Goode et al., 1977). However, their basic difference is that in the former (as described by Bay, 1967b, 1969) higher evaporation causes a more marked water deficit in summer, resulting in a lower outflow and a higher runoff regulation capacity. In the case of the oceanic regime (such as the Scottish example described by Robertson et al., 1968), low summer evaporation produces more uniform hydrological conditions and consistently small storage capacities throughout the year. Thus, in the oceanic regime, the magnitude of the low flow is more dependent on the duration of the dry periods than on the amount of rainfall received during the rest of the year.

With regards to evaporation, both radiation and plant development tend to be limiting at the beginning of the summer, while at the end of that season, moisture availability may be limiting. Water availability is a function of watertable depth (Romanov, 1962), although some tree roots can extract water from greater depths and thus effectively increase the water availability.

Evaporation from wetlands has been commonly calculated as a residual term in the water balance equation (e.g. Bay, 1967a). However, the energy approach has also been employed. Romanov (1961) found that evaporation can be obtained as a function of net radiation, watertable level and development phase of the vegetation. In general, evaporation approaches the potential rate when water is not limiting; otherwise evaporation from swamps is significantly lower than that from open lakes (Linacre et al., 1970).

CHAPTER TWO

STUDY AREA AND METHOD

2.1 The Study Area

Beverly Swamp (43°22'N, 80°7'W) has an average elevation of 268 m above sea level, and occupies an area of 20 km^2. Figure 2.1 shows the upper Spencer Creek basin in which Beverly Swamp is located.

Glaciation has left its marks on the landscape in the form of drumlins, till plains and terminal morraines (Karrow, 1963). Beverly Swamp is the result of a shallow lake that existed more than 10,000 years ago and evolved into its present state by eutrophication and by bog succession (Dept. of Commerce and Development, 1960). The swamp consists of several connected dolomite bedrock depressions topped by a thin layer of peat and underlain by different types of inorganic sediments. The depth of these sediments was recently revealed by a series of boreholes drilled by Ontario Hydro (Fig. 2.2).

The soils of Beverly Swamp have been described by the Ontario Department of Agriculture (1965) as black friable organic debris which is generally decomposed, although wood fragments are common in the peat. The organic layer, rarely over one meter thick, is usually separated from the underlying inorganic formations by a thin layer of marl or "limy mud" which contains shells, reflecting the lacustrine origin of the area. These soils are mildly acid or neutral (Dept. of

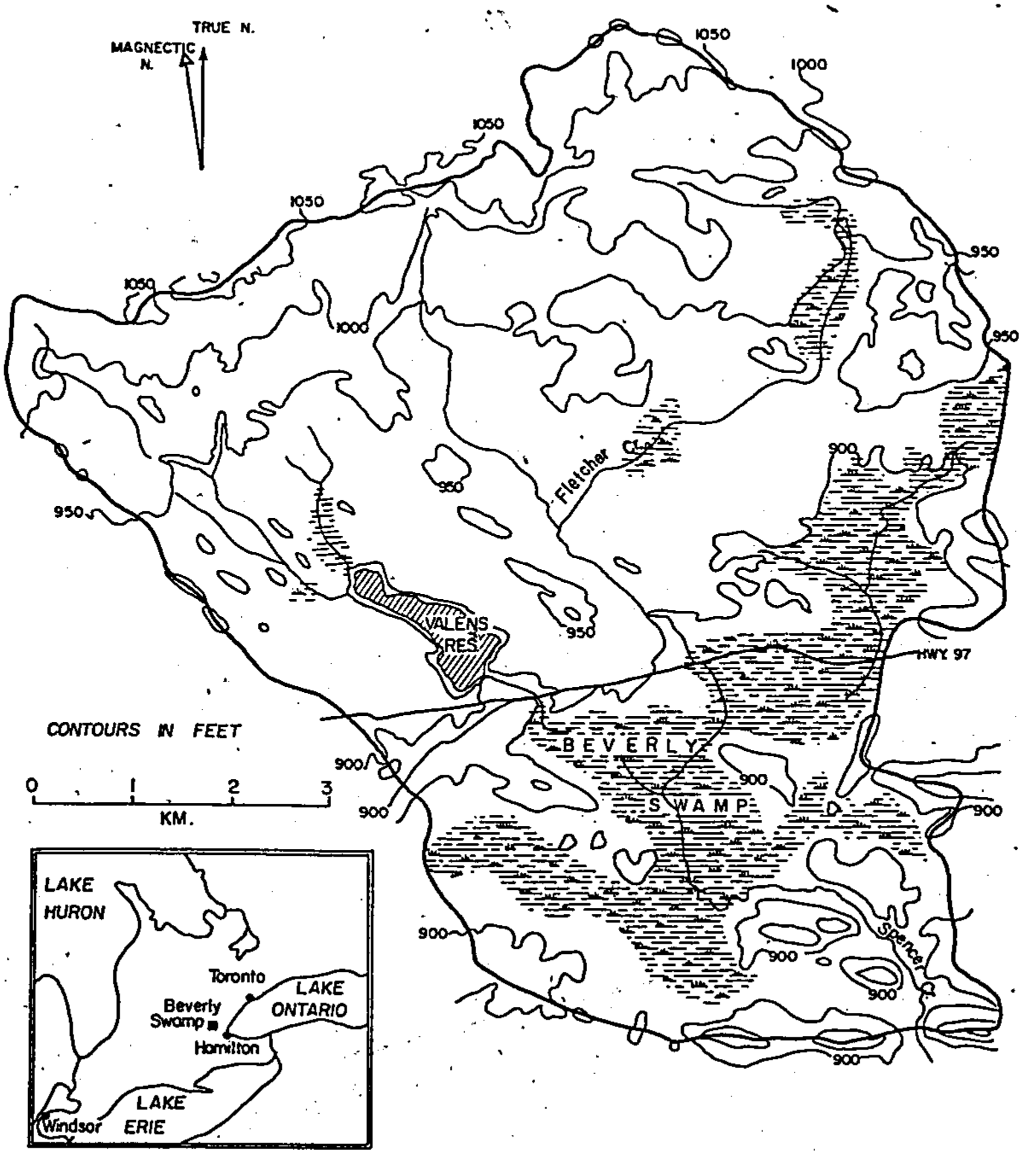


Figure 2.1 Topography of the Spencer Creek basin above Westover.

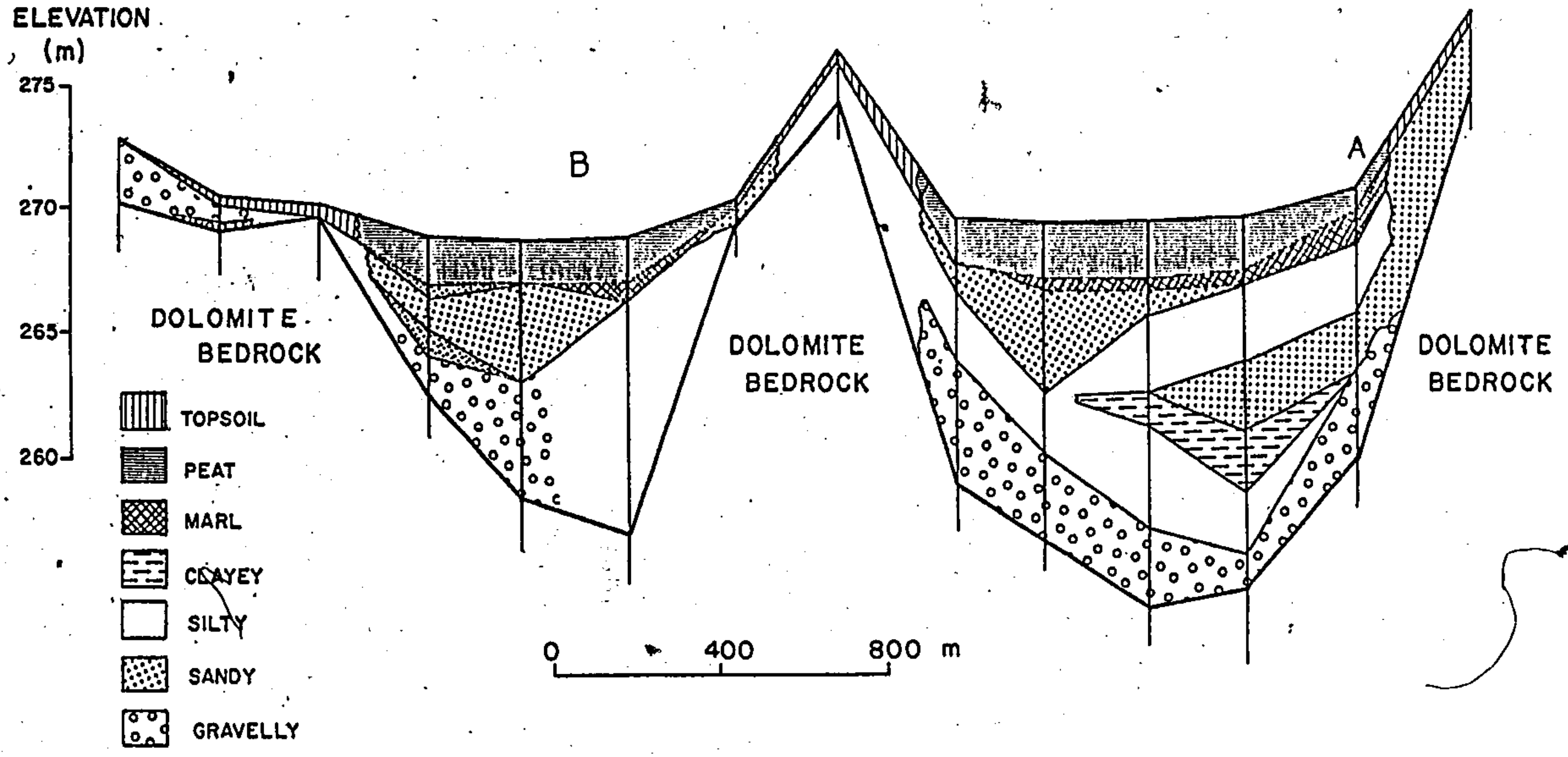


Figure 2.2 Surface deposits along the line from A to B in Figure 2.3; based on Ontario Hydro bore-hole records.

Commence and Development, 1960), and a typical sample of saturated peat has a solid matter content of less than 20 percent by weight, of which 75 percent is organic.

The forest cover of the swamp is far from homogeneous. Along the right-of-way purchased by Ontario Hydro, cedar, aspen and maple are the common species (Johnson, 1974), although birch, ash, elm and basswood also abound (Lewis et al., 1976).

The area has a humid continental climate moderated by the presence of the Great Lakes. Phillips et al. (1972) summarized several climatic variables for the general area using 30-year average values. For the upper Spencer Creek basin several components of the water balance were estimated by Woo (1978), making use of precipitation and streamflow data for the period 1972-1976. This climatic information is presented in Table 2.1.

Beverly Swamp is drained by Spencer Creek and its tributaries (see Fig. 2.3). The flow of Spencer Creek is regulated by the Valens reservoir before it enters the northwestern corner of Beverly Swamp. Within the swamp, this creek branches out and disappears underground. Subsurface flow then takes place southeastwards under a slope of approximately 1 to 1,000, until channelled flow reappears at a zone about 1 km downstream from where Spencer Creek enters the swamp. The major tributary, Fletcher Creek, enters the study area from the northeast and joins Spencer Creek within the swamp. Several flooded trenches created by peat excavation are connected to Spencer Creek in the southern part of the swamp, and the water level in these trenches follows the fluctuation pattern of the creek.

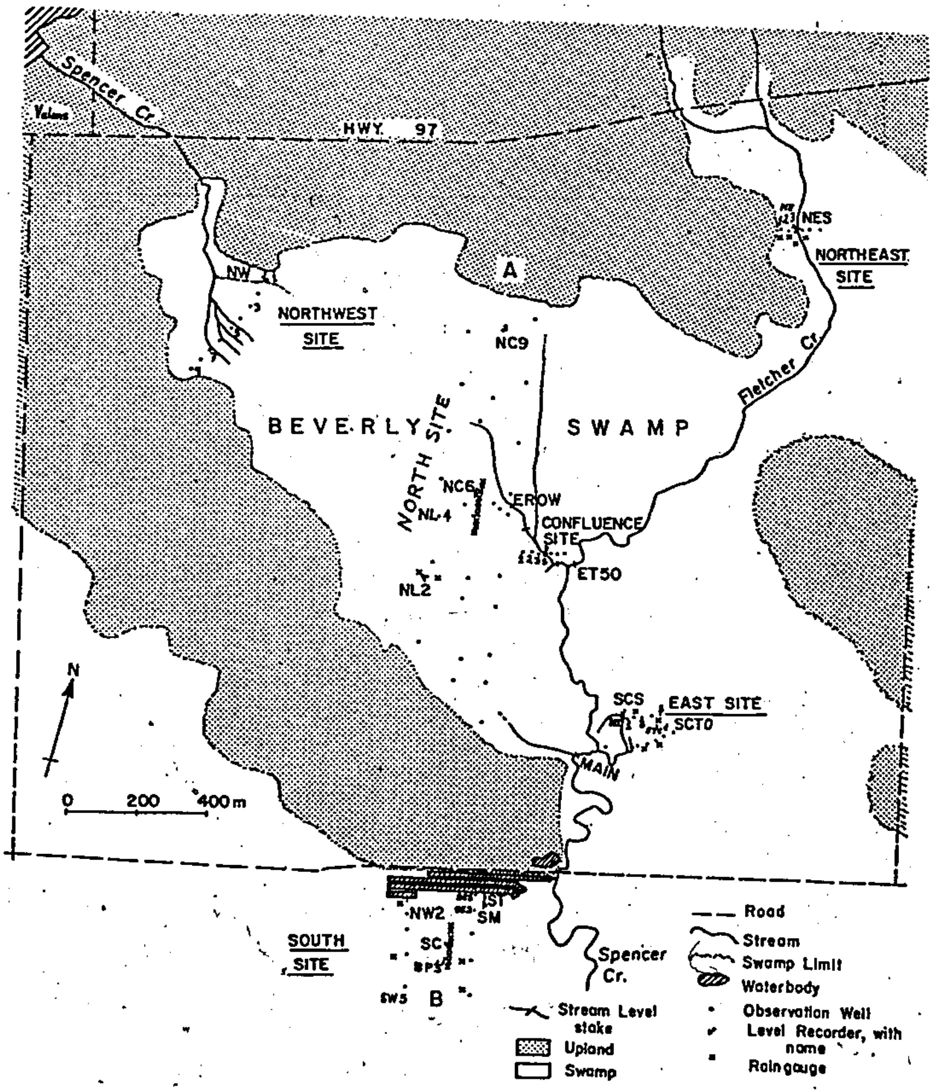


Figure 2.3 The study area.

TABLE 2.1

Climatic Information

	Phillips (1972)*		Woo (1978)**	
	mm	%	mm	%
Total annual precipitation (P)	800	100	925	100
Total annual snow	140	18		
Total annual potential evaporation	610	76		
Total annual actual evaporation (AE)	560	70	583	63
Total annual runoff (P-AE)	240	30	342	37
Mean duration of the snow cover: 95 days				
Mean duration of the frost-free season; 160 days				

* based on 40 years of data
** based on 4 years of data

Given the indicated variation in hydrologic conditions, several sites were chosen within the swamp to examine the major hydrological regimes typical of the swamp. These sites, shown in Figure 2.3, represent the following hydrologic conditions:

(1) The Northeast site is an area affected by an inflowing perennial stream.

(2) The Northwest site is an area affected by a smaller inflowing stream whose flow is artifically regulated.

(3) The Confluence site is an area dominated by a reappearing effluent stream.

(4) The North site is an area with unchannelled flow.

(5) The East site is an area affected by a small intermittent stream.

(6) The South site is an area affected by a body of water (the flooded trenches).

2.2 Data Collection

Following are the various types of data collected during the study season which spans from the spring melt to the winter freeze-up of 1977.

2.2.1 Hydrological Data

At each research site, the watertable was monitored with observation wells, water level recorders and staff gauges (Fig. 2.3).

Between April and November 1977, water level recorders (Ott and Leupold-Stevens Type F) were used to record watertable fluctuations. In addition, manual observations of the water level were taken every three to seven days at the staff gauges and at the wells, which were reinforced by 0.05 m O.D. plastic pipes sunk into the peat to a depth of 1 m. The lower ends of the pipes were plugged but a series of 10 mm diameter holes were drilled on their walls; the groundwater level at the wells was measured with a measuring tape. A Wild self-leveling level was used to survey the elevation of the wells to enable a three-dimensional analysis of the watertable.

The daily discharge records for Spencer Creek below the Valens Reservoir are available from the Hamilton Region Conservation Authority, and the Water Survey of Canada provided daily discharge records for Spencer Creek near Westover (Fig. 2.1). Streamflow at five other points along Spencer Creek and Fletcher Creek was calculated from stage records, using the rating curves shown in Figure 2.4. Individual discharge measurements for the curves were obtained by means of the velocity-area method, using Ott and Price current meters.

2.2.2 Meteorological Data

Evaporation was computed using a form of the combination model described by Slatyer and McIlory (1961). For this study, a simplified version of the model was employed, using net radiation and the slope of the saturated vapour pressure curve as indices for evaporation:

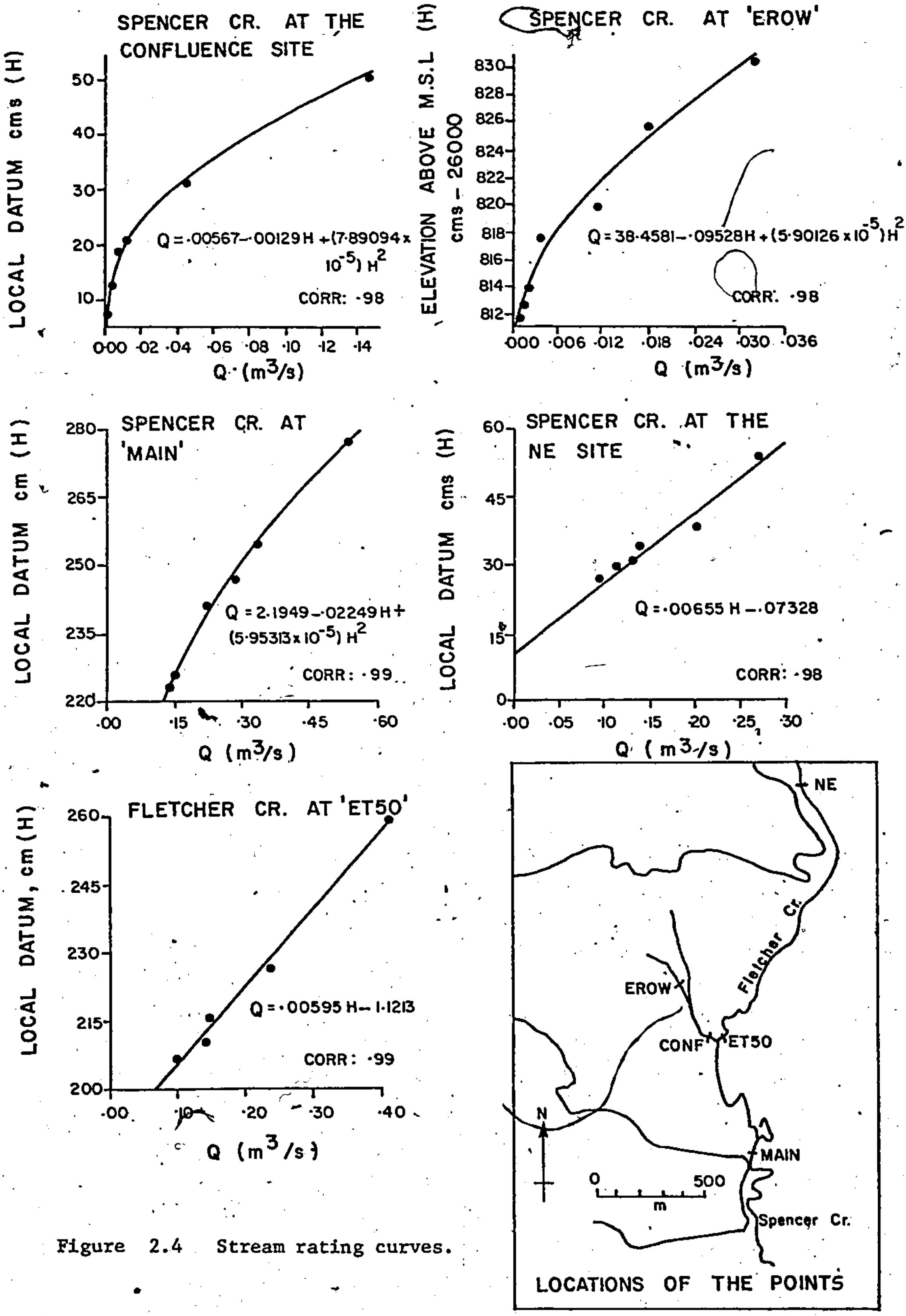


Figure 2.4 Stream rating curves.

$$E = \alpha \frac{S}{S + \gamma} Rn \qquad (2.1)$$

where E is the latent heat flux
α is 1, as an approximation
S is the slope of the saturated vapour pressure-temperature curve
γ is the psychrometric constant
Rn is the net radiation

For Beverly Swamp, net radiation was measured in the summer of 1976 using a Swissteco net radiometer. These data were compared with global radiation for nearby meteorological stations, at Elora (43°39'N, 80°25'W) and Toronto (43°48'N, 79°33'W). An empirical relationship between net and global radiations (Davies, 1967) was derived:

$$Rn = a + bK\downarrow \qquad (2.2)$$

where Rn is the net radiation
$K\downarrow$ is the global radiation
a and b are coefficients obtained by regression

Those relationships were then applied to estimate 1977 net radiation daily totals for Beverly Swamp using global radiation daily totals from both Elora and Toronto stations. The estimated net radiation daily totals were partitioned into bi-hourly estimates, proportional to the available bi-hourly global radiation values.

Air temperature was measured using a thermohygrograph housed in a Stevenson Screen, 20 m above the ground surface (immediately above the forest canopy level). The slope of the saturated vapour pressure-temperature curve was obtained from air temperature measurements using the equations provided by Dilley (1968). The value of α in equation 2.1 was considered to be 1.0 (i.e. equilibrium conditions were assumed).

With these data as two-hourly input, evaporation was calculated using evaporation 2.1. A graph of the resulting evaporation is shown in Figure 2.6.

Continuous rainfall records are available at the Valens climatological station, 1 km northwest of Beverly Swamp, using a Belfort weighing-type rain gauge. In addition, several home-made rain gauges were constructed using plastic bottles with 0.14 m diameter plastic funnels standing at about 0.25 m above the ground surface. These were used at the locations indicated in Figure 2.3 to study the areal variability of rainfall and the magnitude of interception.

To calibrate the continuous rainfall records from Valens, the weekly rainfall data from the forest openings were used as standards. Figure 2.5 shows that the best-fit line in the regression between the weekly recorder gauge catch and the weekly catch at the forest openings, yields an intercept value which is not different from zero at a .95 confidence level. Thus, resetting an intercept value of zero, the line of best fit becomes y = 1.11x, where y is the weekly rainfall in the openings and x is the weekly catch at the recording rain gauge in Valens. This ratio will allow an adjustment of the two-hourly rainfall obtained from the continuous records (Fig. 2.6). From the calibrated data, total rainfall between April 29 and September 25 was

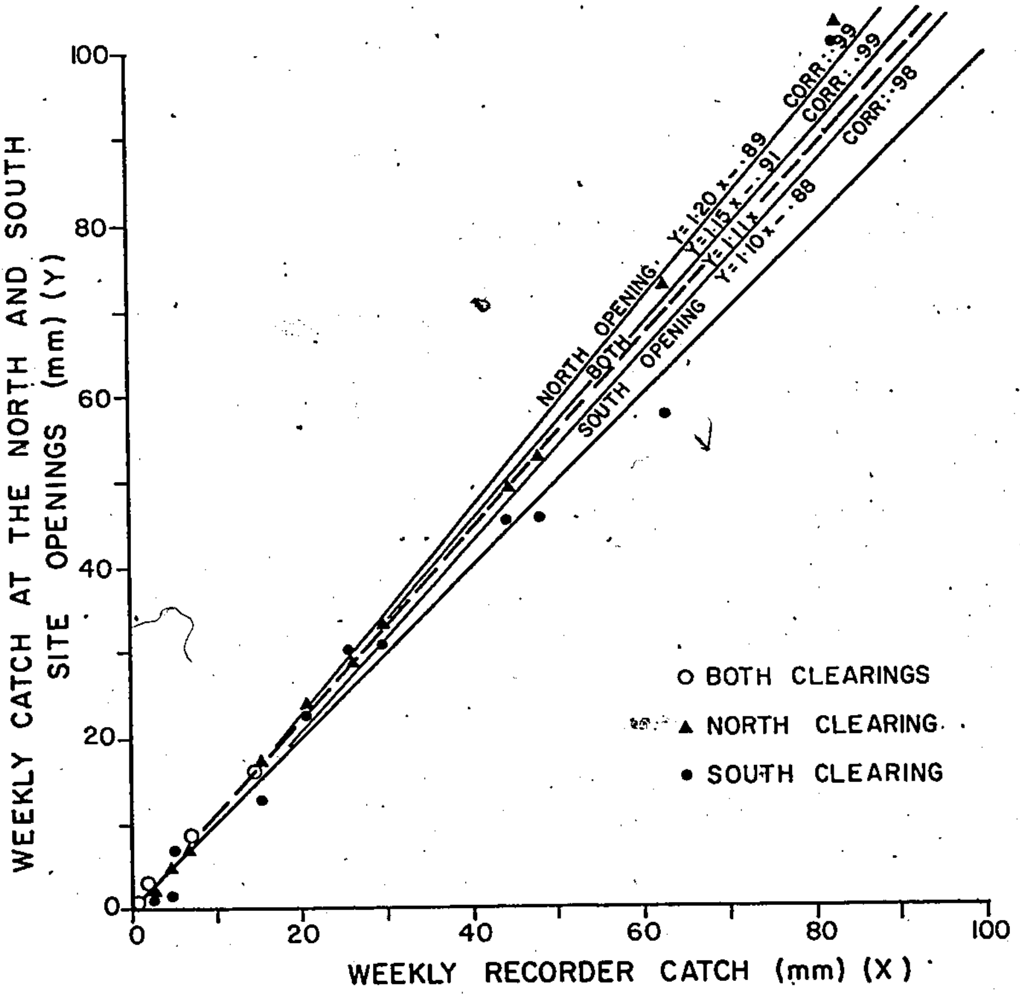


Figure 2.5 Rainfall catch comparisons.

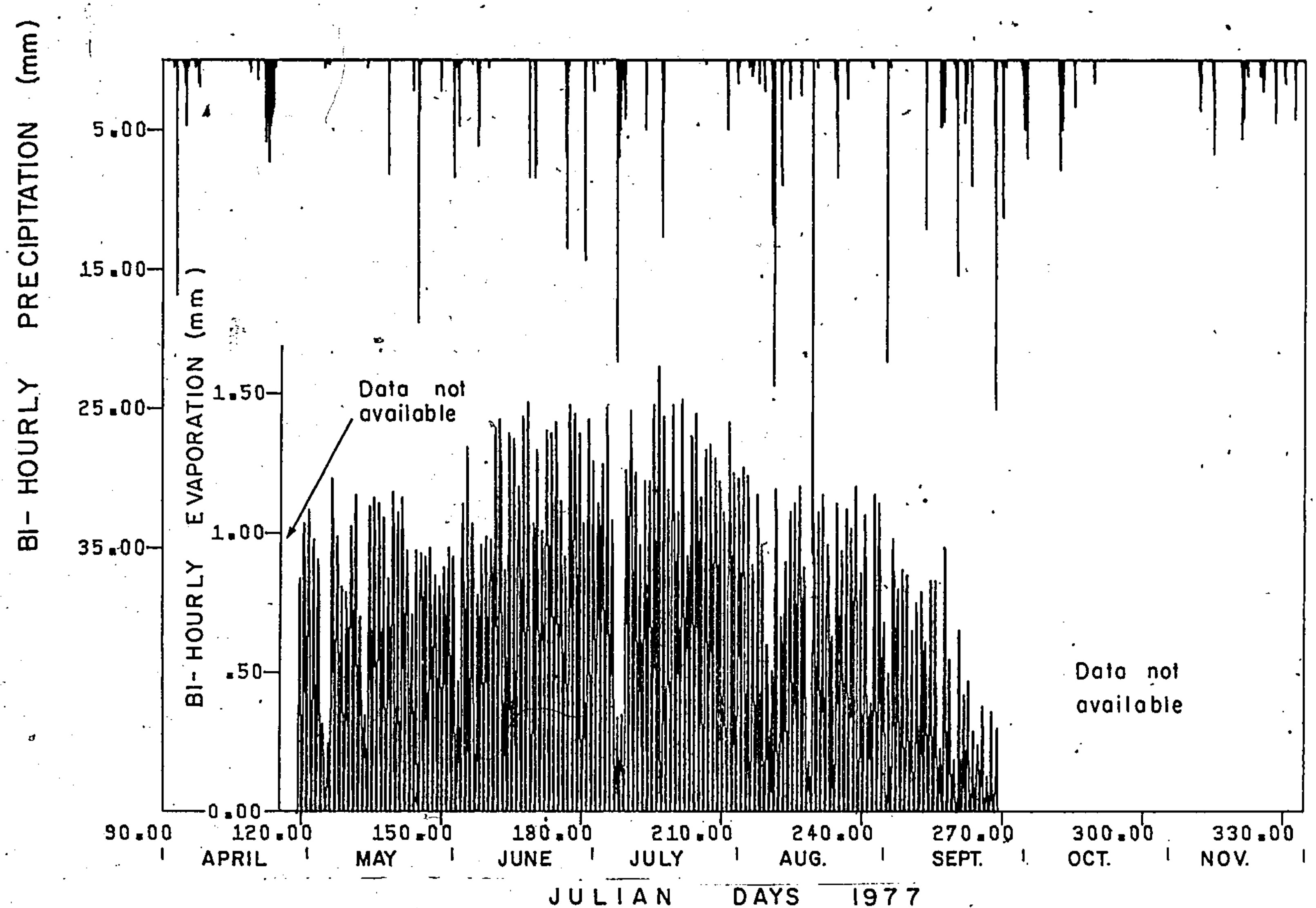


Figure 2.6 Bi-hourly precipitation and evaporation.

TABLE 2.2

SPATIAL VARIATION OF PRECIPITATION

	NORTH SITE	NORTHEAST SITE	EAST SITE	SOUTH SITE
Average site catch as a percentage of the recording raingauge catch (May-Sept.)	103%	92%	95%	98%

INTERCEPTION

	NORTH SITE	SOUTH SITE
Regression between storm catches (mm) in the opening (0) and in the forest (F)	F = .780 - .89 CORR: .99	F = .810 - .27 CORR: .99

541 mm, which was higher than the long-term average for this period.

The non-recording rain gauges provided the data summarized in Table 2.2. This table shows that precipitation varies from site to site, and this is attributed to the random variations in rainfall interception characteristics. This table also shows that the value of interception is about 20 percent.

2.2.3 Soil Data

Table 2.3 summarizes several hydrologic soil parameters for each site. The bulk density and moisture content were calculated by the gravimetric method, using 460 cc and 1270 cc soil samples. The specific yield was obtained following the laboratory procedure described by Johnson (1967), and the hydraulic conductivity according to the field procedure outlined by Luthin et al. (1949).

The tabulated results show a low bulk density which increases slightly with depth. The moisture content of a typical saturated soil sample was around 85 percent by weight; this is comparable to P'yavchenko's (1958) values of 83 to 87 percent for Russian bog peat with 20 to 26 percent ash content.

The specific yield seems somewhat low when compared with Boelter's (1965) values of 10 to 52 percent, although the extreme variability of this parameter makes comparisons difficult. Based on 16 samples, the estimated spatial variation of the specific yield in an area of the swamp is shown in Figure 2.7.A.

The hydraulic conductivity (K) for Beverly Swamp was slightly

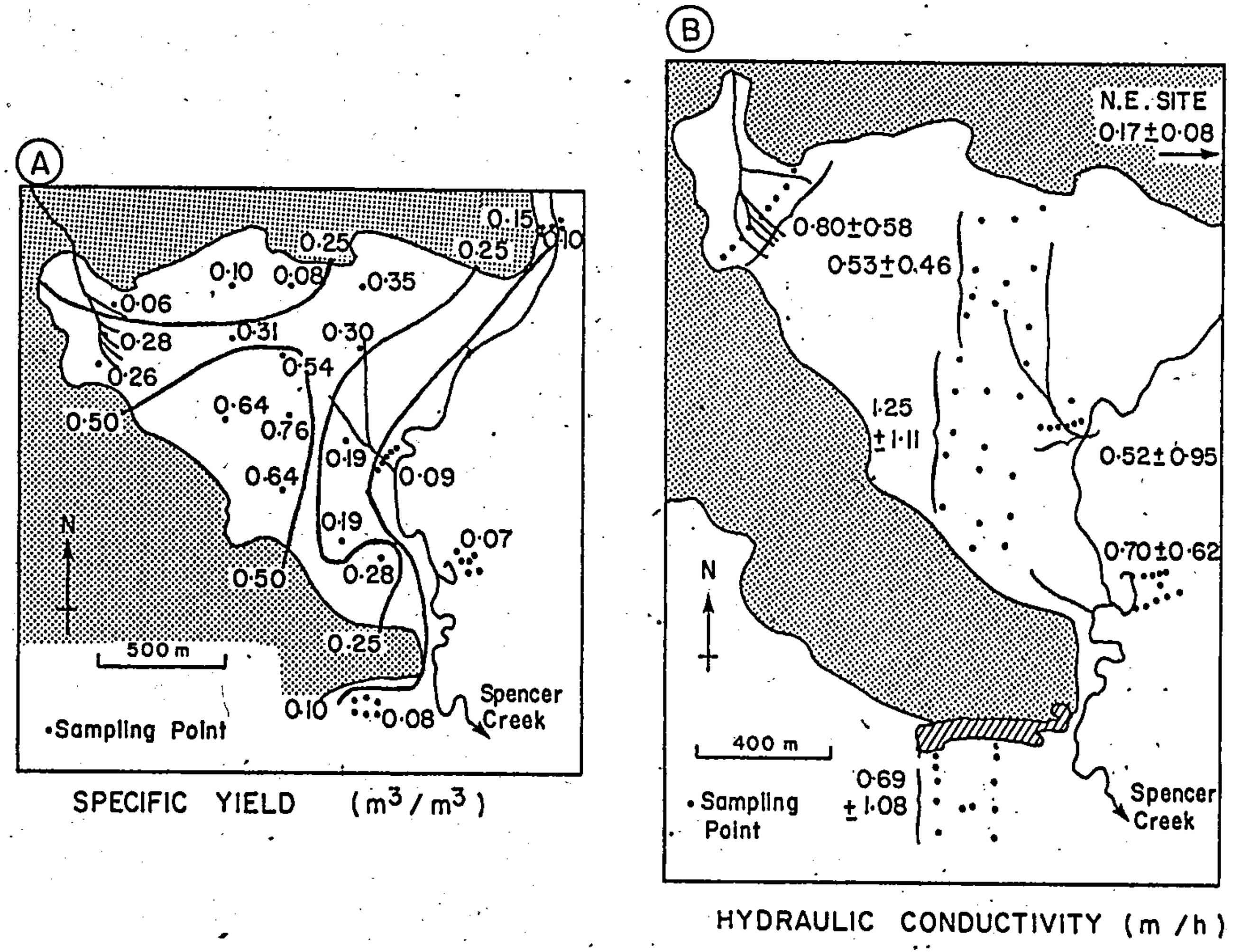


Figure 2.7 Spatial variation of the specific yield and the hydraulic conductivity.

TABLE 2.3

Selected Hydraulic Properties of the Peat Soil at Five Experimental Sites

Location	Sample Depth (cm)	Saturated Sample			$n^{(2)}$	$Sy^{(3)}$ %	$V^{(4)}$ %	$n^{(2)}$ %	$K^{(5)}$ m/h	$V^{(4)}$ %	$n^{(2)}$	$d^{(6)}$ m	$D^{(7)}$ m^2/h
		$G^{(1)}$	Moist. Cont. % wgt	% vol.									
North Site and Northwest Site	0-20 25-45	1.07 1.11	90 90	96 97	6 6	31 23	61 43	22 7	.89	102	29	.9	3.5
Confluence Site	0-20 25-45	1.11 1.11	85 85	95 95	4 4	7 4	44 48	5 5	.52	182	6	1.0	13.0
Northeast Site	0-20 25-45	1.14 1.24	84 80	95 97	4 4	15 9	33 33	5 5	.17	49	6	.5	0.9
East Site	0-20 25-45	1.10 1.12	82 81	91 90	4 4	7 5	100 50	5 5	.70	89	12	1.0	14.0
South Site	0-20 25-45	1.09 1.11	83 83	91 93	5 5	8 7	62 33	6 6	.69	156	11	.9	8.9
Average	0-20 25-45	1.10 1.14	85 84	94 94		14 10	$60^{(8)}$ $41^{(8)}$		.59	$116^{(8)}$ $46^{(9)}$		.84	8.1 V=71%

(1) Specific Gravity (2) Sample Size (3) Specific Yield (4) Coefficient of Variation
(5) Hydraulic Conductivity (6) Mean Aquifer (peat) thickness (5) Diffusivity: $Kd/Sy_{(25-45\ cm)}$
(8) Within each row (9) From Site to site.

TABLE 2.4

Hydraulic Conductivity

Source	K(m/h)	Approximate degree of humification for the given K values
Boelter (1965)	.004-1.4	Well decomposed-undecomposed
Ingram et al. (1974)	.007-0.11	Decomposed
Baden et al. (1963)	.004-0.3	10-2.5 (von POST scale)
Korpijaakko et al. (1972)	.010-1.2	6-1.5 (von POST scale)
This study (site averages)	.170-0.89	Generally decomposed

higher than for other wetlands (Table 2.4). Moreover, Boelter (1965) and Ingram et al. (1974), recognized the difficulties involved in estimating this parameter in peat since a difference in the method alone can introduce an error of up to one order of magnitude. Figure 2.7B shows the sample values of the hydraulic conductivity at several points in the swamp.

CHAPTER THREE

WATER LEVEL REGIMES

3.1 Water Balance During the Study Period

A water balance study was performed for the main basin and for its three sub-basins (Fig. 3.1). The period during which the water balance was calculated extended from April 29th to September 25th, two dates when the water levels in the swamp were approximately equal. This ensures that the magnitude of the change in storage is minimized.

In this case, the water balance equation takes the following form:

$$P - NR = E + \Delta S \qquad (3.1)$$

where P is the precipitation
NR is the net runoff (outflow-inflow)
E is the evaporation
ΔS is the change in storage
all the above are measured in mm.

Table 3.1 shows the values derived for the various terms of equation 3.1. This table shows that, for the period analyzed, evaporation was the dominant term since ΔS was zero for the swamp, and for non-swamp areas it is considered to have been small, or perhaps even negative. For the entire basin (A+B+C), runoff accounted for 11 percent of precipitation.

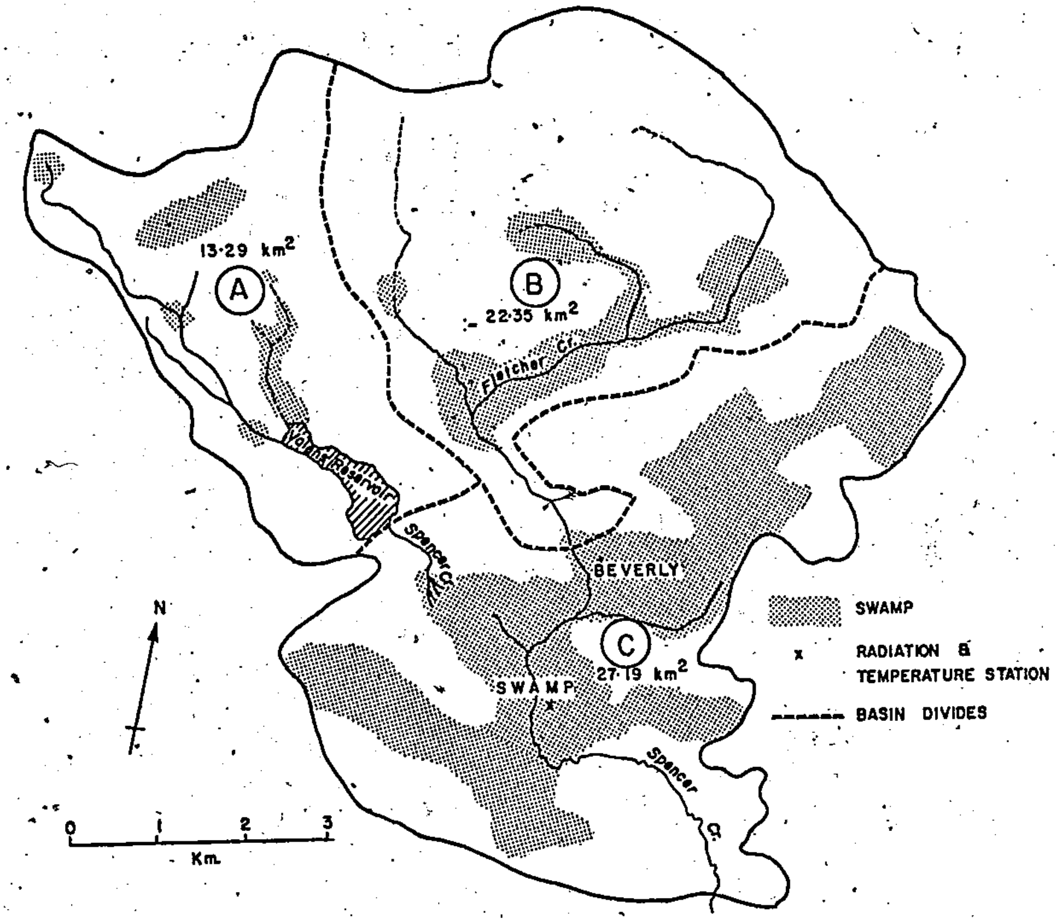


Figure 3.1 The three sub-basins considered in the water balance.

TABLE 3.1

Values of the Water Balance Components, between April 29th and September 25th.

Basin	P	NR		E + ΔS	
	mm	mm	% of P	mm	% of P
A	541	34	6	507	94
B	541	94	17	447	83
C	541	45	8	496*	92
A + B	541	72	13	469	87
A + C	541	41	8	500	92
B + C	541	67	12	474	88
A+B+C (Total)	541	60	11	481	89

*compared with 572 mm obtained from the equilibrium model.

Evaporation for the same period was also computed with the equilibrium model (Chapter Two), and the value calculated for the swamp was 572 mm. This estimate of evaporation exceeds the value obtained with the water balance method. Such a discrepancy can be partially accounted for by the fact that the former estimate was derived for a location at the center of the swamp (Fig. 3.1). There, evaporation is expected to be larger than for any one of the basins, which have large fractions of drier non-swampy terrain. However, the computed value of swamp evaporation is considered to be reasonable, and daily estimates from the equilibrium model will be used in a numerical model which describes the water level responses to evaporation, streamflow and precipitation inputs (Chapter Four).

3.2 Temporal Variations of the Water Level

Throughout the study season, the position of the watertable was monitored at all the study sites. The results are presented in Figures 3.2 to 3.7. For comparison, two hydrographs for the previous summer are also presented for the South Site and the East Site.

During the course of a year, high levels occur during the snowmelt period, which correspond with low evaporation. As snow melts and evaporation increases, there is a gradual decline in water levels which reach a minimum towards the end of the summer. Afterwards, levels tend to rise again, depending on precipitation, and remain high until the winter freeze-up. Superimposed on this annual pattern, individual storms cause noticeable rises in the hydrograph. This is because it takes

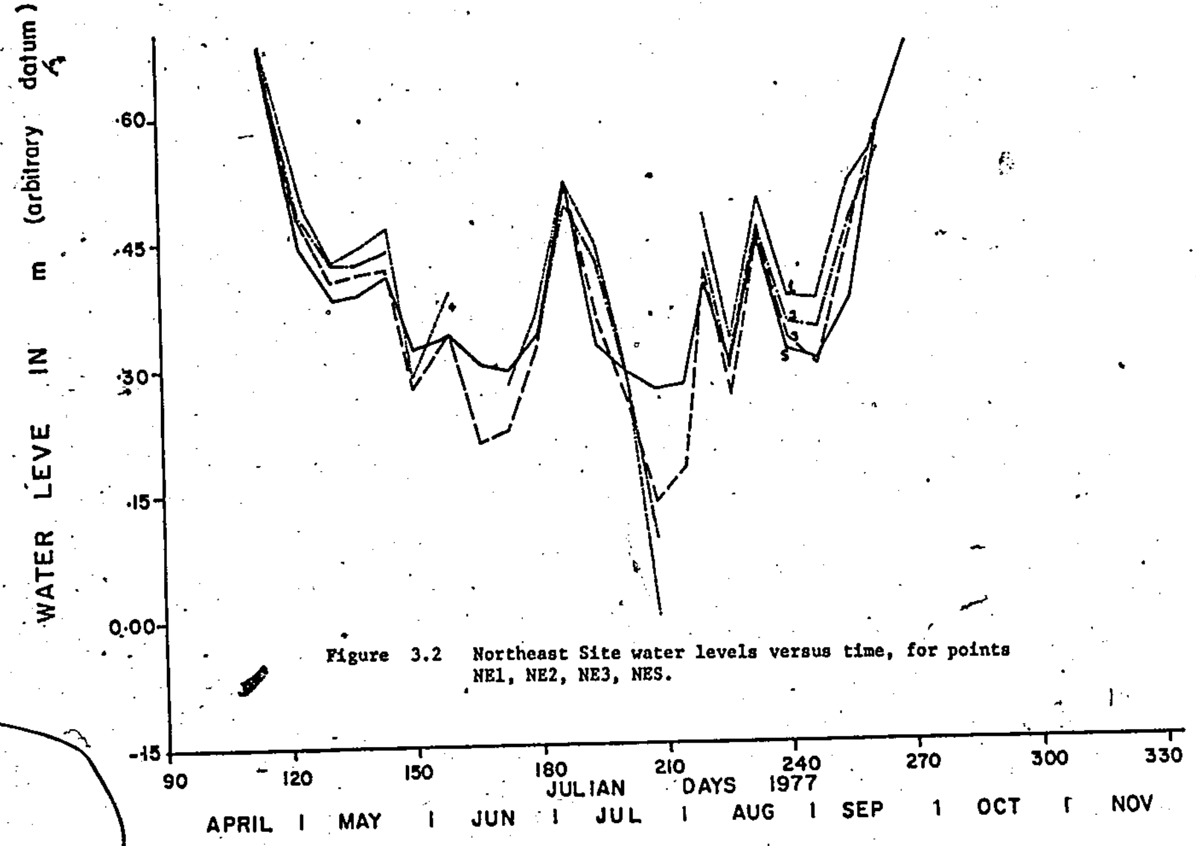
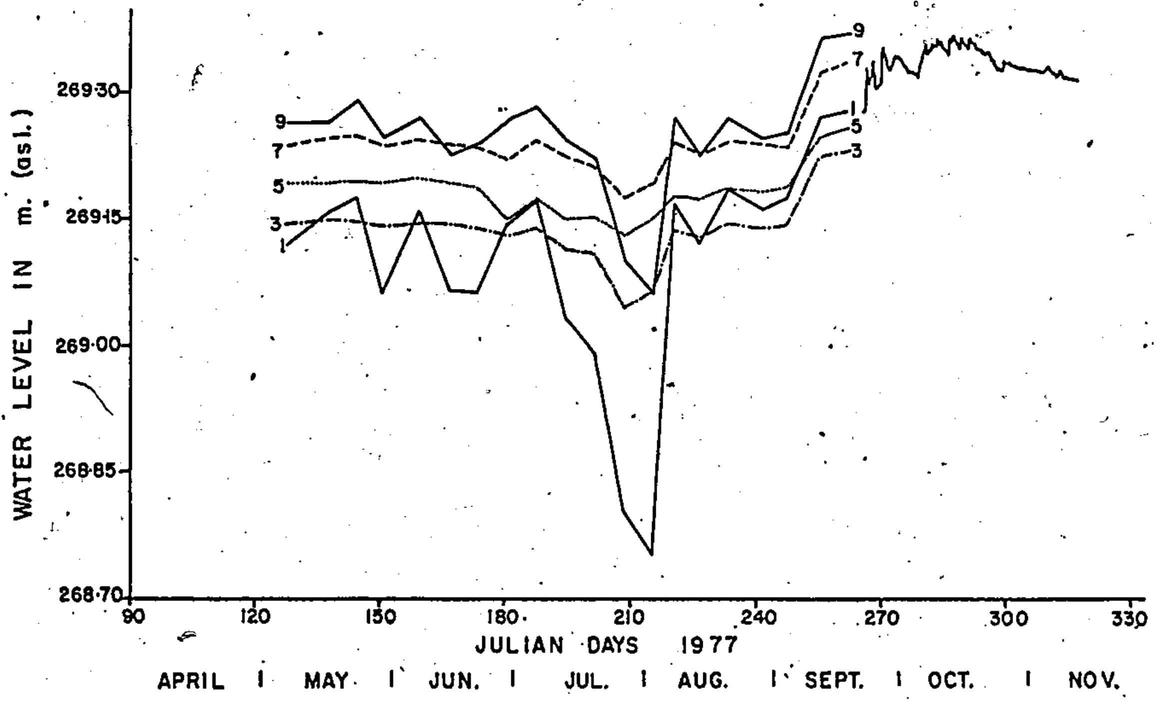


Figure 3.2 Northeast Site water levels versus time, for points NE1, NE2, NE3, NES.

Figure 3.3 Northwest Site water levels versus time, for points 1, 3, 5, 7, 9.



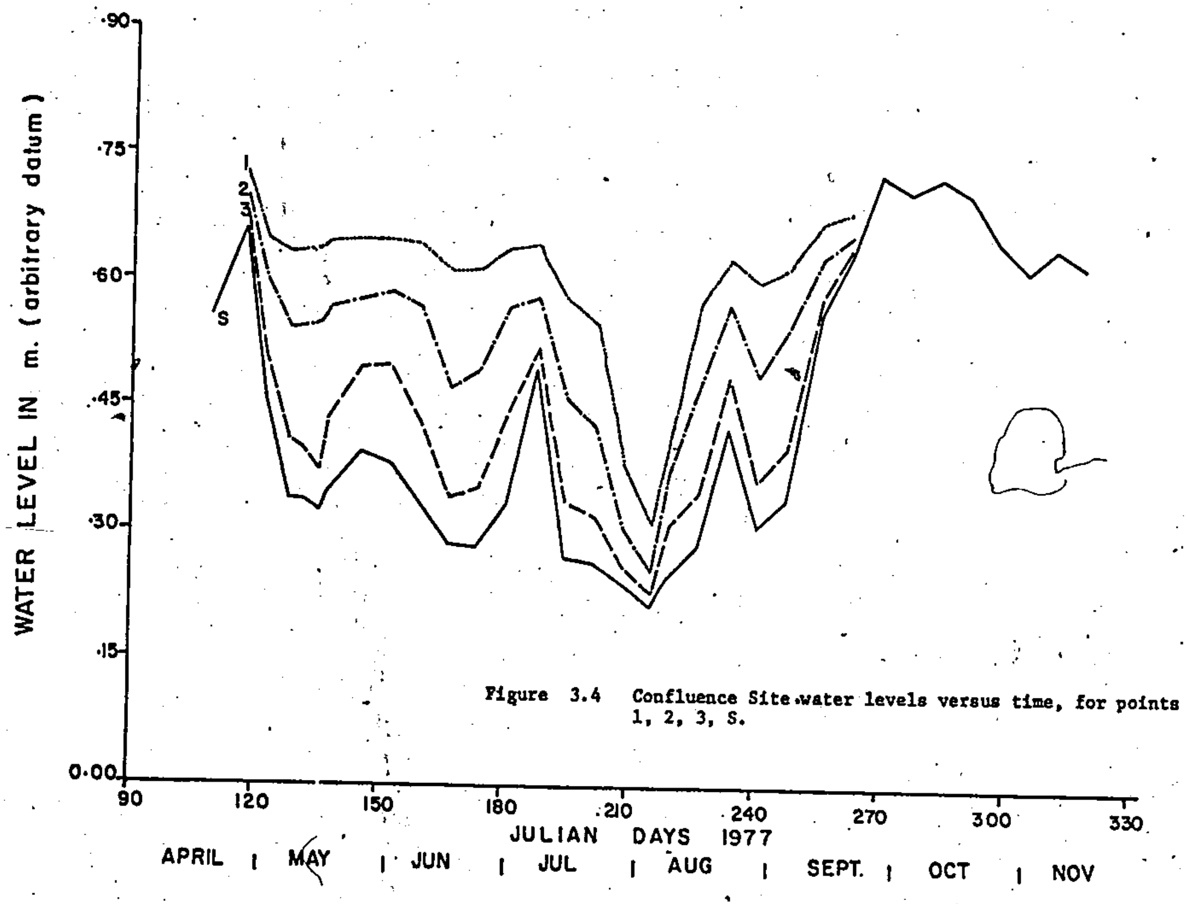


Figure 3.4 Confluence Site water levels versus time, for points 1, 2, 3, S.

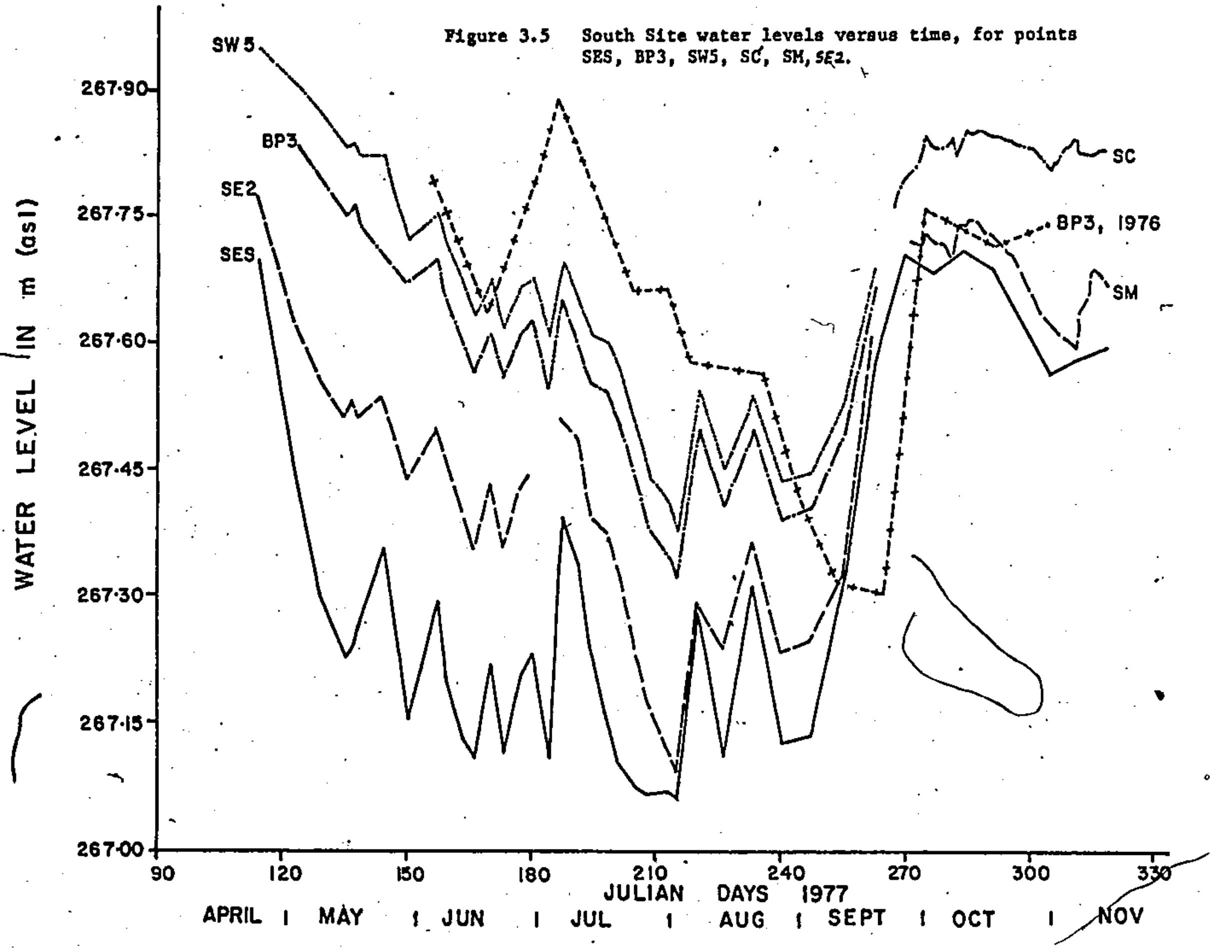


Figure 3.5 South Site water levels versus time, for points SES, BP3, SW5, SC, SM, SE2.

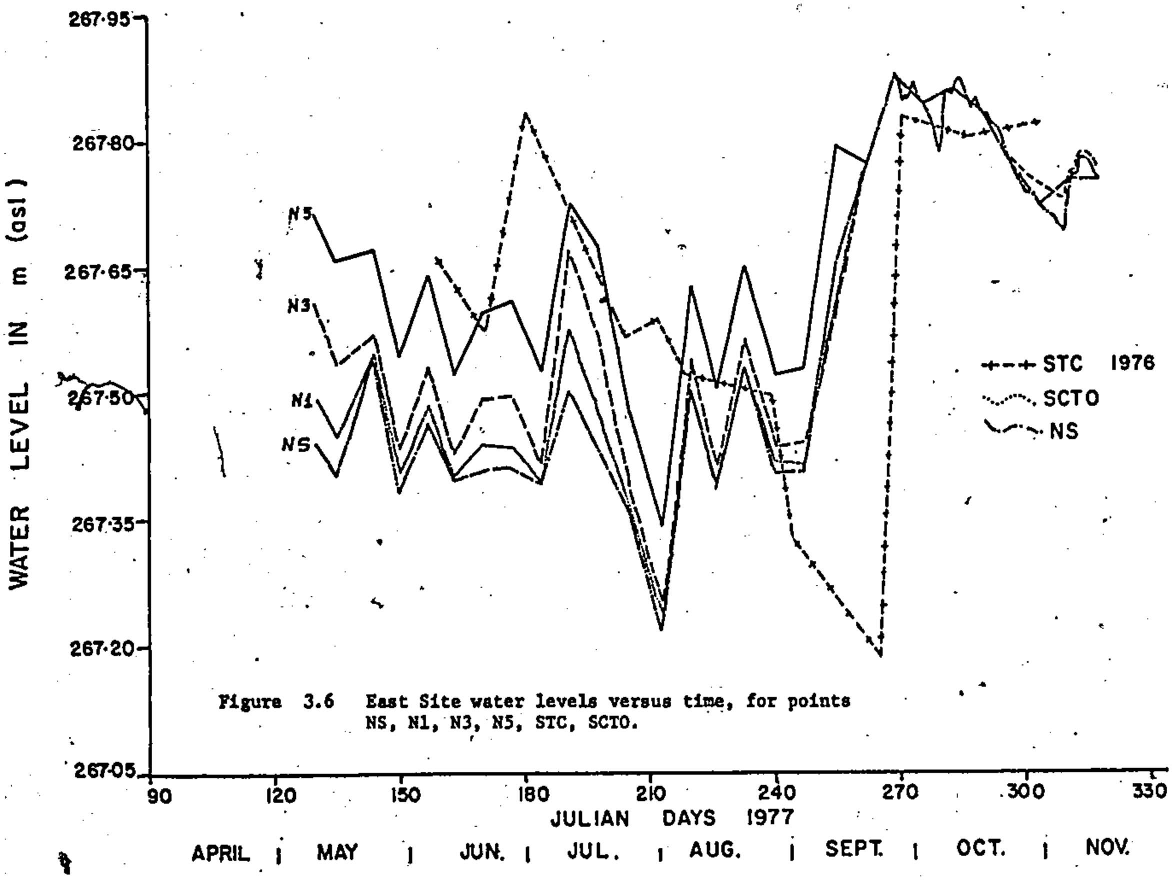


Figure 3.6 East Site water levels versus time, for points NS, N1, N3, N5, STC, SCTO.

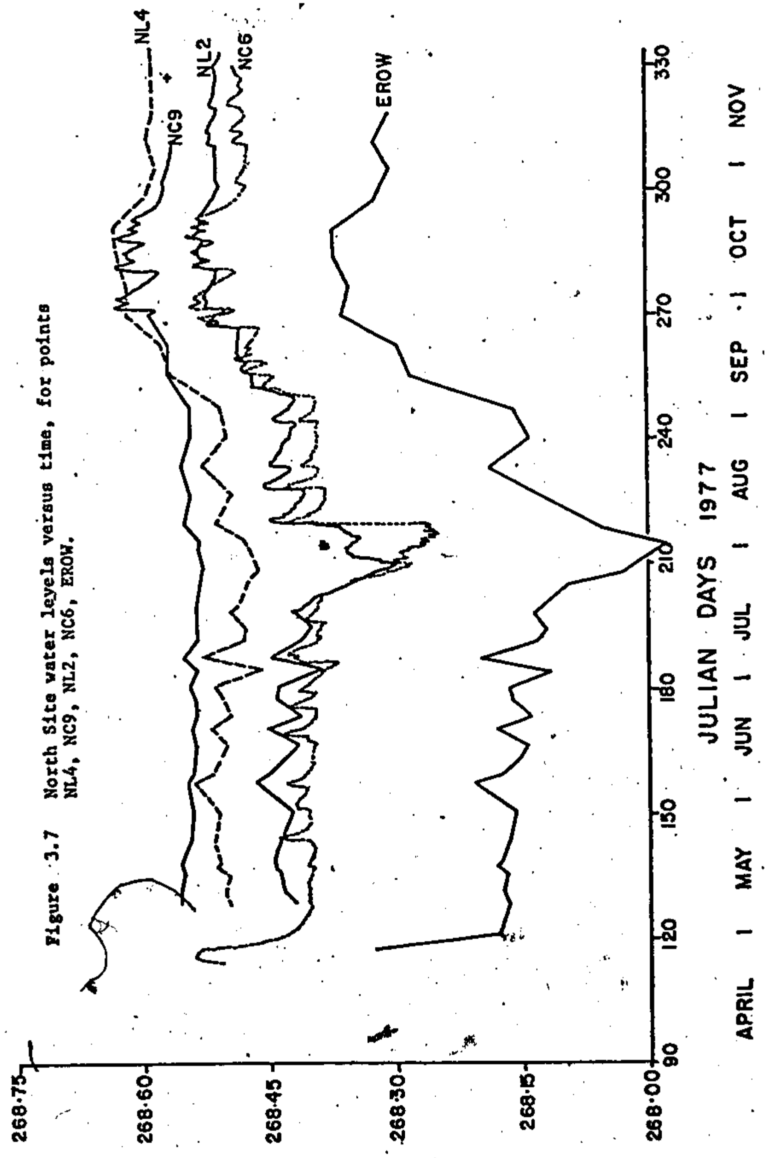


Figure 3.7 North Site water levels versus time, for points NL4, NC9, NL2, NC6, EROW.

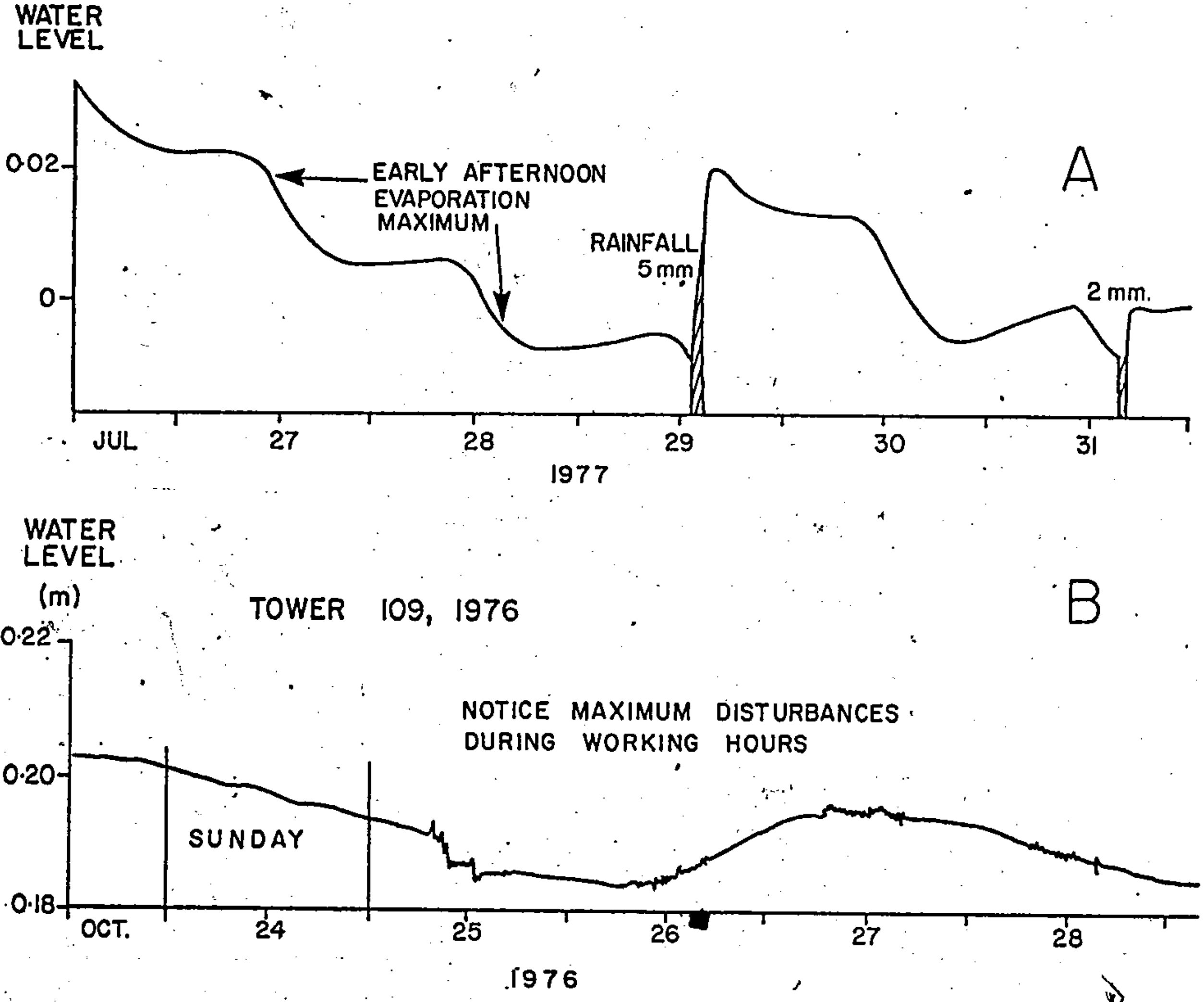
a relatively short period without rain or, similarly, a small amount of precipitation, to cause a considerable fluctuation in the watertable. The general pattern of the described regime agrees with the finding of Palkovics et al. (1975) that, for a forested watershed, time of year and precipitation are the most significant factors affecting watertable and streamflow levels.

During 1976 (Figs. 3.5 and 3.6), abundant rain at the end of June temporarily raised the watertable above the ground surface. Afterwards, levels dropped, and minimum levels were reached at the end of the summer, before rising suddenly to normal autumn levels after a storm desposited over 100 mm. of rainfall on September 19th. In 1977 (Figs. 3.2 to 3.7), lack of precipitation during late April and most of May resulted in a rapid decline of levels. Relatively low precipitation allowed the levels to fall until early July when a large storm raised the levels again. A decline followed, at the end of which, seasonal minimum levels were achieved at the beginning of August. After, two major storms augmented the levels temporarily, and abundant rainfall at the end of September rose them up to autumn levels. In October and November, low precipitation allowed levels to decline, but because of reduced evaporation, the drop was not substantial.

These two years discussed illustrate the variability of the general regime from one year to another.

Continuous water level records show that the watertable is very responsive to water inputs and losses. Even very low magnitude storms affect the watertable instantly, and daily cycles of evaporation also produce diurnal variations in the water levels (Fig. 3.8.A). The

FIGURE 3.8
WATER TABLE RESPONSES



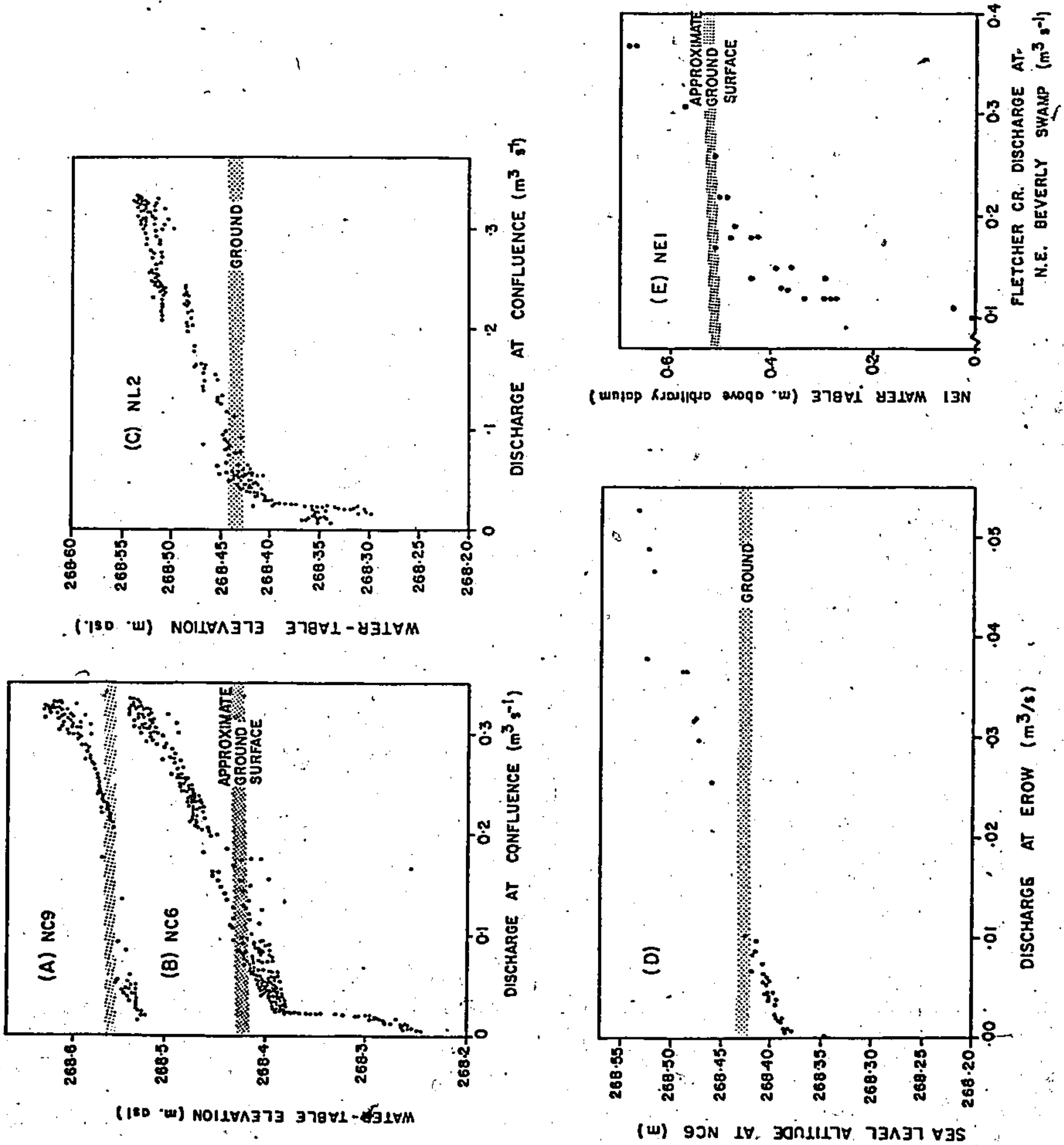
sensitivity of the water level is further shown by Figure 2.8.B. which records the fluctuations in the watertable induced by nearby drilling activities carried out by Ontario Hydro.

3.3 Groundwater Level and Streamflow

3.3.1 Seasonal Trends

An important relationship that has not been adequately quantified is that between the water levels in an area of a swamp and the outflow from that area. To examine that relationship, the water levels at NL2, NC6 and NC9 (Fig. 2.3) were related to the outflow measured at the Confluence Site. In addition the levels at NC6 were also related to the outflow at Point EROW. The water level at NE1 and the discharge of Fletcher Creek were similarly compared. Figure 3.9 reveals non-linear relationships between groundwater level and stream outflow. When both the water level and streamflow were low, streamflow was not very responsive to water level changes; instead, at higher levels, a small rise in the water level would result in a large increase in outflow. This is due to two related factors: a decrease in specific yield with depth and a corresponding change from predominantly surface flow to slower subsurface flow. Those two factors reinforce each other, producing the observed relationships (Fig. 3.9), which, although similar to the stage-discharge rating curve of any stream or reservoir, differ from the latter in that they exhibit a kink a few centimeters below ground level. This kink represents a level at which the two aforementioned factors change at a higher rate. Only Chapman (1965) found a distinctive kink

Figure 3.9 Relationship between water level and outflow for different points.



comparable to those in this research, although Romanov (1961) also represents rating curves with outflow greatly reduced at low water levels. The hydrographs that correspond to graph B are shown in Figure 3.10.

These graphs, then, support Bay's (1964) claim that, hydrologically speaking, peatlands do not extend downwards very much.

3.3.2 Individual Period Analysis

The scatter in the rating curves shown in Figure 3.9 suggests the presence of a hysteresis effect. Such an effect is partly attributed to the lag time between the locations for which levels are given and the outflow point. When this cause for the hysteresis has thus been accounted for, the remaining variations in the rating curves are due to the fact that a given water level can correspond to watertables with different slopes (and therefore, to different discharges), depending on whether stage is rising or falling.

Three water releases from the Valens reservoir during periods without precipitation provided flood waves which enable the mentioned hypothesis to be checked. Figure 3.11.A presents the resulting level and discharge hydrographs, and Figure 3.11.B the actual rating curves for that period, between Points NL2, NC6 and NC9, and the outflow point at the Confluence Site. The latter figure shows that the curves loop clockwise, as each wave passes. If a new curve for NC6 is constructed by lagging the levels by a mean wave travel time of eight hours, a rating curve that loops counterclockwise results, which is the case of a streamflow rating curve. Thus, the two effects of the scatter in the

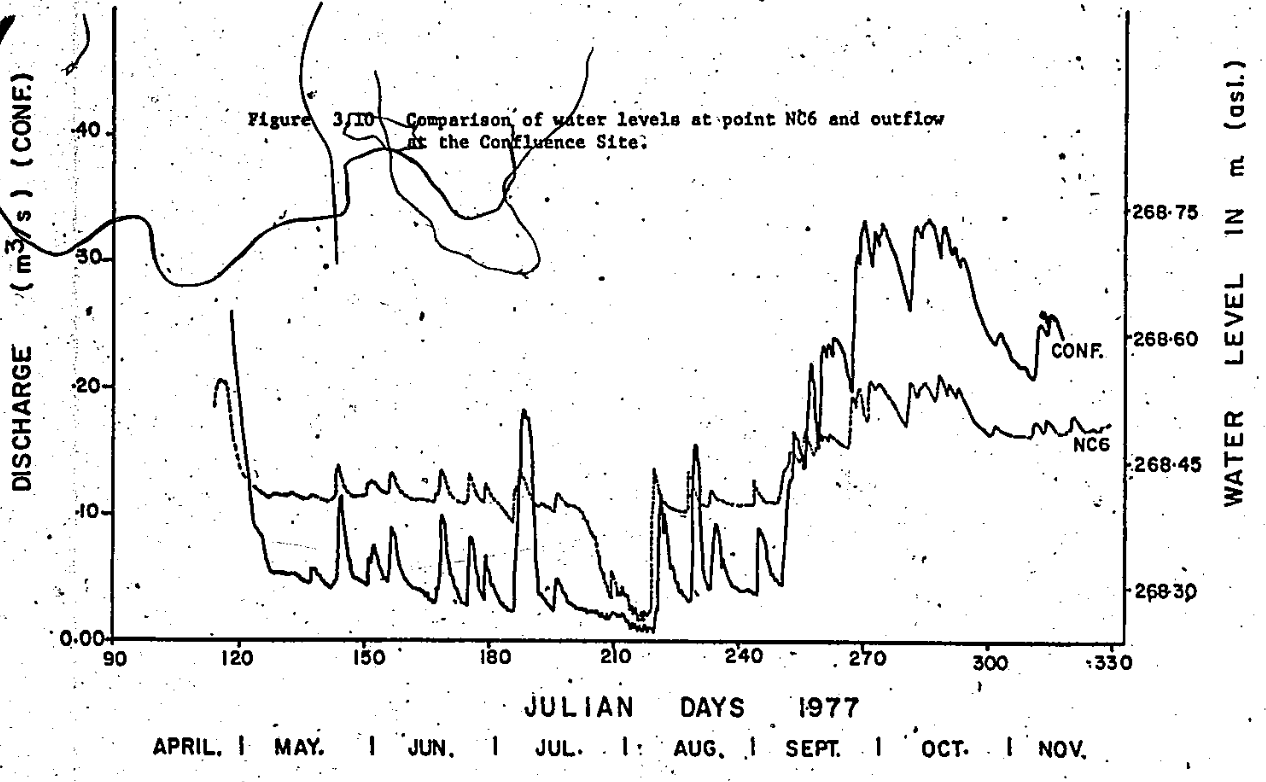


Figure 3.10 Comparison of water levels at point NC6 and outflow at the Confluence Site.

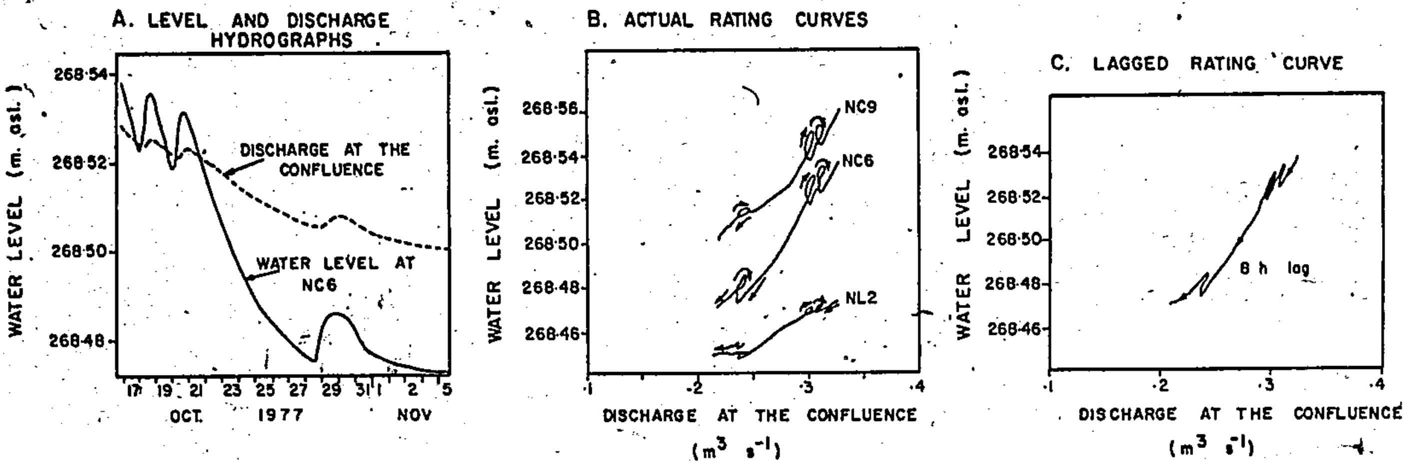


Figure 3.11 Relationship between water level at Point NC6 and outflow at the Confluence Site for three flood waves.

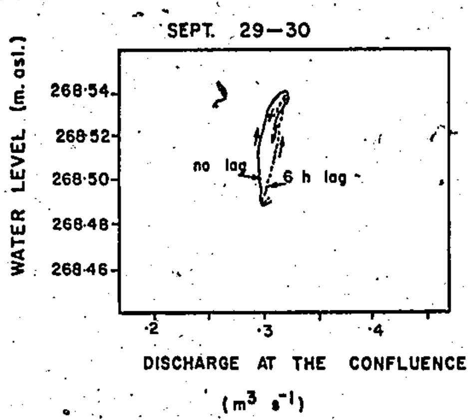


Figure 3.12 Actual and lagged rating curves for the beginning of the flood wave on September 29-30.

seasonal rating curves have been separated and identified. Figure 3.12 shows the available actual and lagged rating curves for another flood wave which, although incomplete, substantiates the previous findings.

However, during periods of rain, this separation is obscured by a simultaneous input of precipitation to all parts of the study area. Figure 3.13 analyzes a large storm on July 6-7; the stage and discharge hydrographs are shown in Figure 3.13.A and the actual rating curve in Figure 3.13.B. The latter shows a large-magnitude clockwise loop indicative of both the large magnitude of the storm and a long lag of about 24 hours (calculated from two-day running means), or 14 hours (from the peaks alone). The considerable lag time is attributable to a reduced lateral flow at the generally low summer levels. When the 14-hour lag is applied to the levels at NC6, the loop contracts substantially, and with the 24-hour lag, it disappears completely (Fig. 3.13.C). Because of reduced lateral flow at these levels, the only indication of the expected counterclockwise loop is provided by the net counterclockwise displacement of the line between its first and last parts.

Figure 3.14.A presents another summertime storm, at even lower watertable levels than the previous one. Owing to minimal lateral flow, there was no measurable lag between NC6 and the Confluence Site. The hydrographs rose in direct response to the storm rainfall contribution in the vicinity of each observation site, although the clockwise loop rotation suggests the presence of some lateral flow. In Figure 3.14.B, higher levels and consequently higher lateral flows resulted in a wave that moved between the two study points in six hours. When the two hydrographs are lagged by this amount, the rotation of the loop is again

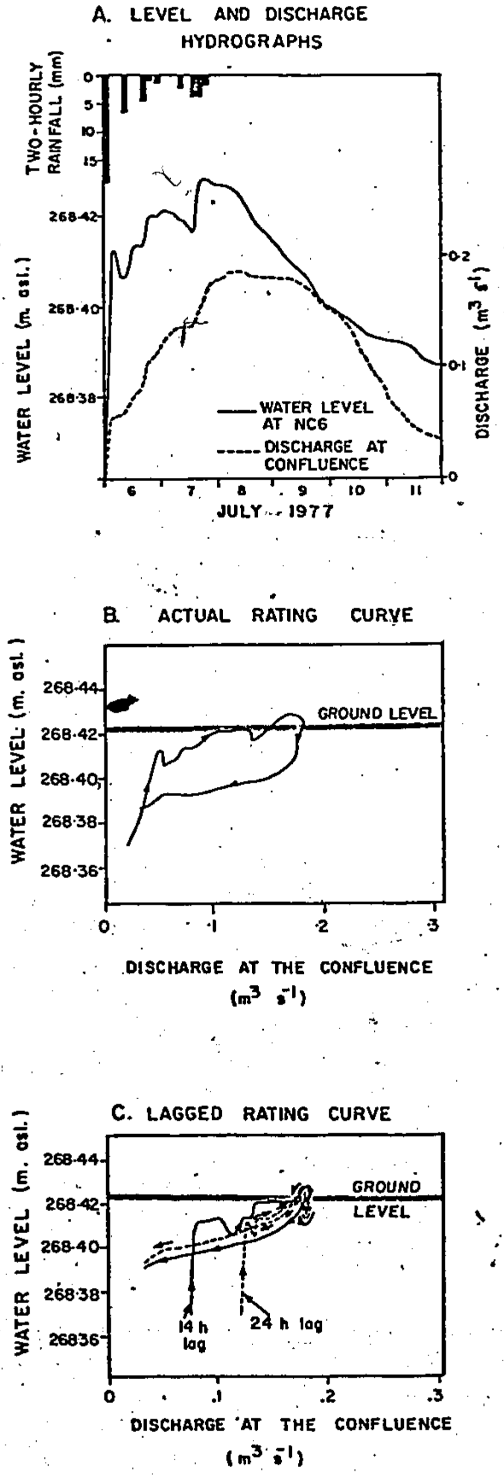


Figure 3.13 Relationship between water level at Point NC6 and outflow at the Confluence Site, for the large storm of July 6-7.

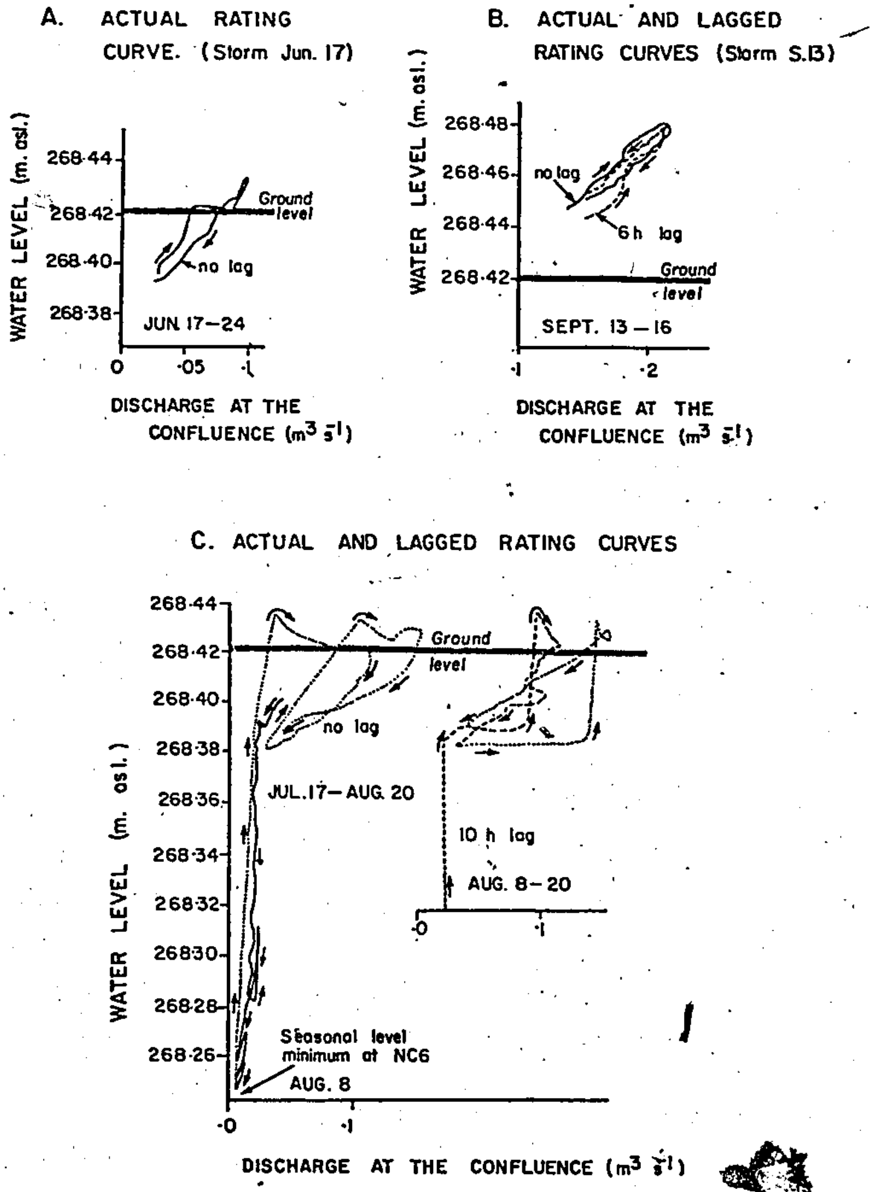


Figure 3.14 Relationship between water level at Point NC6 and outflow at the Confluence Site, for various periods.

changed to counterclockwise. A similar pattern was exhibited by the two storms that occurred after the summer level minimum (Fig. 3.14.C).

This approach, then, provides a method to relate the water levels in an area of the swamp to the outflow from that area, and sheds light upon the nature and magnitude of the processes involved.

3.4 Runoff Regulation by Beverly Swamp

Swamps are considered to act on water flow as hydrological capacitors, temporarily absorbing part of large water inputs and releasing water during dry periods. A large stream entering the swamp and flowing across it along a well defined channel will be less affected by the swamp because there is not as much lateral exchange with the water stored in the swamp. This is illustrated by a comparison of the hydrographs for Fletcher Creek at the Northeast Site and for the trenches at the South Site (Figure 3.15). Streamflow attenuation was not noticeable at higher or low flows. An additional fact is that during the driest period of the summer, flow remained almost constant between the Northeast Site (NE) and a point of Fletcher Creek just above the Confluence Site (ET50), as shown in Figure 3.16 (see Figure 2.3 for the location of the gauging sites). This indicates that although the stream was influent at its upper reaches (Figs. 3.2 and 3.22), the rate of water loss from Fletcher Creek tended to decrease as the creek passed through the swamp. During periods of high flow, the contribution from the swamp is considerable and, therefore, attenuation is also small (Fig. 3.15).

In the case of a small stream crossing or starting at the swamp,

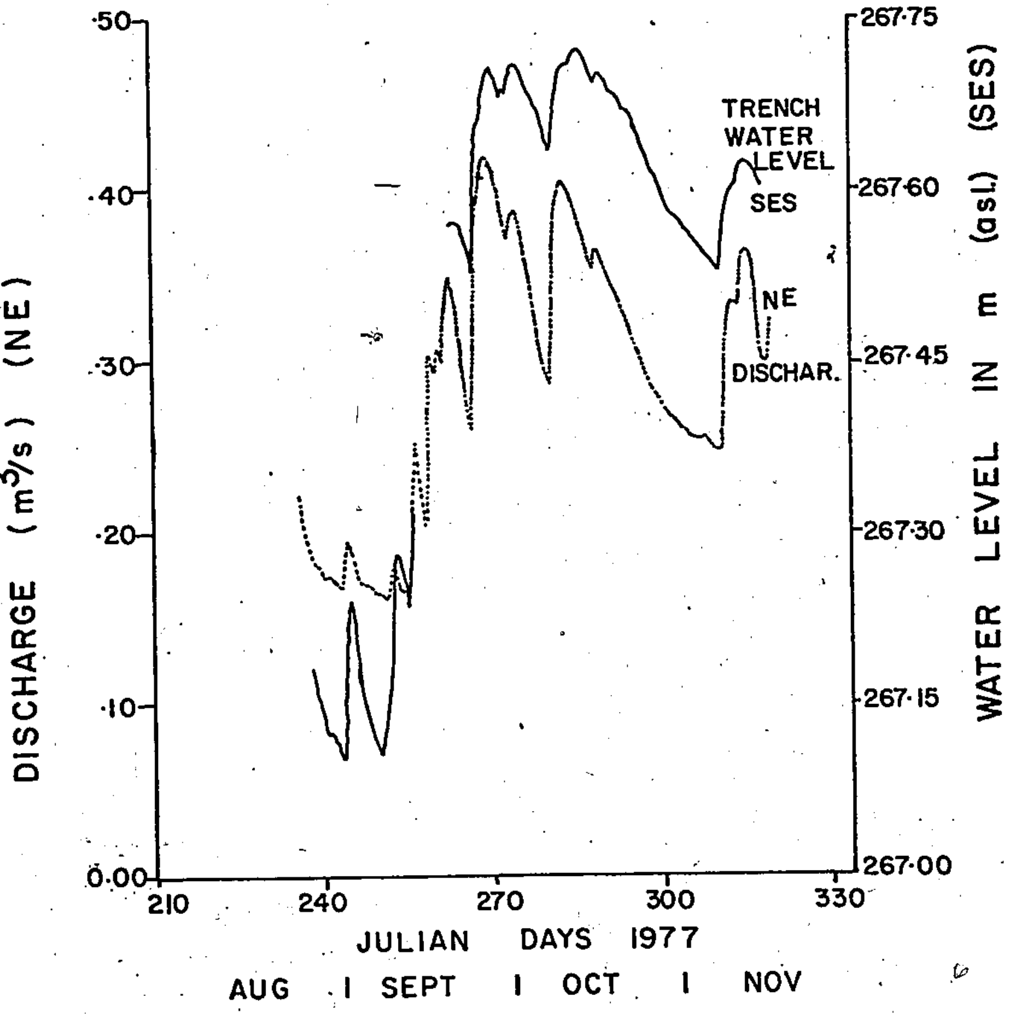


Figure 3.15 Comparison of the discharge of the main stream entering the swamp (Fletcher Creek), and the water level at the trenches of the South Site.

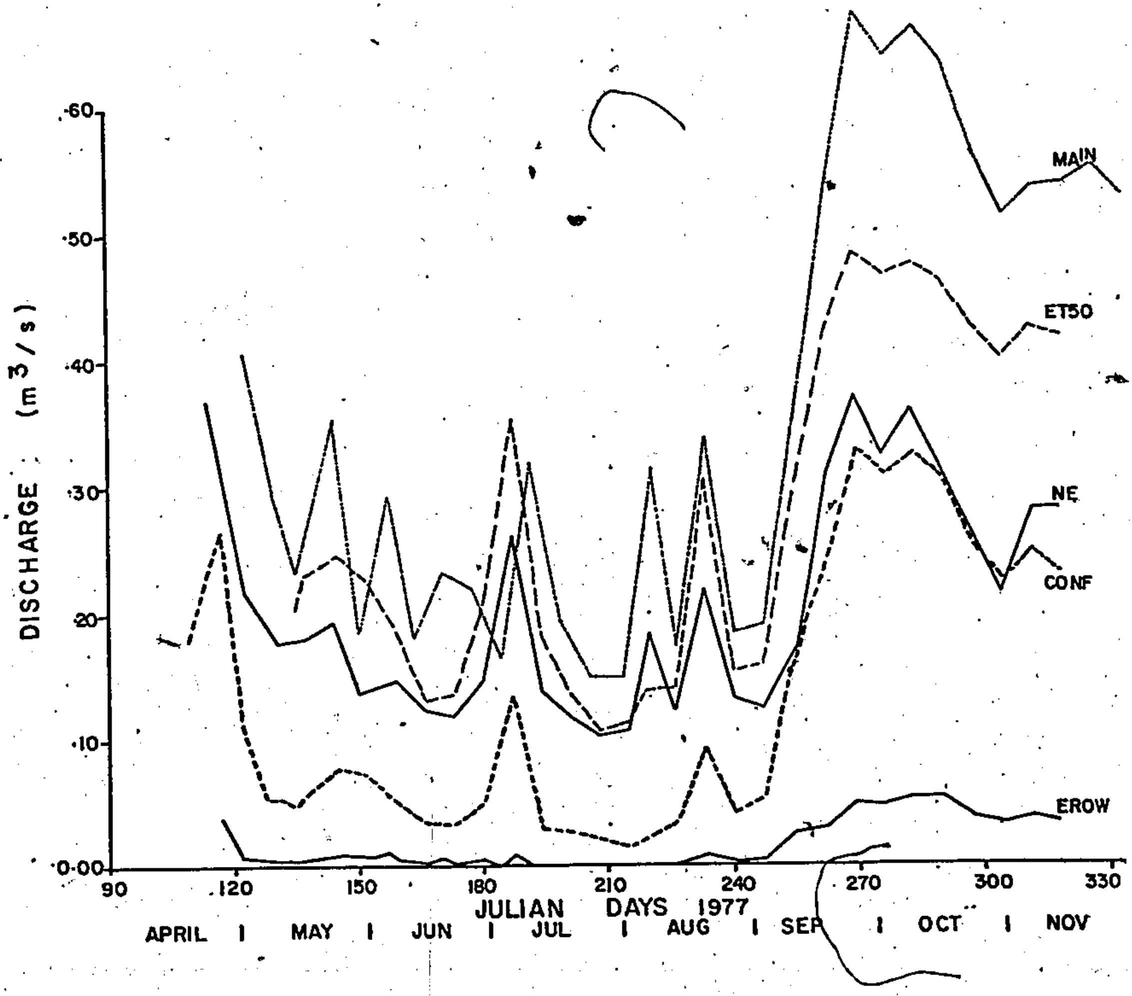


Figure 3.16 Seasonal discharge of Fletcher Creek and Spencer Creek at various points in the swamp (see Figure 2.3 for site locations).

significant attenuation could be expected; however, since the discharge involved is small, this attenuation produces little effect on the hydrology of the swamp as a whole. As an example, consider the area extending from the Northwest Site, across the North Site, and down to the Confluence Site. The controlled inflow from the Valens dam enables detailed study of the regulatory capacity of the area in two ways. First, when water is released suddenly from the Valens dam, a clear pulse is created. The propagation of this wave provides a test for the attenuation capacity of the area. Second, when a constant amount of inflow is maintained (e.g. 0.03 m^3/s for most of the summer), the regulatory capacity of the area in terms of rainfall, can be evaluated.

Figure 3.17.A and B show the inflow, outflow and the water level hydrographs at various points in the area concerned. When the inflow from the dam is low and constant, the area does not have a long retention period for the water derived from rainfall, even when the storms were large. The water levels and the outflow drop back to pre-storm values within several days, indicating a low water holding capacity and, therefore, a poor runoff regulation ability.

During the study period, there were several instances when waves were produced by releases of water from the Valens reservoir. Seven of these waves can be used to examine the runoff regulation capacity of Beverly Swamp. In Figure 3.17.B those parts of the hydrograph rises caused exclusively by the arrival of the waves are hachured, and the time at which thoses rises passed the Northwest Site is denoted by short vertical lines on each hydrograph. The duration of the rainstorms (which often masked the hydrograph rises produced by the waves) is represented

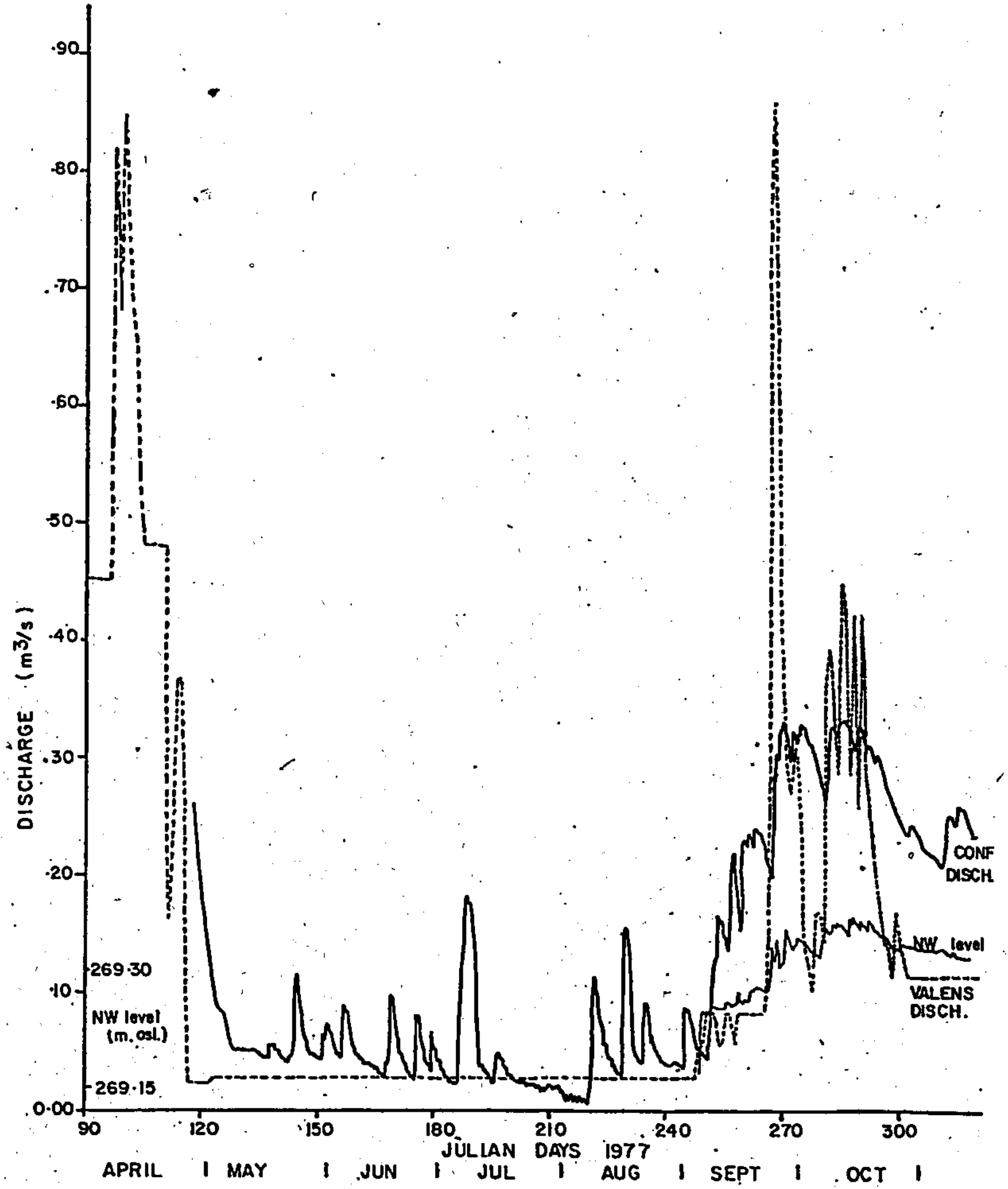


Figure 3.17A Inflow from Valens and outflow at the Confluence Site.

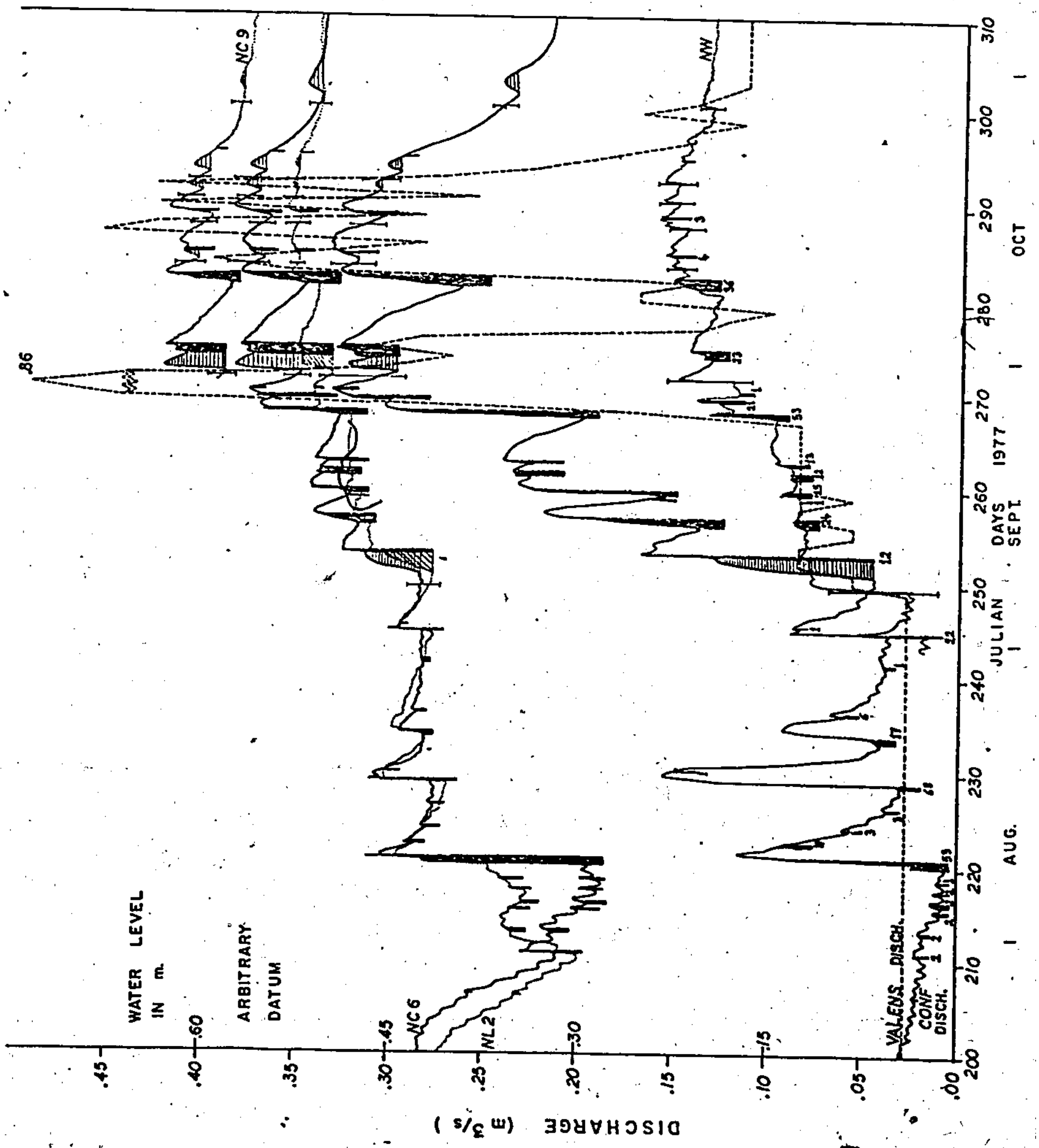


Figure 3.17B Large-scale diagrams for the general northern area of the swamp. See text for explanations.

by the width of the shaded bars under the hydrographs, and the rainfall amounts (in mm) are denoted by the number below each bar. Sharp responses to the Valens reservoir releases remain noticeable as far downflow as the Confluence Site, indicating that even flashy inflows of small magnitude are poorly attenuated. The dampening of the peaks in the inflow (Fig. 3.17.A) is partly due to a subsurface spreading of that flow over the area, and partly to the fact that all of that flow did not pass through the Confluence Site.

The last three waves of the study period flowed across the area to the Confluence Site quite undisturbed, and they appear superimposed on the recession limb of the general hydrograph for that period. The presence of this relatively sharp recession during this period of low evaporation proves that it is not the releases from the Valens dam that are responsible for the swamp's relatively high autumn levels, but, rather, a high ratio of precipitation to evaporation.

Figure 3.18 presents the isochrones for the arrival of the seven selected waves, based on the continuous hydrograph records at the five locations shown. The patterns is areally similar in all cases, but the gradient of the isochrones varies substantially. In general, the wave translation time depends on water levels, with higher hydraulic conductivity near the surface resulting in a faster translation velocity at higher levels. Figure 3.19 quantifies the degree of this variability; the water level at the middle of the rising limbs at the four points below the Northwest Site was taken as representative of the entire release's hydrograph and was plotted against the time of arrival of the wave front. The result is an inverse logarithmic relationship

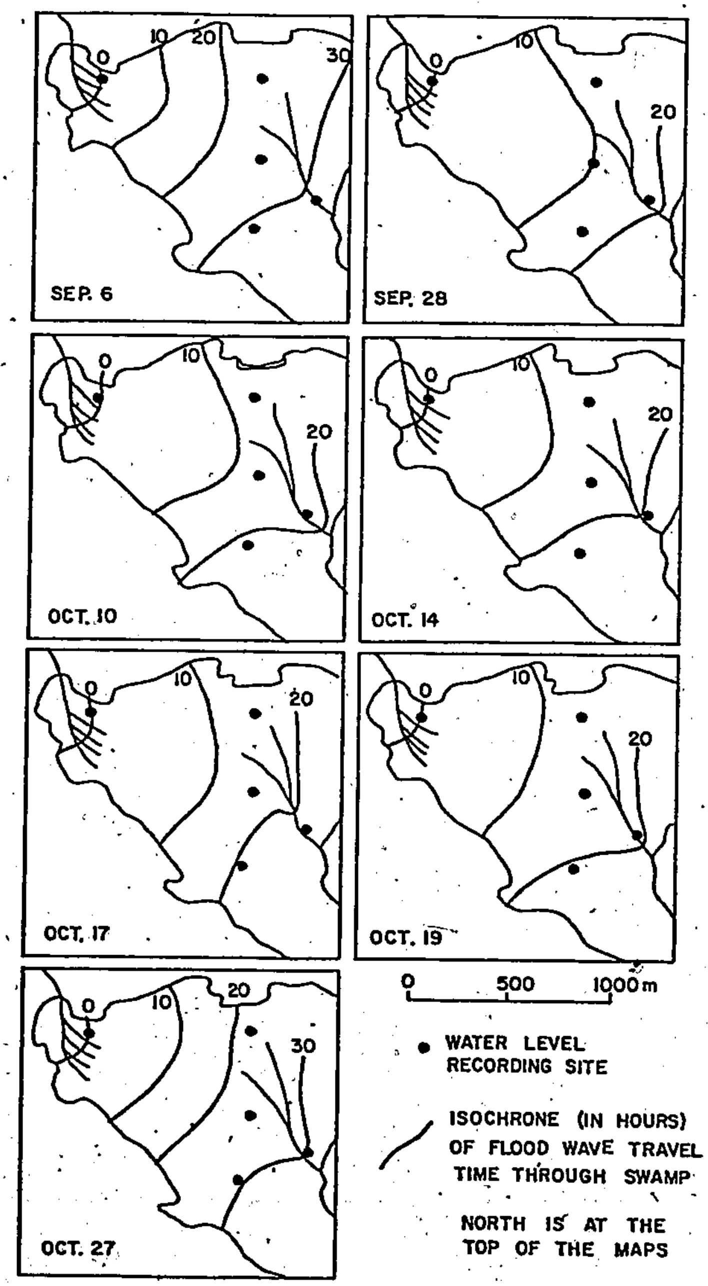


Figure 3.18 Isochrones for the arrival of the wave fronts, in hours.

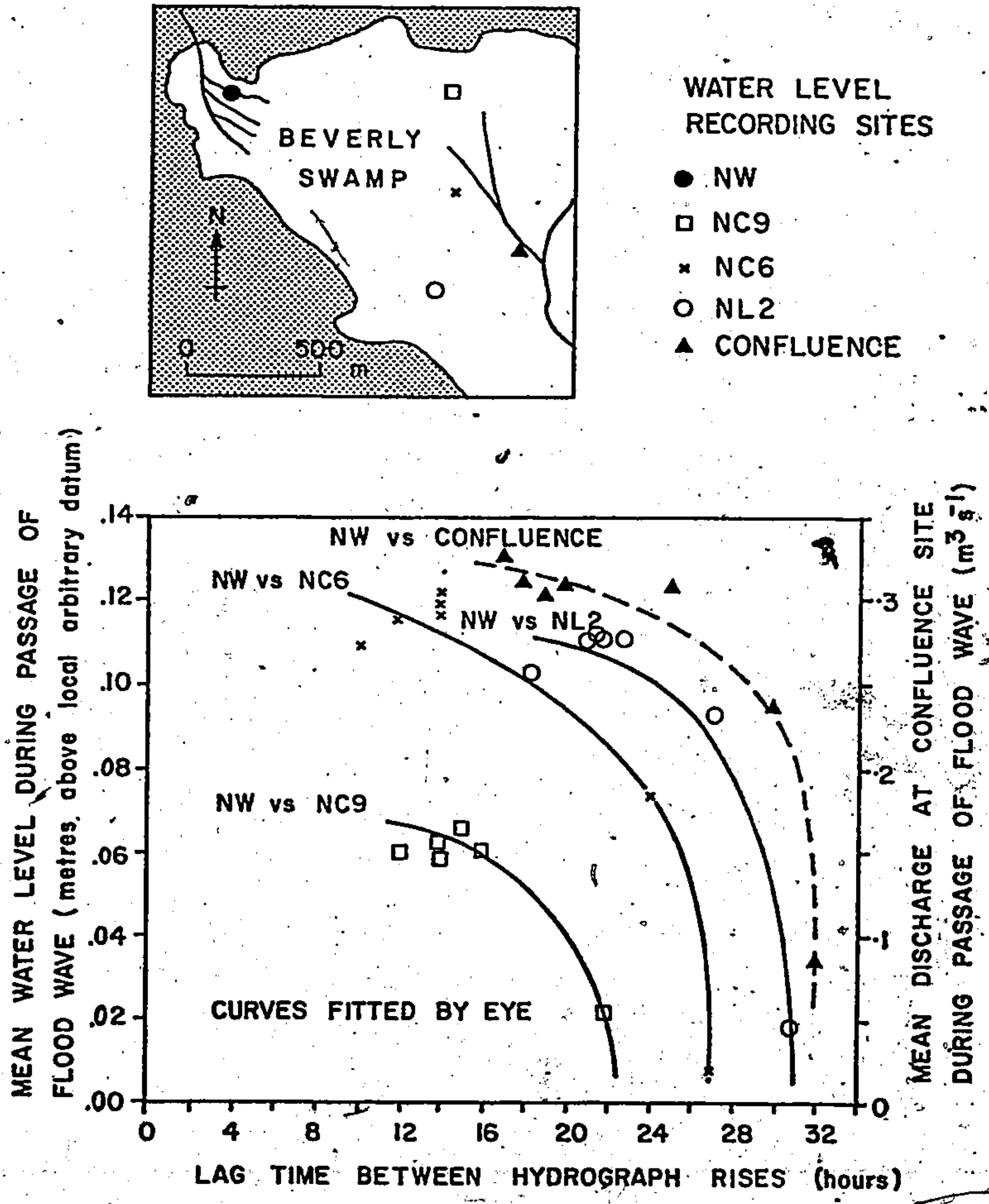


Figure 3.19 Lag time between the hydrograph rises at the NW Site and the rises at various points in the swamp.

between the two variables, confirming once more the active role of swamp water levels in determining the magnitude of hydrologic processes.

3.5 Spatial Variations of the Water Level Regime

The study area is dominated by low gradients sloping towards the main water courses (Fig. 3.20.A). With a large hydraulic conductivity, these gradients are sufficient to affect the general direction of the water flow through most parts of the swamp throughout the entire year. This evidence agrees with Heinselman's (1970) peatland classification in which swamps have concave profiles to sustain confluent drainage. Water level regimes at any given site will be strongly affected by this regional trend, and local water level variations will be superimposed on it. Similarly, short-term water level fluctuations were considered in Section 3.2 as superimposed on the long-term seasonal regime.

At a more localized scale, water level regimes will also depend on the conditions of the particular study plot. An analysis of the regimes at the different representative sites outlined in Chapter Two provides adequate information on the behaviour of the water level in Beverly Swamp, and possibly in other swamps as well.

Two types of water level regimes can be distinguished in a swamp. The first is a "periodically effluent" regime. This regime applies to an area adjacent to a stream that enters the swamp and imposes its levels on the watertable in its vicinity. During dry periods the areas affected by this regime become water sinks and flow becomes influent. However, the flow often becomes effluent in the wet season.

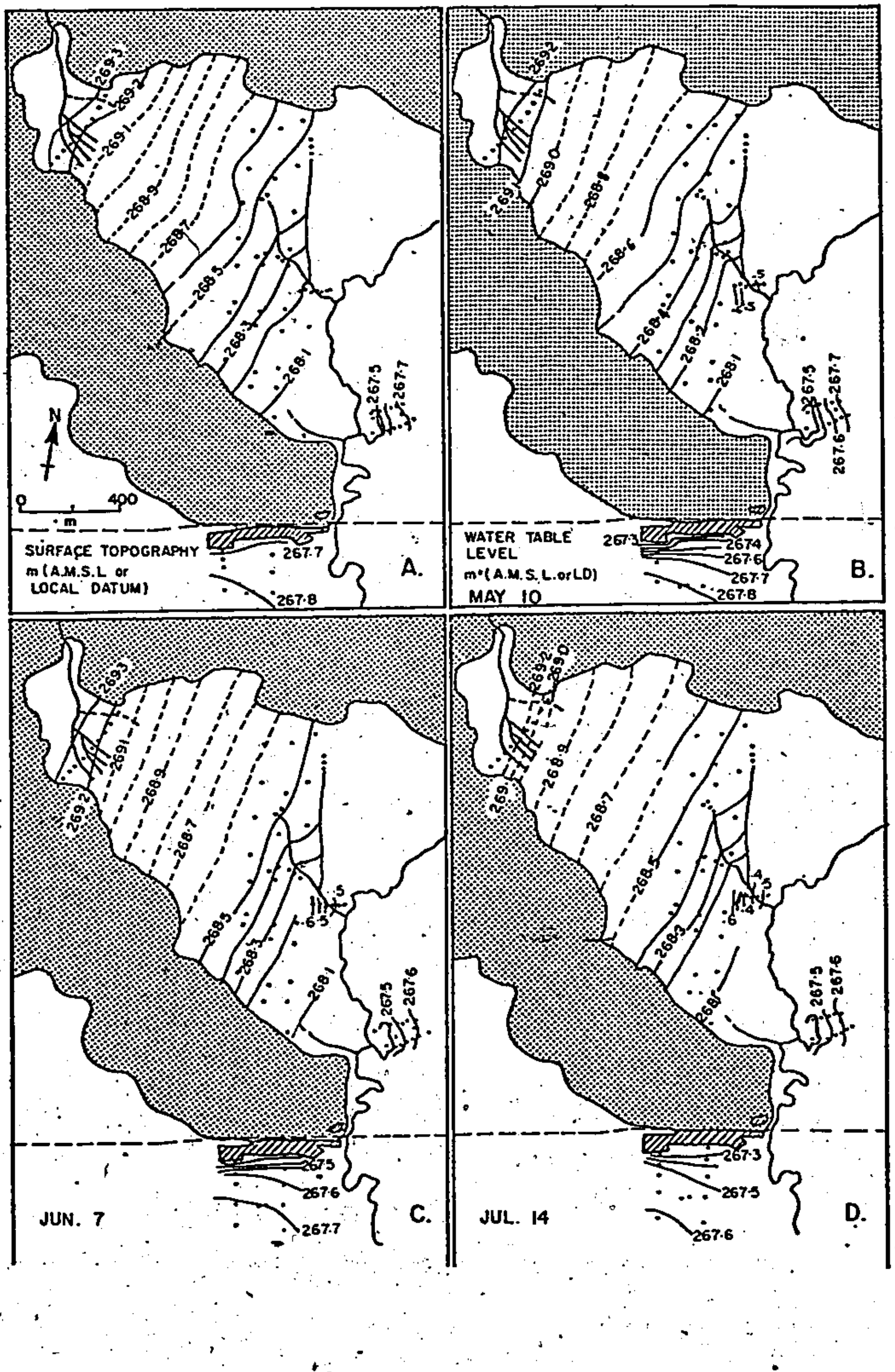
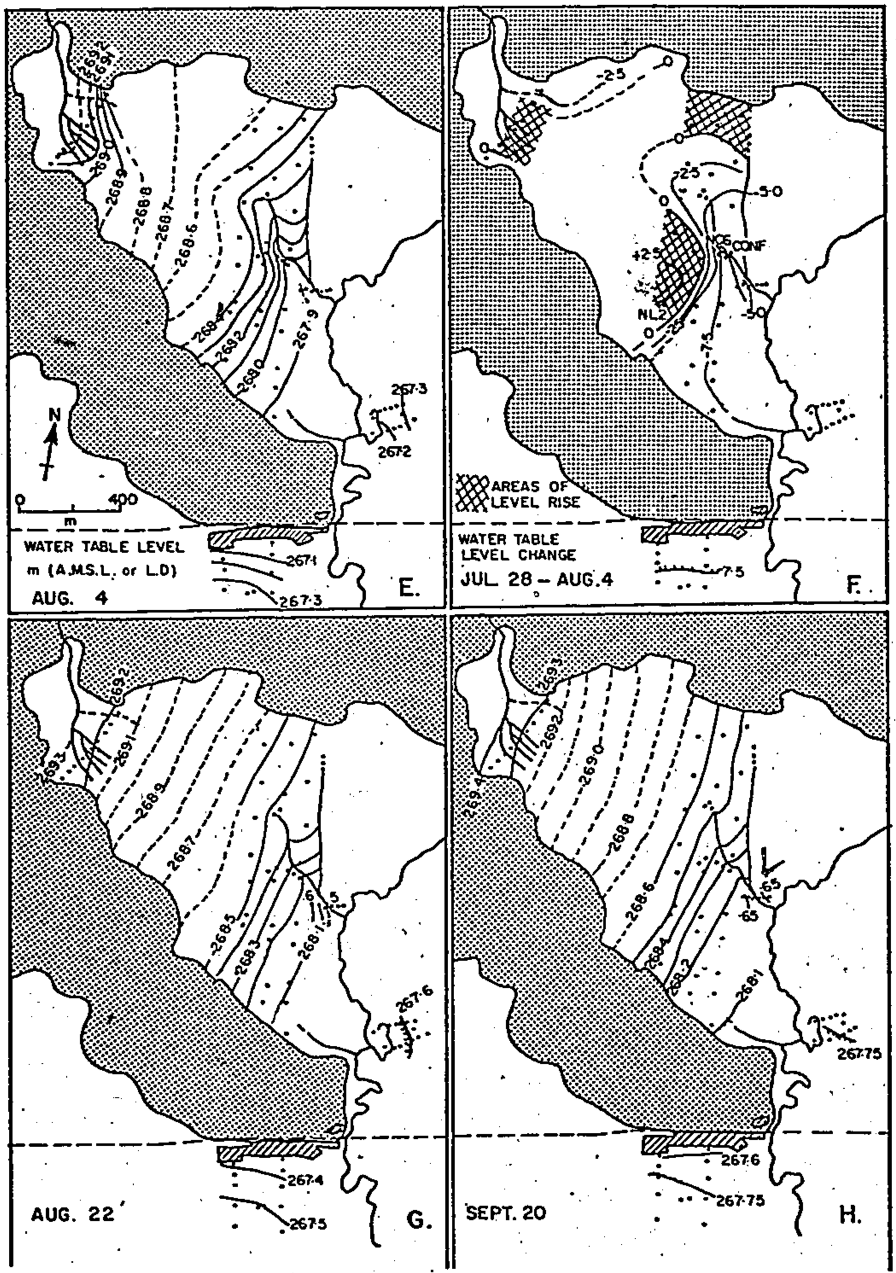
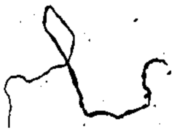


Figure 3:20 Surface topography and watertable position at different dates.

Figure 3.20 (continued)





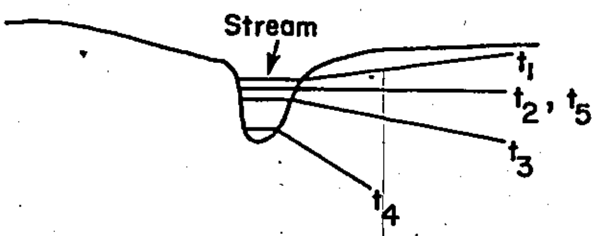
The second type is the "predominantly effluent" regime. This regime is experienced by those areas that drain into streams, the flow of which depends almost exclusively on the water levels in the area. Thus, in this case, the regime of the watertable is imposed onto the nearby stream which will always be subject to effluent flow. If a stream is large, it may convey the "periodically effluent" regime into, and perhaps across, the entire swamp, especially if the channel is well defined. Streams that start at the swamp and are exclusively fed by precipitation (assuming negligible lateral contributions of groundwater from outside the swamp) will show a typical "predominantly effluent" regime.

The preceding distinctions are important because the local water level regime is largely determined in that manner. Figure 3.21 shows typical profiles representing the stream level and watertable fluctuations of both regime types.

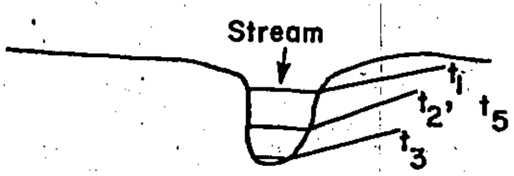
These two regimes become less recognizable further away from streams, since variations in the groundwater level regime will be introduced by factors other than stream level such as spatial variations in hydraulic conductivity, topography, etc.

3.5.1 The Northeast Site

This site is dominated by Fletcher Creek, the largest of the streams flowing into the swamp. The stream level is often higher than the adjacent watertable and thus, the regime at this site is "periodically effluent". Figure 3.22 shows uniform flood levels for April 25th, at the end of the snowmelt season. For the other dates, the stream is either effluent or



PERIODICALLY EFFLUENT REGIME



PREDOMINANTLY EFFLUENT REGIME

Figure 3.21 Watertable fluctuations associated with the two types of regimes, at different stages.

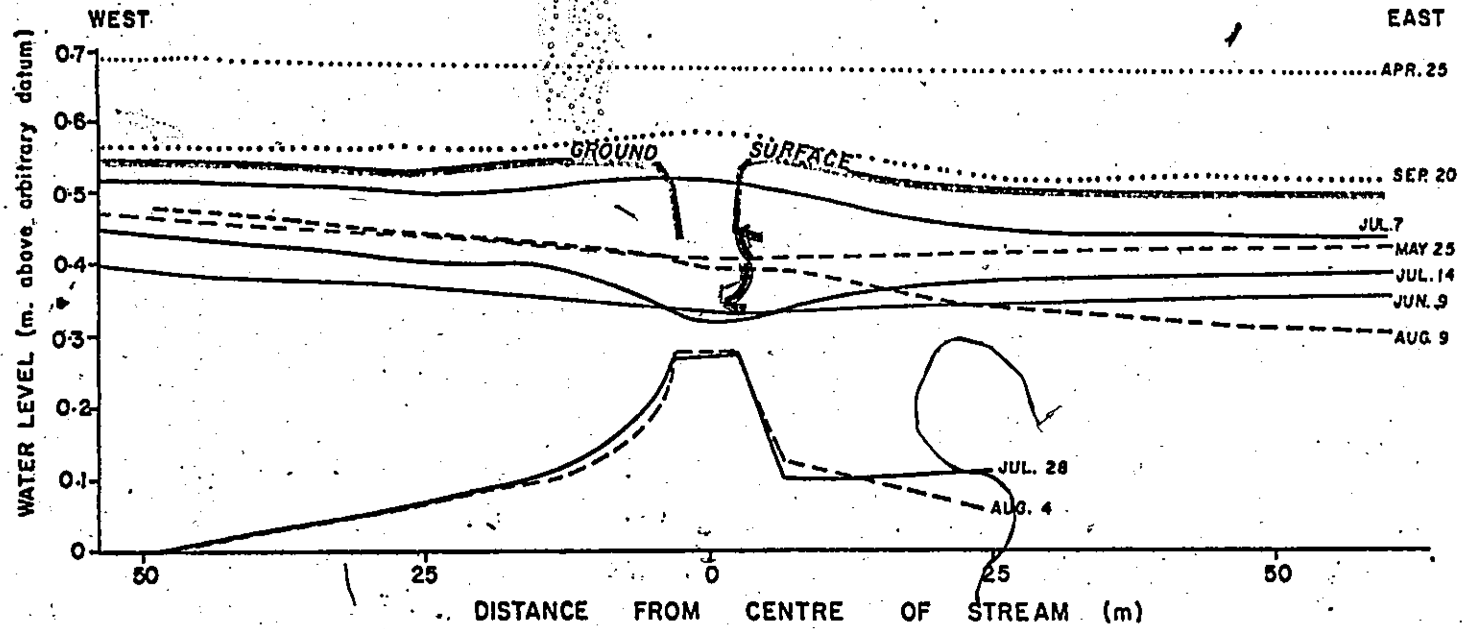


Figure 3.22 Northeast Site water levels. Cross-section.

influent, with a very marked influent flow at the beginning of August, when the swamp experienced minimum levels. Between April 25th and the summer minimum , the range in stage in Fletcher Creek was 0.4 m while at Point 1, the range was 0.7 m, indicating that during summer, this site acts as a water sink.

3.5.2 The Northwest Site

This site is affected by the entrance of Spencer Creek whose flow is controlled by the Valens Reservoir, one kilometer upstream. At this site, Spencer Creek branches out into four major subchannels.

Figure 3.23 shows that the watertable is dominated by a "periodically effluent" regime imposed by Spencer Creek. Here, flow regulation at the Valens dam is of considerable importance. Summer flow, for instance, was kept at 0.03 m^3/sec, preventing the water in the subchannels from dropping below a certain level even when the area nearby was experiencing a water deficit. This accounts for the considerable influent flow of August 4th, when the level at the subchannels was only 0.1 m lower than on September 20th, while at Point 1 the difference was more than 0.5m.

3.5.3 The Confluence Site

This site is drained by Spencer Creek, about 100 m upstream from its confluence with Fletcher Creek. After the bulk of Spencer Creek's flow has diffused underground at the western side of the North Site, there is a gradual channelling of flow again near the Confluence Site. At this site, Spencer Creek can be considered as being "re-created", and the

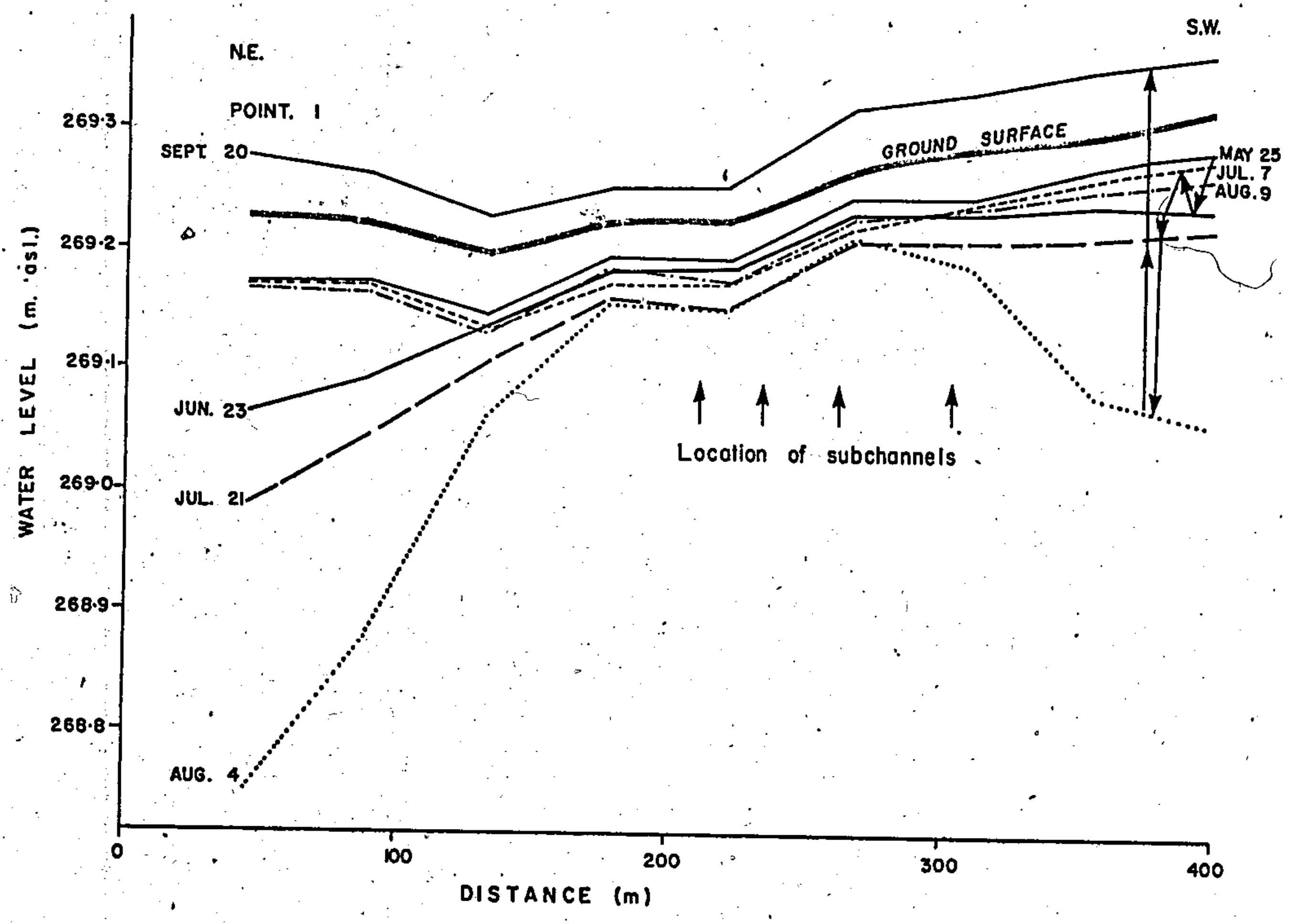


Figure 3.23 Northwest Site water levels. Cross-section.

resulting regime is thus "predominantly effluent". Figure 3.24 shows Spencer Creek to be effluent at all times. On April 28th, flooding produced an almost horizontal water surface, but as the flood receded, water levels dropped faster at and near the stream because of better drainage. This resulted in a convex watertable on both sides of the stream. As levels approached their summer minimum (on August 4th) and the flow in the stream decreased, the watertable away from the stream caught up with the stream level and the watertable was again flattened. The maximum drop of levels during the study season was approximately 0.45 m. In late summer, levels rose and the rising sequence retraced the profiles produced during the dropping stage.

3.5.4 The South Site

This site is located next to several water-filled trenches produced by peat excavation several decades ago. These trenches are connected to Spencer Creek, and both the creek and the trench water levels affect the watertable regime of this site to a small degree, but precipitation keeps the watertable higher than the level at the trenches so that water flow is towards them. Only on July 7th was the level of a small section of the site slightly lower than the trench water level (Fig. 3.25). Thus, this area experiences a "predominantly effluent" regime. Close to the trenches, however, the water level affects the aquifer levels in as much as the aquifer is more or less backed up or allowed to drain. Due to this and to the larger size of the area, the water level regime, at least in a short time scale, was not as typically "perennially effluent" as that at the Confluence Site. The seasonal

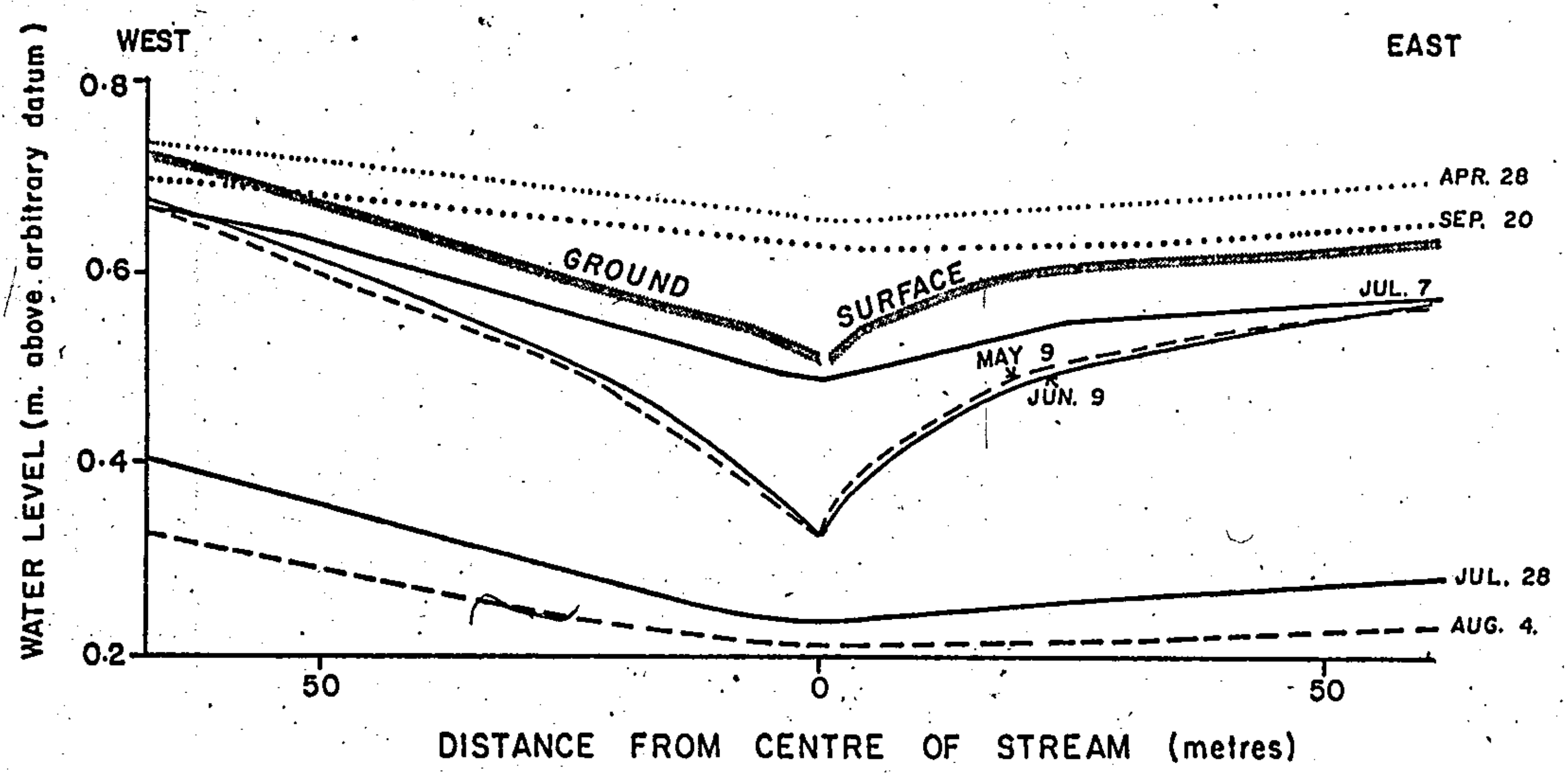


Figure 3.24 Confluence Site water levels. Cross-section.

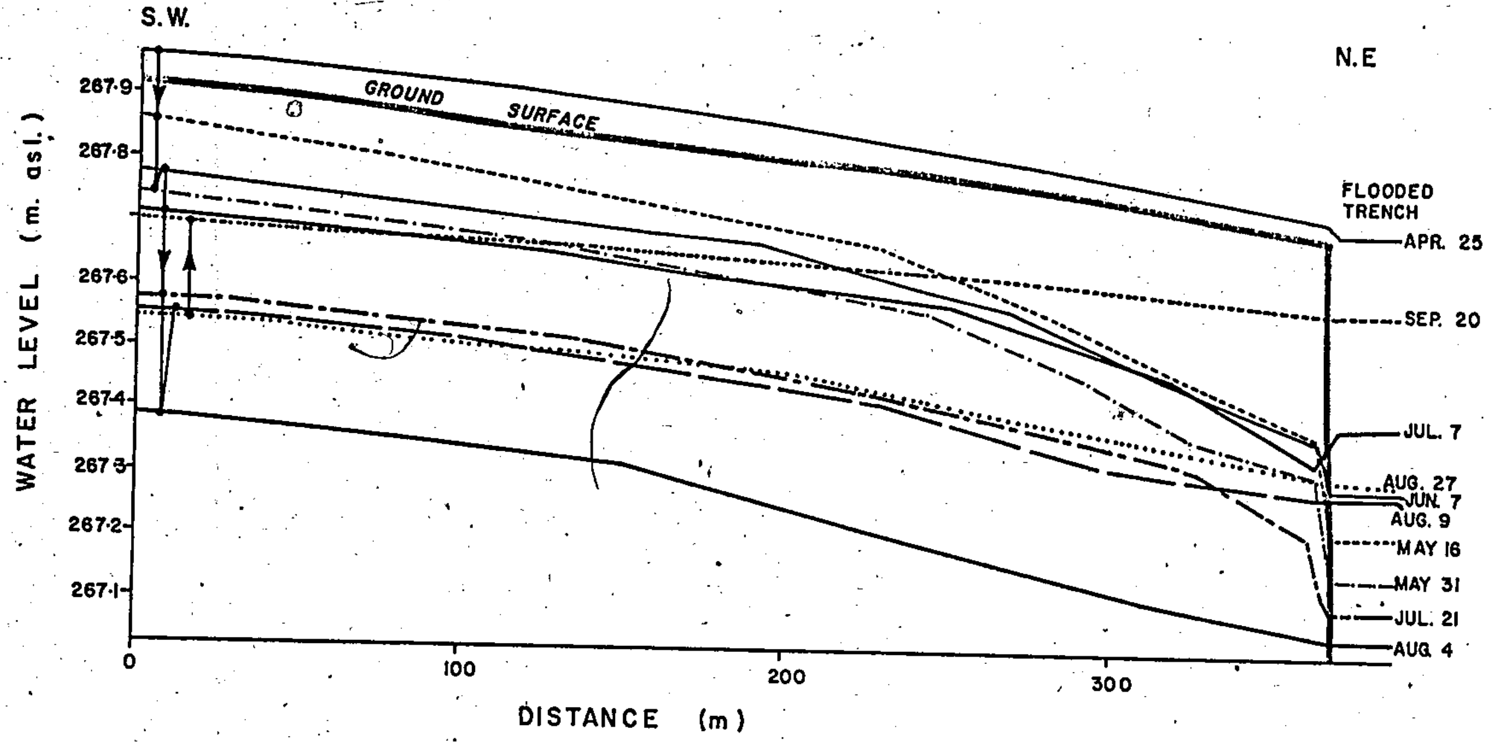


Figure 3.25 South Site water levels. Cross-section.

water level fluctuation was about 0.6 m.

3.5.5 The East Site

This site extends eastward from a small tributary channel of Spencer Creek. This channel is quite shallow and runs dry in summer.

Subsurface flow is always towards the channel for the same reasons as in the South Site. The absence of definite stream banks results in flooding rather than in influent flow. The seasonal fluctuation of the watertable was about 0.4 m.

A "predominantly effluent" regime, then, appears to take place (Fig. 3.26), even though at high levels the stream level is not entirely dependent on the watertable of the nearby areas. It should be noted in Figure 3.26 that the northeastern section of the profile for September 13th was exceptionally high. This is because the levels were measured during a storm and an uneven accumulation of rainfall in the area was still evident. A few hours later, lateral flow removed these heterogeneities.

3.5.6 The North Site

This site, spanning 1.3 km across an entire section of the swamp, is the least influenced by a stream or an open water body. Its water level regime is visibly influenced by the general slope of the area (Fig. 3.20). Figure 3.27 is a three-dimensional plot of the water levels, and it shows the considerable areal variations in the fluctuations, especially from the center-west section to the center-east one. These fluctuations are the result of a heterogeneous flow pattern combined with variations in

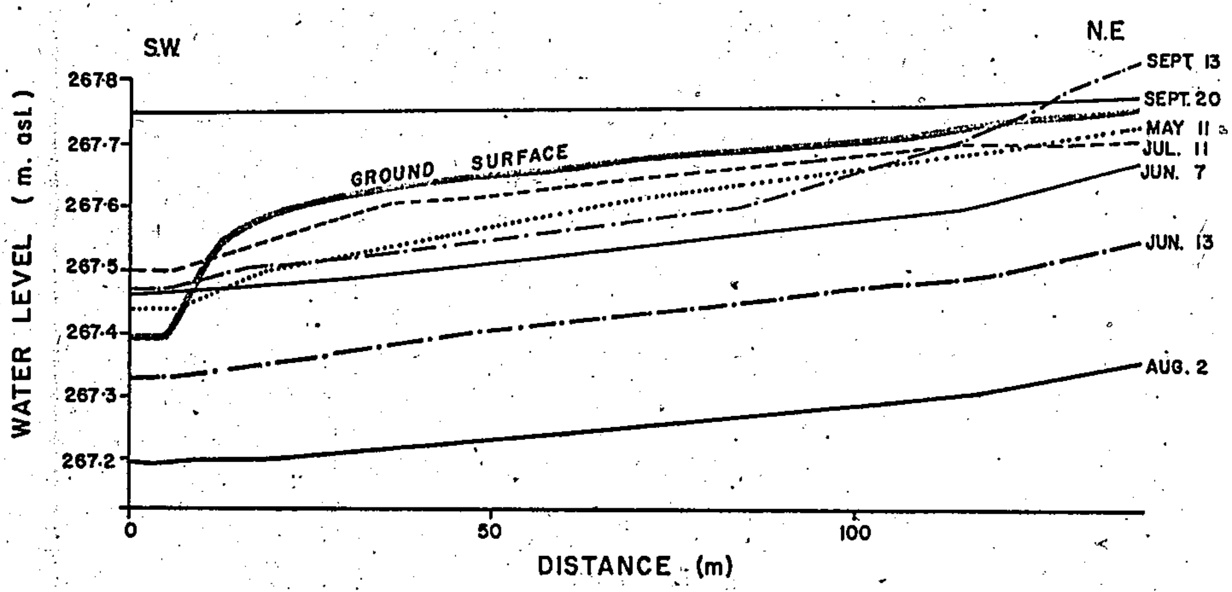


Figure 3.26 East Site water levels. Cross-section.

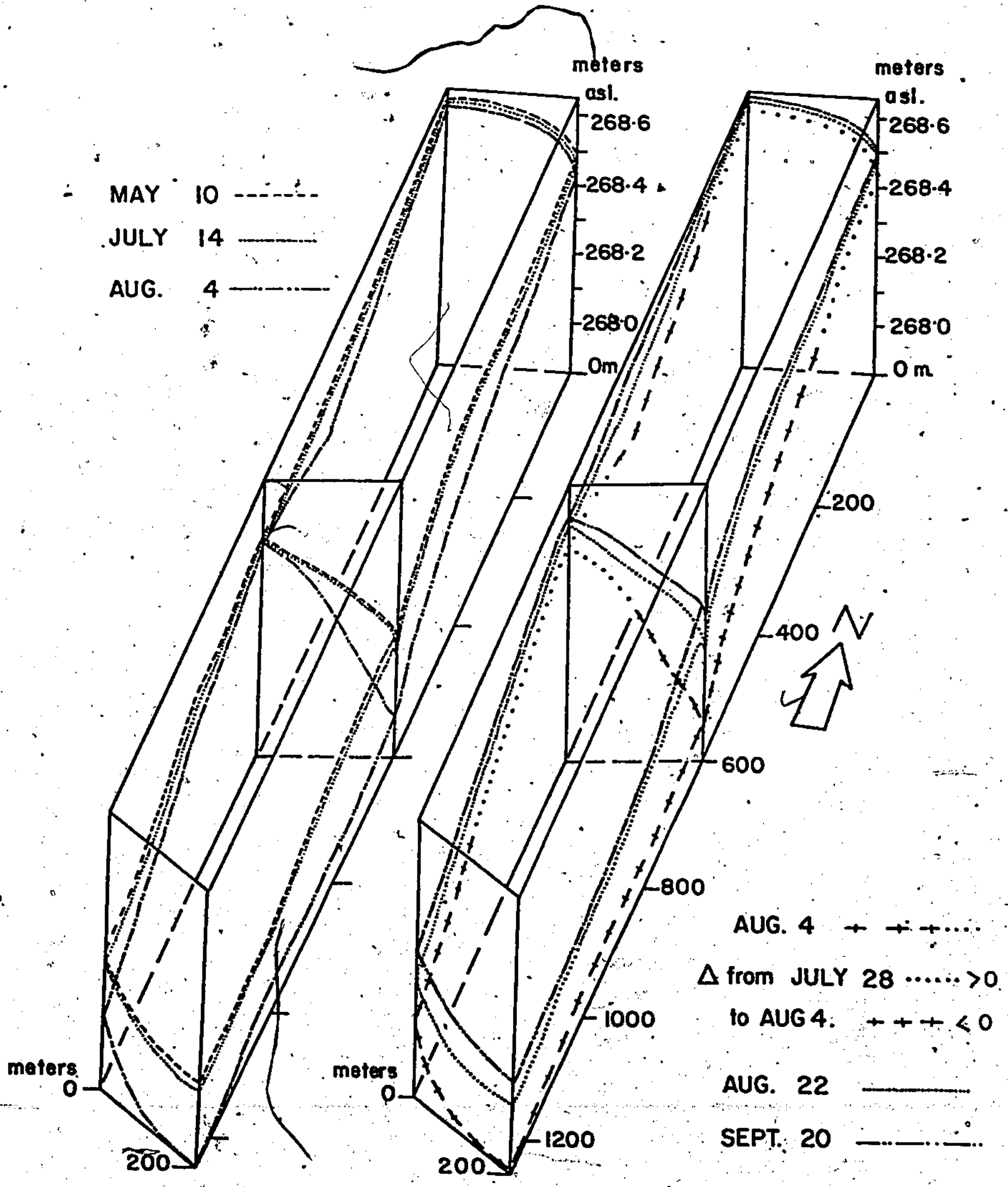


Figure 3.27 North Site water levels. Cross-section.

soil characteristics. Figure 3.20 shows that when levels are high, the flow pattern is uniform, with most of the flow taking place at or near the surface. When levels are low, as on August 4th, the watertable contours produce a trough along which part of Spencer Creek re-emerges as the levels rise. A relatively better drainage along that watertable trough may explain several variations observed. Figures 3.20.F and 3.27 present examples of short and long level fluctuations at this site. The center-east and center-south sections of this site experience a maximum seasonal range of levels (0.25 to 0.3m), while the range at the center-west and north sections was under 0.1 m (Fig. 3.27). The average level range for the entire site is lower than for other sites, reflecting partly the higher average specific yield of this site (Table 2.3).

Figure 3.20.F shows, at a reduced time scale, that the seasonal minimum water levels were reached earlier in the sections of minimum variability. Continuous water level records show that at Point NL2, minimum levels were reached on July 28th - 29th, at Point NC6 on August 5th - 6th (Figure 3.6), and at the Confluence Site on August 7th - 8th. This is explained by the fact that the sections of minimum level variation had risen during these days (July 28th to August 8th) as a result of several minor rainstorms, and possibly, of an unrecorded water release from the Valens dam (see the small level rise near the channels at the Northwest Site). However, those rises during this period were accompanied by a water level drop in the sections of maximum seasonal level variation. This areal correspondence at both time scales suggests that the sections of minimum variability represent zones where water is retained as in a shallow dam; water can only flow out by overflowing

into the sections of maximum variabiltiy which have efficient drainage. This must be caused by local heterogeneities in the soil properties.

This overflow hypothesis explains both the short and long term phenomena discussed; the water retained in the sections of minimum level variation will not drop much in summer because of the high resistance to lateral flow that they are subject to, and they will not rise by much during wet periods because a small rise will suffice to initiate overflow out of the area. Hence the small level variability. Areas of maximum variation reach low levels in summer due to their efficient drainage, while during wet periods they are flooded by overflow from the other areas. Since that water cannot be drained because it is backed up by the general flood levels of the area, the levels rise to the same level as those in the rest of the site, creating the uniform watertable observed in periods of high levels. This explains the high level variability of these sections; and, since they are located at or near the site of streams (Fig. 3.20.F), this hypothesis appears to be ratified. The described differential level changes during the first days of August also support this hypothesis: the areas of maximum variability discharged the water received during those days, plus some more, which resulted in a net drop in levels. The areas of minimum variability being unable to drain as easily, used that extra water received to raise their levels slightly, since during this dry period, even these areas would have some water deficit in spite of the retention effect.

The water level regime of this site is a combination of "periodically effluent" in the sections of minimum variability, and "predominantly effluent" in the sections of maximum variability, their "stream" being the unchannelled but rather localized flow of Spencer Creek. This site's regime also illustrates how the transition between the two types of regimes takes place.

CHAPTER FOUR

WATERTABLE MODELING

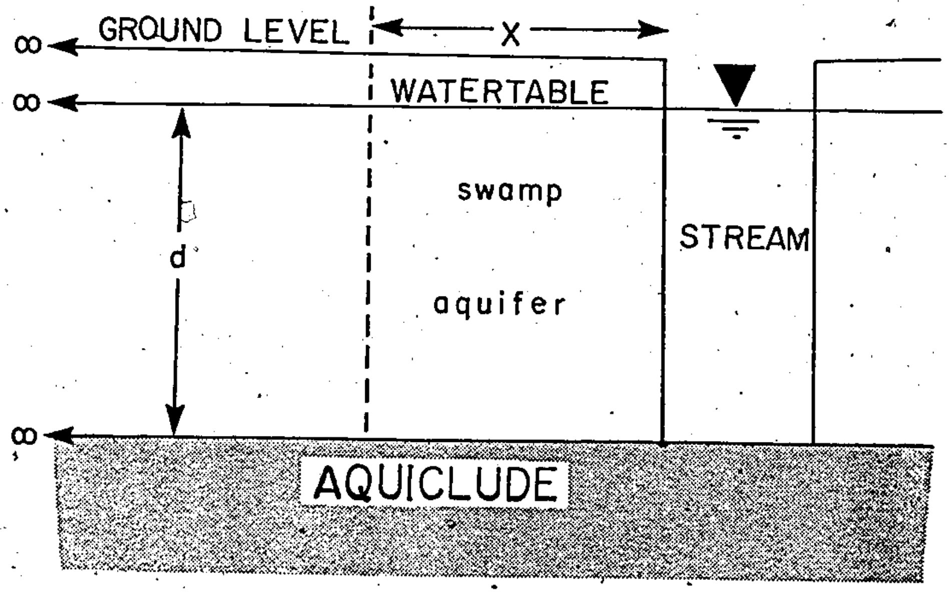
4.1 Background

The previous chapter has demonstrated a close relationship between the water level regimes of streams and their adjacent aquifers in a swamp. In this chapter, a numerical model is proposed to generate the water level hydrograph for points in the swamp adjacent to a stream. The input information needed includes the stage record of the stream, the evaporation estimates and rainfall data for the swamp, an initial water level at the study point, soil parameters, and the distance of the study point from the stream bank.

This model is based on the work of Pinder et al. (1969), developed from a heat flow analogue (Carslaw and Jaeger, 1959). The cross-section shown in Figure 4.1 shows the type of aquifer assumed for the model. Since Beverly Swamp consists of a layer of peat overlying a marl aquiclude, this assumed aquifer appears to be appropriate.

The stream level hydrographs are digitized in two-hourly increments, and the effect of each increment in stream level on the water level at point x, at time t, is calcualted by means of equation 4.1 (Appendix I).

$$h_n = \sum_{i=1}^{n} [(\Delta L_i) \operatorname{erfc} (\frac{x}{2\sqrt{D\Delta t(n-i)}})] \qquad (4.1)$$



X = distance from the stream to the point whose water level is to be predicted.

d = thickness of the saturated zone.

Figure 4.1 Aquifer assumed for the model.

where h_n is the water level at point x and at the end of the time period n, [L].

$n = t/\Delta t$, and there are n periods between time 0 and time t.

Δt is the duration of each time increment, [T].

i is the number of time intervals since time 0.

ΔL_i is the change in stream level between time $(i-1)\Delta t$ and $i\Delta t$; that is, $\Delta L_i = SL(i)-SL(i-1)$, [L].

SL(i) is the stream level at time period i, [L].

x is the distance between the stream and the study point, [L].

D is the diffusivity, a ratio of transmissivity (hydraulic conductivity times the saturated thickness) to specific yield, $[L^2\ T^{-1}]$.

erfc is the complementary error function, defined as

$$\mathrm{erfc}(b) = \frac{2}{\sqrt{\pi}} \int_b^\infty \exp\,(-\lambda^2)\,d\lambda$$

Equation 4.1 was used by Pinder et al. (1969) in a model that further assumed a homogeneous and isotropic aquifer, equal initial stream and aquifer levels, and an absence of precipitation and evaporation.

Two modifications to Pinder's model are made here to account for precipitation and evaporation, and to accommodate unequal initial stream and aquifer levels.

Bi-hourly differences between precipitation and evaporation are divided by the average specific yield of the aquifer to convert the inputs into water level changes. The result is subtracted from the stream level change for that time interval:

$$\Delta H_i = SL(i) - SL(i-1) - \frac{P(i) - E(i)}{Sy} \qquad (4.2)$$

where $P(i)$ is the precipitation received during the (i-1)th interval.

$E(i)$ is the evaporation during the (i-1)th interval.

Sy is the average specific yield for the aquifer.

Then, ΔH_i replaces ΔL_i in equation 4.1. The value of $[(P(i) - E(i)/Sy]$ is also added to the accumulated contributions toward the water level at time t.

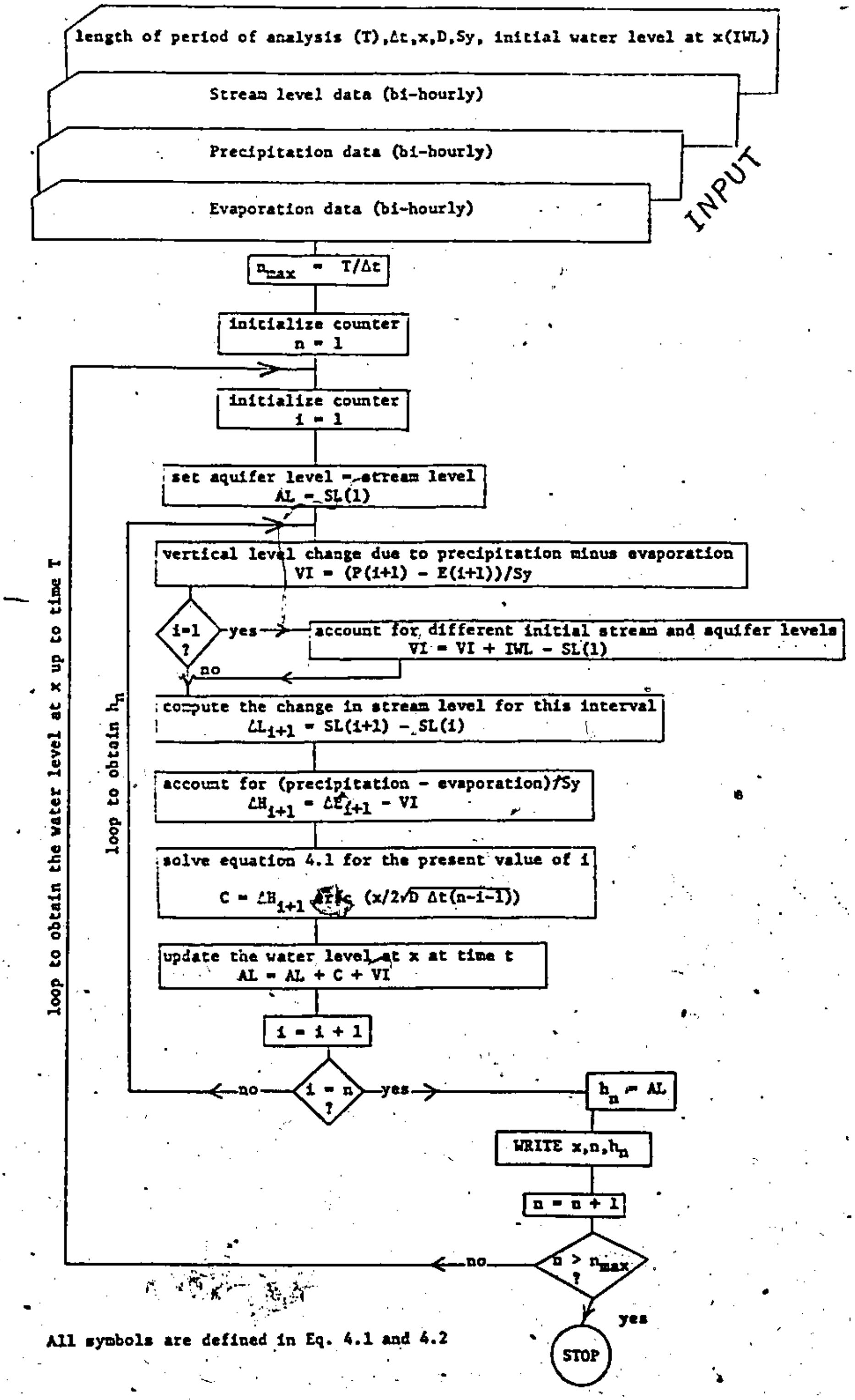
To account for unequal initial stream and aquifer levels, the model considers the initial level difference as a sudden input of ΔH at the first iteration. The error produced by this initial addition decreases with time because the new assumed initial water level in the aquifer catches up with the actual one.

Figure 4.2 shows the flowchart of the computer program used for this model.

4.2 Application of the Model

In Beverly Swamp, this model was applied to the data from the Northeast, South and Confluence Sites (Fig. 4.3), the first site being representative of a "periodically effluent" regime and the last two of a "predominantly effluent" regime. Thus, the model can be appraised under both regime types

For Points NE2 and NE3 (Fig. 4.4 and 4.5), the model performed well using the mean values of specific yield and diffusivity that were field determined for the site (Table 2.3). The marked influent flow that



All symbols are defined in Eq. 4.1 and 4.2

Figure 4.2 Flow chart showing the computational procedure involved in the generation of water level data at a point in the swamp which is affected by a stream.

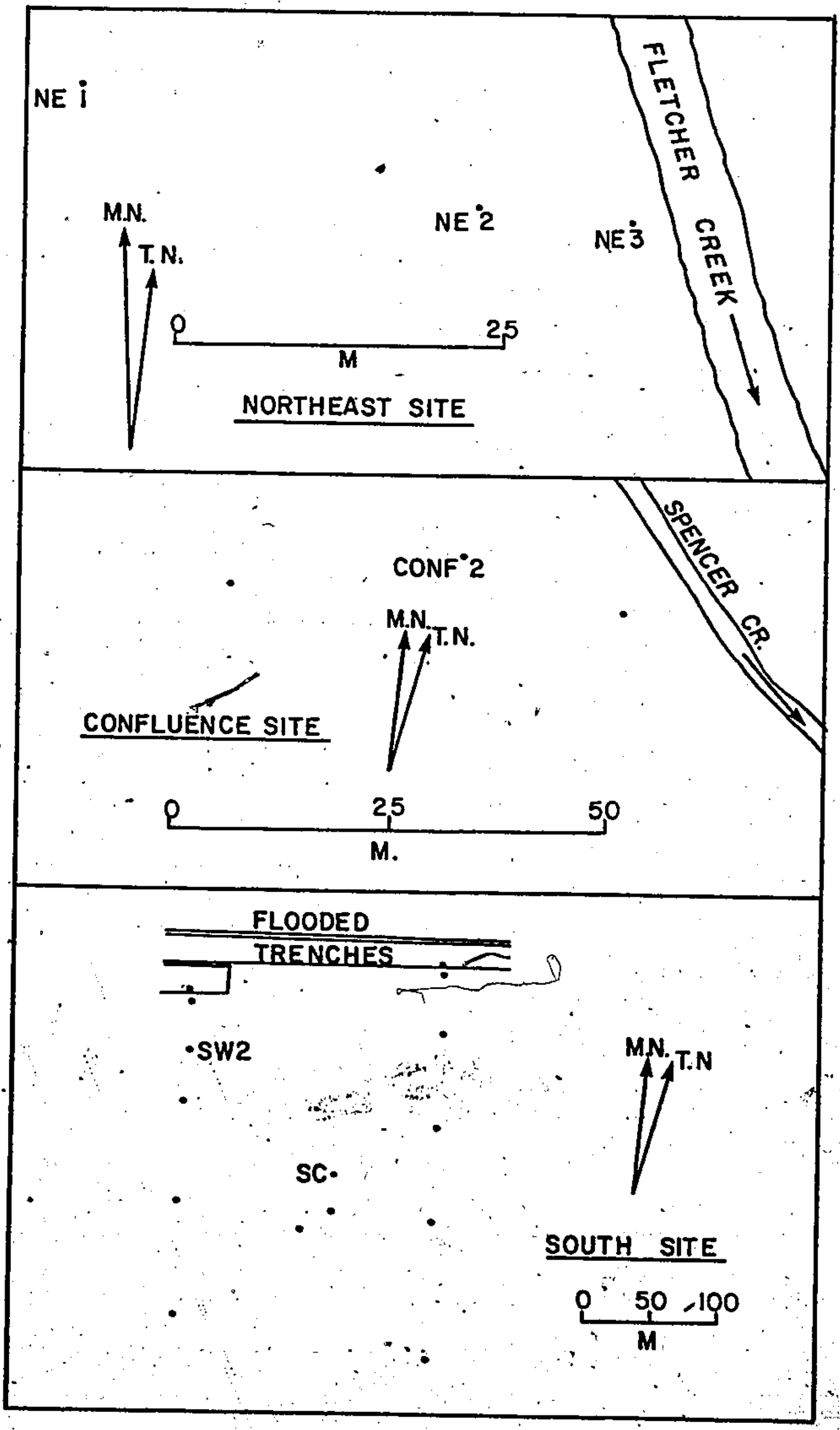


Figure 4.3 Sites used for the model.

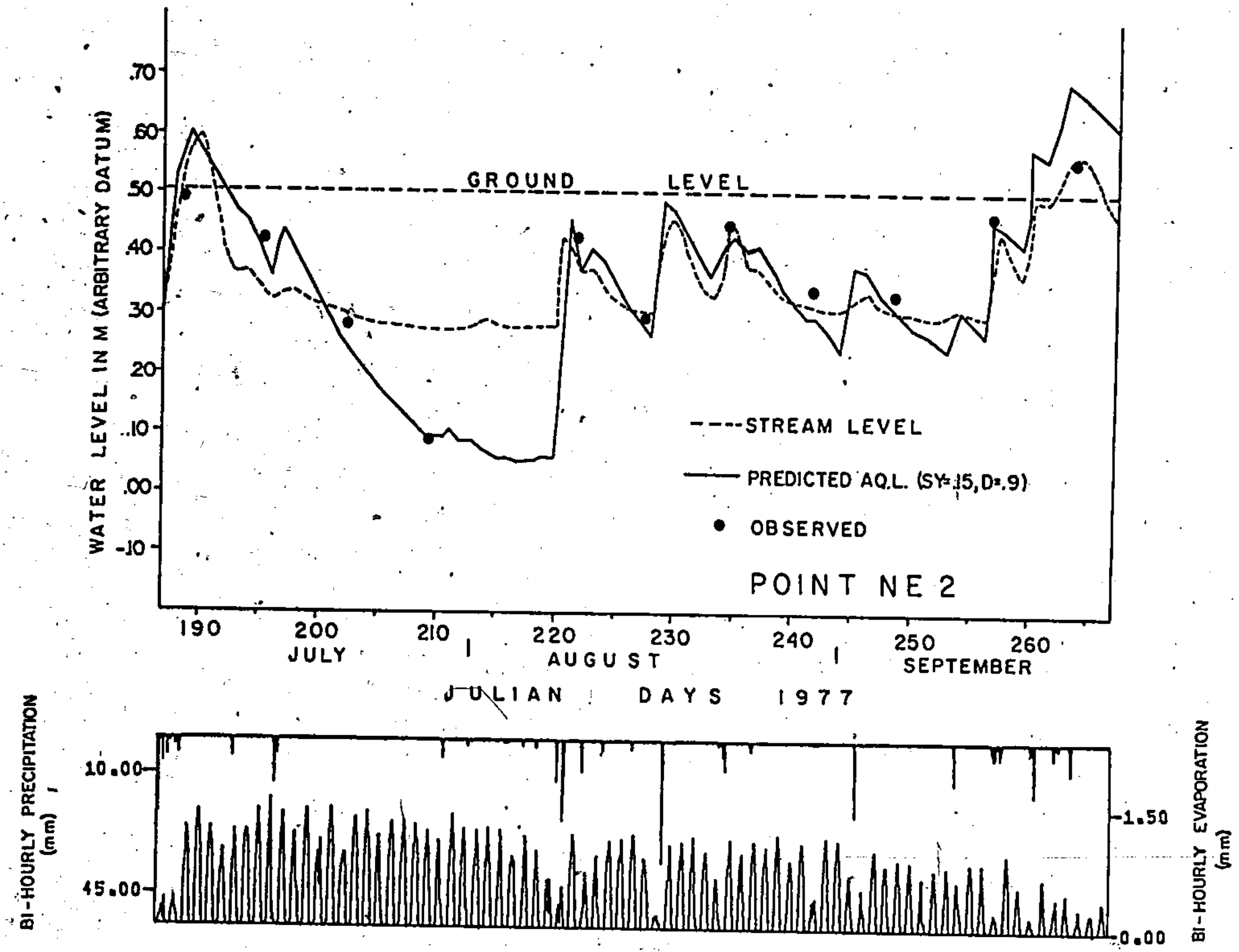


Figure 4.4 Performance of the model for Point NE2.

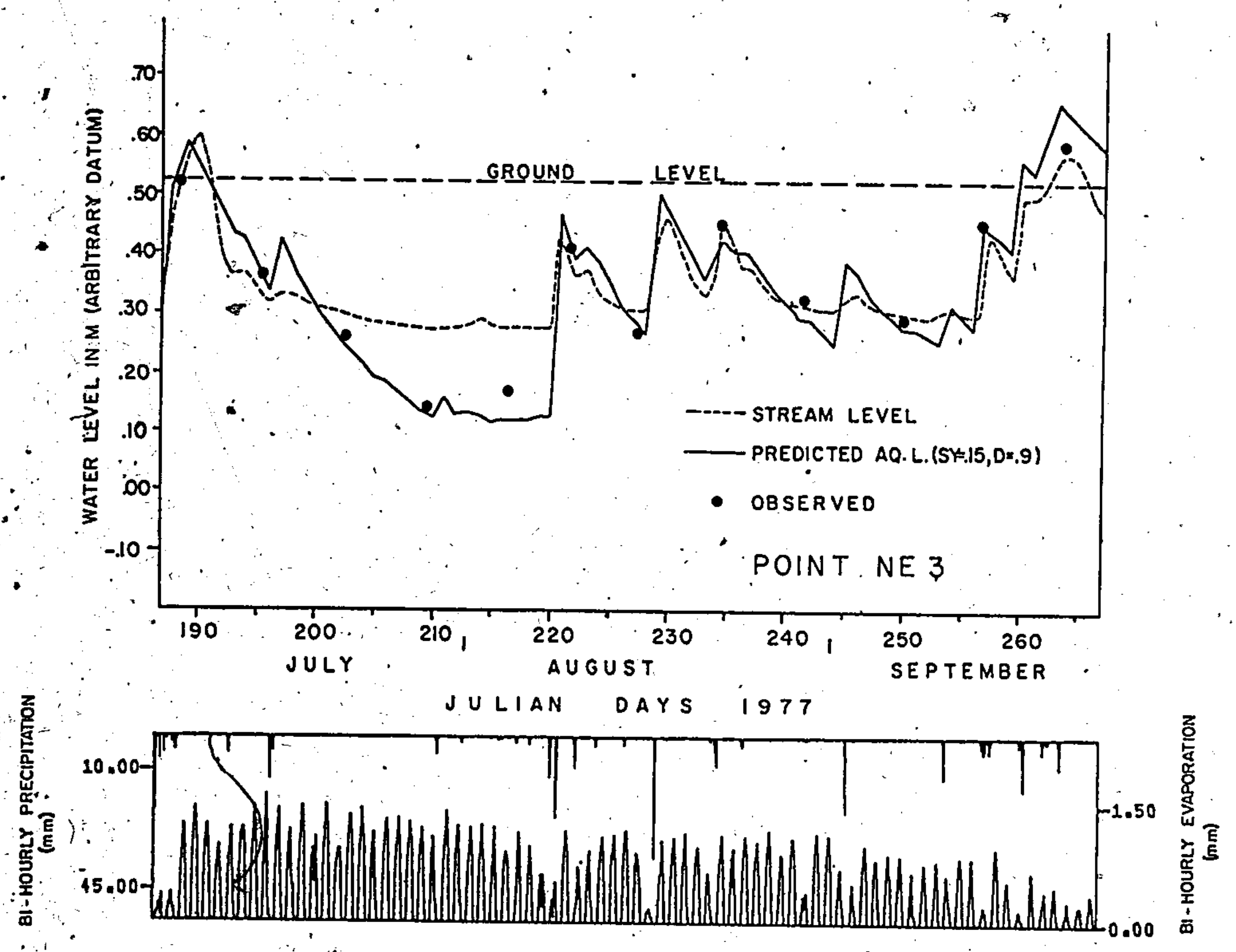


Figure 4.5 Performance of the model for Point NE3.

took place during the driest period of the summer is well predicted. High values are overestimated when the area was flooded because the actual specific yield changes to 100 percent. However, this is not crucial since when the swamp water levels rise above the ground surface, the levels at the study point can be satisfactorily predicted by setting them equal to those in the stream.'

Point NE1 (Fig. 4.6) was close to the edge of the swamp. The model performed well until the driest part of summer, after which the levels were underestimated. This may be caused by the assumption that the soil parameters were constant through space and through time. More detailed field data would provide an input of varying soil parameters into the model. Also, as for the previous two points, flood levels were overestimated.

For Point CONF 2 (Fig. 4.7), the model consistently underestimated the actual values. It is suggested that this is due to the fact that a substantial amount of lateral inflow has not been included in the model. This flow contribution was able to maintain in the aquifer higher levels than in cases where lateral inflow is minimal (such as at the Northeast Site). The model could be improved by inputting lateral inflow in the same manner as precipitation, although it might be difficult to estimate the magnitude of this flow.

For the South Site (Fig. 4.8), using the soil parameters obtained in the field ($Sy = .08$, $D = 8.9$), the predicted hydrographs underestimate the low values and overestimate the high ones. Since this site has a "predominantly effluent" regime, the same reasons as for the Confluence Site are offered to explain the underestimates. The overestimates, as

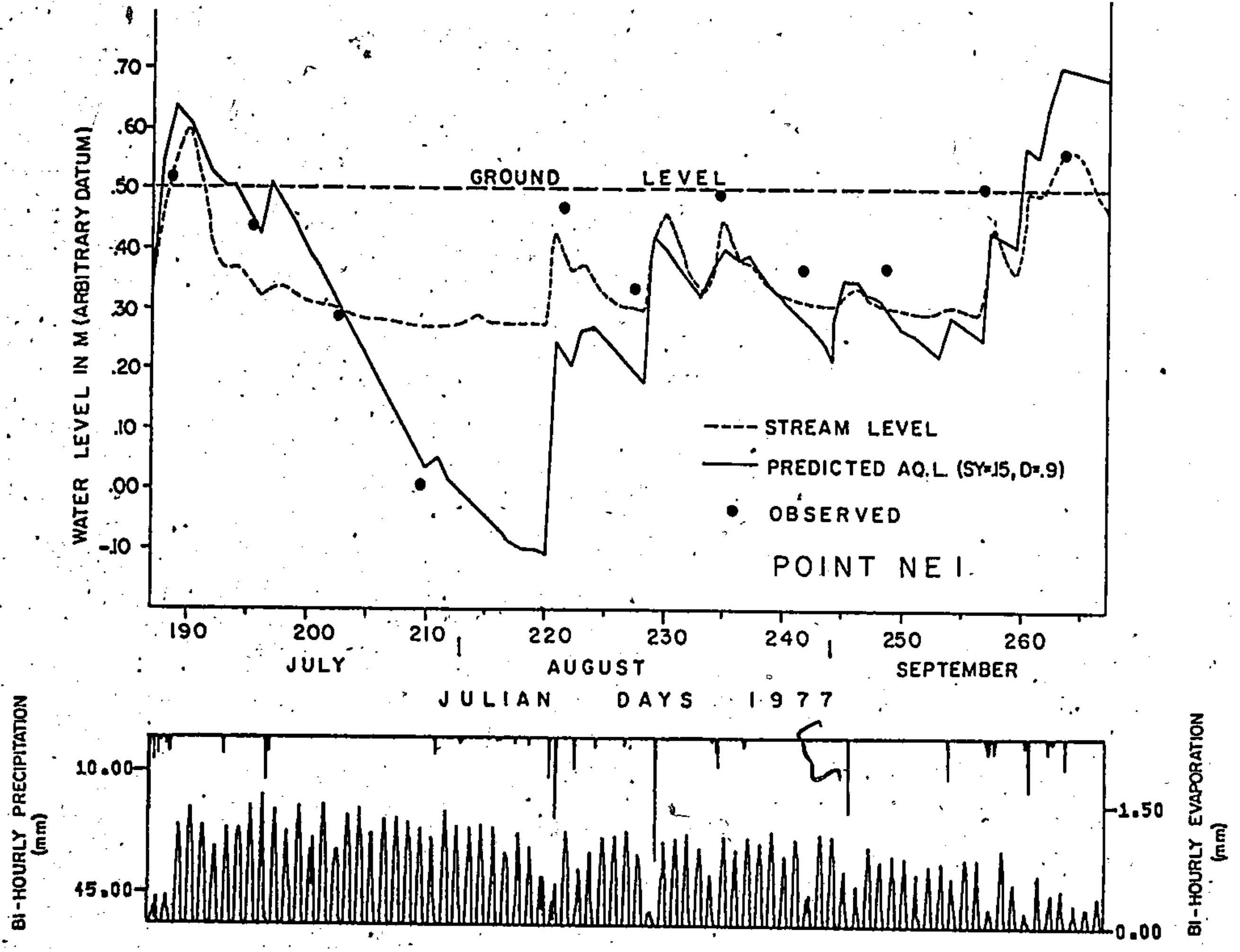


Figure 4.6 Performance of the model for Point NE1.

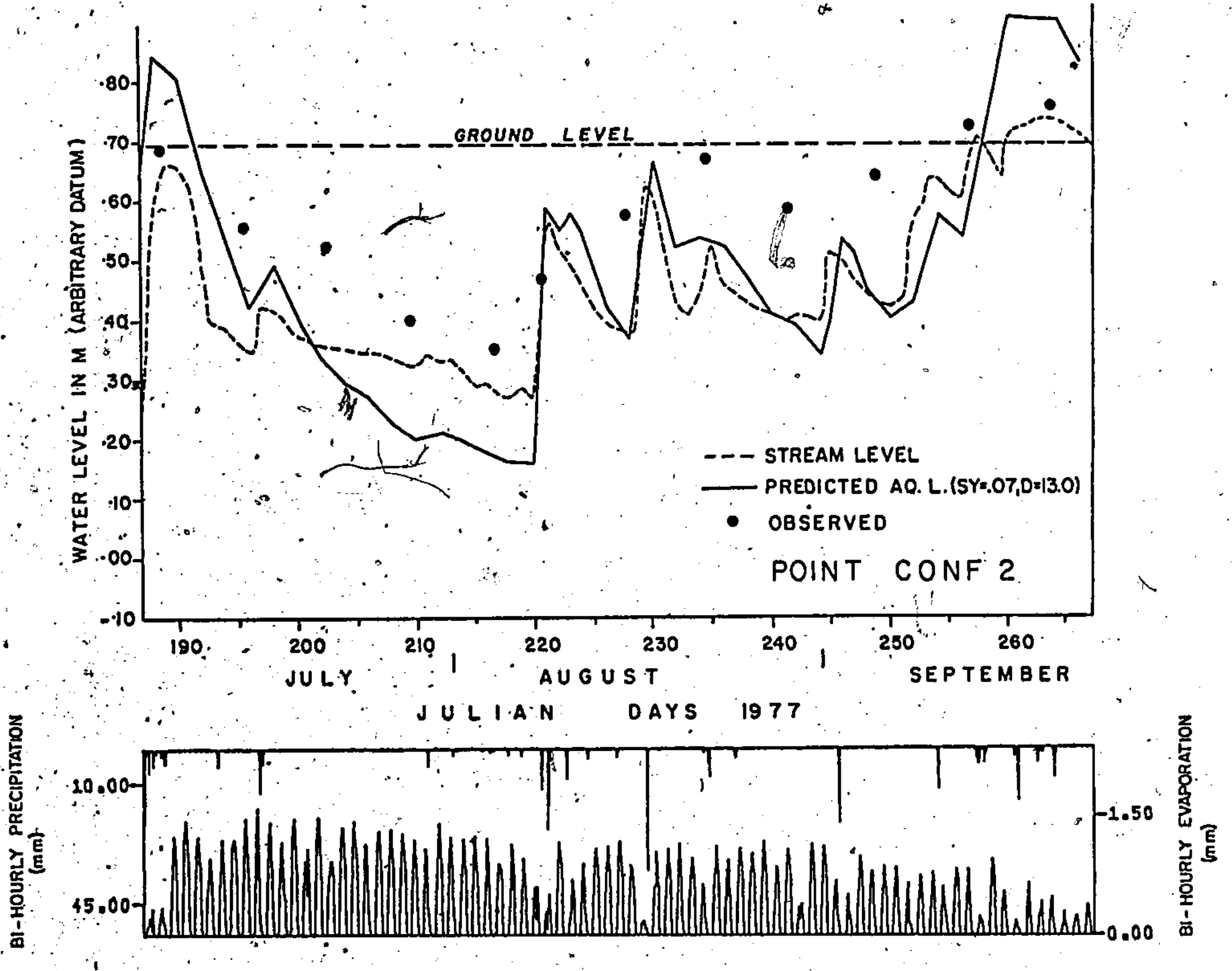


Figure 4.7 Performance of the model for Point CONF2.

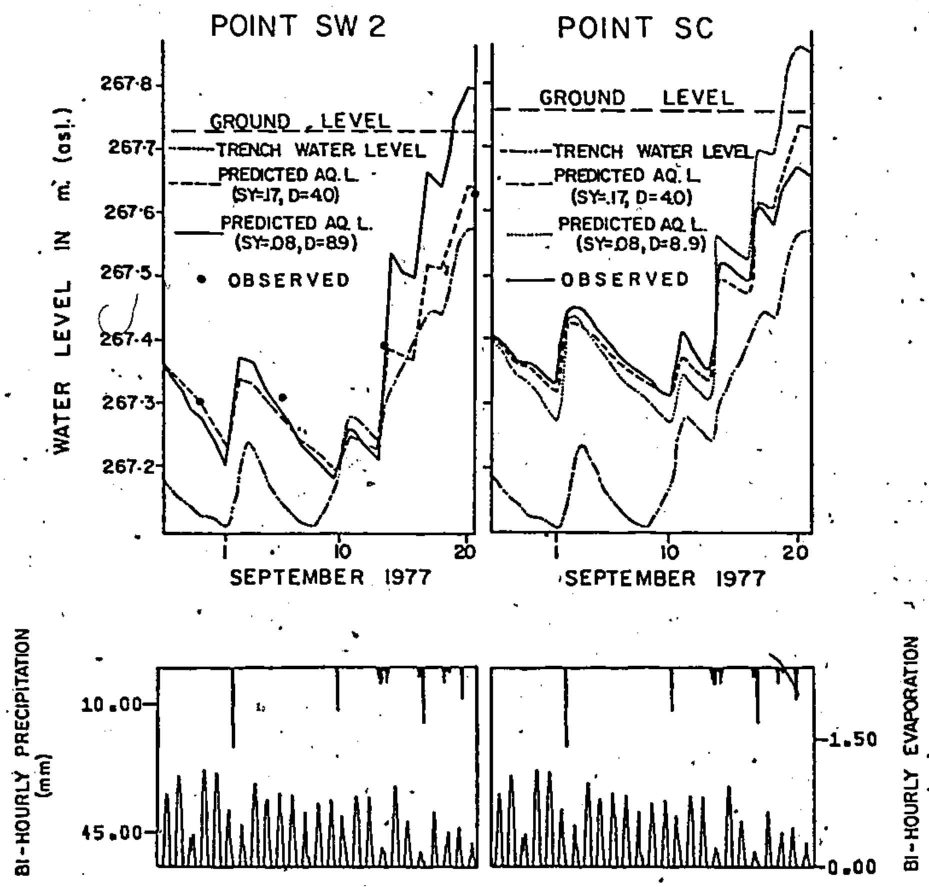


Figure 4.8 Performance of the model for Points SW2 and SC.

in all the other analyzed points, are due to an increase in the specific yield toward the upper peat layers. Using a parameter optimization procedure, a better fitted hydrograph was obtained using different soil parameters (Sy = .18, D = 4.0), as shown in Figure 4.8.

It is concluded, then, that this model, in its present state is adequate in predicting swamp water levels. However, its performance is superior when applied to "periodically effluent" regimes than when used for "predominantly effluent" ones. Given an increased amount of high quality field data, the suggested modifications would improve the performance of the model in both cases.

SUMMARY AND CONCLUSIONS

Intensive monitoring of several hydrologic variables of Beverly Swamp from April to November 1977, enabled a detailed analysis of the behaviour of the watertable.

The relationship between the water levels in an area of the swamp and the outflow from it, was analyzed at two time scales. At the seasonal scale, this relationship is non-linear, with a sharp increase in the responsiveness of the outflow when water levels were close to or above the ground level. This is attributed to a sudden change in soil conditions near the ground surface, thus influencing the flow characteristics. At another time scale, individual responses to storms or translating flood waves were analyzed, and the resulting stage versus discharge relationship showed two effects. The first one involves the fact that, as the watertable drops, there is a progressive increase in the travel time between the point at which the levels are measured and the outflow point. The other effect is that, for a given watertable elevation, its slope can be different depending on whether the stage is rising or falling. This in turn leads to different outflows for a given water level, and hence, a hysteresis on the stage versus discharge rating curves. Lagged rating curves that accounted for the first effect showed the consequences of the second one alone. This separation method is shown to be useful in studying the relationship between the water levels in an area of the swamp and the outflow from that area, and it sheds light on the nature and magnitude of the processes involved.

The water level regimes of the swamp are classified under two general types, according to the relationship between the streams and the aquifer. Streams flowing into the swamp impose their own regime on the surrounding aquifer, and the result is a "periodically effluent" regime with marked summertime influent flow. After flowing through the swamp for a distance, the watertable regime becomes "predominantly effluent". This regime is also associated with the area around a stream that originates at the swamp. In this case, stream levels are a result of the surrounding watertable, and the flow is effluent. This spatial analysis provides, then, a geographical approach to the study of swamp water level regimes, which was difficult to achieve by analyzing the water level records at single-points.

Stream level, evaporation and rainfall data were used in a numerical model which synthesizes the water level hydrographs at several sites in the swamp. This model worked better when applied to "predominantly effluent" ones because of the large amount of lateral inflow in the latter regime. However, the overall performance of the model is considered to be satisfactoy.

In view of the above mentioned relationships between the swamp outflow and the various hydrologic inputs, the runoff regulating capacity of the swamp can be assessed. When water levels are low, or when water inflows are flashy but of small volume, runoff attenuation is inversely proportional to the watertable elevation. However, runoff attenuation becomes minimal when swamp levels are high (such as after heavy storms or during the snowmelt period), or when stream inflows are of large volume or long duration. The regulation capacity is also low for streams crossing the swamp in well-defined channels. Hence, the runoff regulation capacity of the swamp is variable, depending on the mode of flow and on the general depth of the swamp's watertable.

APPENDIX I

Derivation of Equation 4.1

The derivation of Equation 4.1 is based on a heat flow analogue discussed in Carslaw and Jaeger (1959). In their linear flow model, the temperature v at a point x is a function of time t, such that

$$\frac{\partial^2 v}{\partial x^2} - \frac{1}{\kappa}\frac{\partial v}{\partial t} = 0, \quad a < x < b \qquad \text{(A.1)}$$

$$v = v_0(x), \quad t = 0, \quad a < x < b \qquad \text{(A.1.a)}$$

$$v = v_1(t), \quad x = a, \quad t > 0 \qquad \text{(A.1.b)}$$

$$v = v_2(t), \quad x = b, \quad t > 0 \qquad \text{(A.1.c)}$$

where

$$\kappa = \frac{K}{\rho c}$$

and

K is the thermal conductivity of the medium

ρ is the density of the medium

c is the specific heat of the medium

The equation of heat flow was solved by the Laplace transformation method, which gives

$$\int_0^\infty \exp(-pt)\,\frac{\partial^2 v}{\partial x^2}\,dt - \frac{1}{\kappa}\int_0^\infty \exp(-pt)\,\frac{\partial v}{\partial t}\,dt = 0 \tag{A.2}$$

yielding

$$\frac{d^2\bar{v}}{dx^2} - \frac{p}{\kappa}\bar{v} = -\frac{1}{\kappa}v_0(x), \quad a < x < b \tag{A.3}$$

For a semi-infinite region, and considering the initial temperature $v_0(x)$ to be zero,

$$\frac{d^2\bar{v}}{dx^2} - \frac{p}{\kappa}\bar{v} = 0, \quad x > 0 \tag{A.4}$$

Taking v, and thus $\bar{v}$, to be bounded as $x \to \infty$,

$$\bar{v} = \frac{V_0}{p}\exp(-\sqrt{p/\kappa})x \tag{A.5}$$

with the conditions

$$v = \phi(t), \quad x = 0, \quad t > 0$$

for the case where $\phi(t) = V_0$ is constant.

Carslaw and Jaeger then provided the following solution

$$v = V_0 \operatorname{erfc}\frac{x}{2\sqrt{\kappa t}} \tag{A.6}$$

The heat flow analogue was used by Pinder et al. (1969) to determine the response of a homogeneous isotropic aquifer to fluctuations in river stage. The stage hydrograph was approximated by a series of discrete steps as influenced by individual increments in river stage, solving the equation

$$\frac{\partial^2 h}{\partial x^2} = \frac{1}{D} \frac{\partial h}{\partial t} \qquad \text{(A.7)}$$

where

$$\Delta h(0,t) = \begin{cases} 0 & \text{when } t \leq 0 \\ \Delta L_i & \text{when } t > 0 \end{cases} \qquad \text{(A.7.a)}$$

$$\Delta h(x,0) = 0, \quad x \geq 0 \qquad \text{(A.7.b)}$$

(symbols defined in Equation 4.1 and 4.2).

For a semi-infite aquifer,

$$\Delta h(\infty, t) = 0 \qquad \text{(A.7.c)}$$

and the solution of Carslaw and Jaeger (Eq. A.6) was applicable, yielding

$$\Delta h_i = \Delta L_i \ \text{erfc} \ \frac{x}{2\sqrt{Di\Delta t}} \qquad \text{(A.8)}$$

(symbols defined in Equation 4.1)

To obtain the aquifer level at a distance x from a stream at time $n\Delta t$,

$$h_n = \sum_{i=1}^{n} [(\Delta L_i) \ \text{erfc} \ (\frac{x}{2\sqrt{D\Delta t(n-i)}})] \qquad \text{(A.9)}$$

which is equation 4.1.

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