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SOME INTERRELATIONSHIPS BETWEEN GROUND WATER AND SWAMP FORESTS IN THE WESTERN UPPER PENINSULA OF MICHIGAN

by

Donald Robert Satterlund

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan

1960

Doctoral Committee:

Professor Samuel A. Graham, Chairman
Professor Stephen H. Spurr
Professor Kenneth P. Davis
Associate Professor Erich E. Steiner
Associate Professor Robert Zahner

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This work was conducted on lands of the Ottawa National Forest with the kind permission of Victor Dayharsh, Forest Supervisor.

Donald R. Satterlund
October, 1959

TABLE OF CONTENTS

Chapter		Page
	ACKNOWLEDGEMENTS	ii
	LIST OF TABLES	v
	LIST OF FIGURES	vii
I	INTRODUCTION	1
	Review of previous work	2
	The locality studied	4
II	METHODS OF STUDY	7
	General considerations	7
	The water factor	9
	Soil characteristics	19
	Root characteristics	20
	Structure of forest stands	21
	Site quality and growth	21
III	ACTIONS OF GROUND WATER UPON THE FOREST	23
	Classification of swamps by water level characteristics	23
	Swamp soils	30
	Ground water and tree roots	32
	Root development in swamp type I-A	34
	Root development in swamp type I-B	44
	Root development in swamp type II-A	44
	Root development in swamp type II-B-1	54
	Root development in swamp type II-B-2	59
	Root development and redox potential	68
	Root development and seepage	68
	The moisture supply in the root zone	72
	Quantity	72
	Distribution	7[illegible]
	Nutrients in ground water	82
	Ground water and forest composition	84
	Ground water and forest growth	94
	Site quality	95
	Annual radial growth and water levels	100
	Effects of ground water modified by micro-relief	114
	Indirect influences of ground water	115
	Wind	115
	Fire	117
	Insects	118
	Disease	118

Page

Chapter

IV REACTIONS OF SWAMP FORESTS UPON GROUND WATER 120
Interception 120
Evapo-transpiration 123
Evaporation from the soil 139
Evapo-transpiration by swamp types 143
Water storage in swamp forests 144

V SUMMARY AND CONCLUSIONS 147
Suggestions for future research 156

LITERATURE CITED 160

APPENDIX A 167

APPENDIX B 169

LIST OF TABLES

Table		Page
1	Fluctuations of water level following precipitation in a source area (CC-2) and a reception area (CC-1) of seepage stormflow	28
2	Swamp soil development in relation to ground water characteristics	31
3	Relation of redox potential of ground waters to state of decomposition of organic soil and location in swamp	33
4	Characteristics of sample plots in swamps with a shallow, essentially stable water level (Type I-A)	35
5	Root development on plots characterized by persistent high water levels in relation to rate of seepage	69
6	Variation in soil moisture content by depth in swamp soils influenced by ground water - summer of 1957	81
7	Specific conductance of ground water on swamp plots	83
8	Composition of swamp forests where water level is shallow and stable	85
9	Species composition of swamp forests by height class. Water level shallow and stable	86
10	Composition of swamp forests where water levels are shallow and stable in spring, and thereafter fluctuate with precipitation	88
11	Species composition of swamp forests by height class. Water levels shallow and stable in spring, and thereafter fluctuate with precipitation	89
12	Composition of swamp forests where water level fluctuates directly with precipitation	90
13	Species composition of swamp forests by height class. Water level fluctuates directly with precipitation	91

Table		Page
14	Composition of swamp forests where high water levels are always deeper than 18 inches from soil surface	92
15	Species composition of swamp forests by height class. Water levels always lower than 18 inches from soil surface	93
16	Site index of spruce and fir as related to site characteristics in swamp forests of western upper Michigan	96
17	Relation of tree crown development to position of the tree with respect to micro-relief features	116
18	Moisture use from the soil layer above the water table. Plot CC-1, summer of 1957	131
19	A comparison of factors affecting water use in 1956 with those of June 18 - July 5, July 13-16 and 22-23, 1957 at plot CC-1	134
20	Water loss in Cedar Creek Swamp from trenched and untrenched plots and a standard U. S. Weather Bureau evaporation pan during selected periods in 1957	140

LIST OF FIGURES

Figure		Page
1	Map of study area	5
2	Diagram of apparatus used to measure seepage flow	11
3	Hydrograph of ground water level at well CC-1, July 27 to August 3, 1956	13
4	Method of estimating transpiration from ground water levels	15
5	Water level types in different swamps during 1957	25
6	Soil profile and root distribution, plot E-1	36
7	Soil profile and root distribution, plot P-3	36
8	Soil profile and root distribution, plot C-1	37
9	Soil profile and root distribution, plot C-2	37
10	Soil profile and root distribution, plot C-3	38
11	Soil profile and root distribution, plot C-4	38
12	Soil profile and root distribution, plot P-2	40
13	Soil profile and root distribution, plot C-5	40
14	Mean root density in relation to water levels, organic soils, swamp type I-A	41
15	Mean cross-sectional area of roots in relation to water levels, organic soils, swamp type I-A	41
16	Vertical penetration and form of balsam fir roots in type I-A swamps	43
17	Vertical penetration and form of white spruce roots in type I-A swamps	45
18	Vertical penetration and form of black ash roots in a type I-A swamp	45

Figure		Page
19	Soil profile and root distribution, plot P-1	46
20	Soil profile and root distribution, plot CC-1	48
21	Soil profile and root distribution, plot E-3	48
22	Vertical penetration and form of hard maple roots in type II-A swamps	50
23	Vertical penetration and form of white cedar roots in type II-A swamps	51
24	Vertical penetration and form of hemlock roots in type II-A swamps	52
25	Vertical penetration and form of yellow birch roots in type II-A swamps	53
26	Vertical penetration and form of black spruce roots in type II-A swamps	53
27	Vertical penetration and form of balsam fir roots in type II-A swamps	55
28	Vertical penetration and form of white spruce roots in a type II-A swamp	55
29	Vertical penetration and form of red maple roots in a type II-A swamp	56
30	Soil profile and root distribution, plot E-2	56
31	Soil profile and root distribution, plot U-2	57
32	Vertical penetration and form of white cedar roots in a type II-B-1 swamp	60
33	Vertical penetration and form of tag alder roots in a type II-B-1 swamp	60
34	Soil profile and root distribution, plot U-1	61
35	Soil profile and root distribution, plot P-4	62
36	Soil profile and root distribution, plot CC-2	63
37	Vertical penetration and form of balsam fir roots on upland and swamp border, type II-B-2	65

Figure		Page
38	Vertical penetration and form of yellow birch roots in a type II-B-2 swamp	66
39	Vertical penetration and form of red maple roots in a type II-B-2 swamp	66
40	Vertical penetration and form of hard maple roots on upland and swamp border, type II-B-2	67
41	The relation between redox potential and rate of ground water seepage in several swamps	71
42	Mean soil moisture storage deficit in relation to water levels in type I-A swamps, summer of 1957	74
43	Soil moisture storage deficit in relation to water level in a type I-B swamp, summer of 1957	75
44	Mean soil moisture storage deficit in relation to water levels in type II-A swamps, summer of 1957	77
45	Soil moisture storage deficit in relation to water level in a type II-B-1 swamp, summer of 1957	78
46	Mean soil moisture storage deficit in relation to water levels in type II-B-2 swamps, summer of 1957	79
47	Site index of spruce-fir in relation to water level types	98
48	Site index of spruce-fir in relation to redox potentials of ground water	98
49	Relationship between site index of spruce-fir and white cedar where they are associates on the same swamp plots	101
50	Rating curve of fall of water level at plot CC-1 by days since last rain exceeding 0.25 inch	103
51	Rise of water level at plot CC-1 in relation to amount of precipitation received in the preceding 24 hours ...	104
52	Relationship between daily precipitation at Cedar Creek swamp and Stambaugh, Michigan during the summers of 1956 and 1957	106
53	Relationship between calculated and measured water levels, plot CC-1, summers of 1956 and 1957	106

Figure		Page
54	Relationship between water levels at plot CC-1 and in swamps of various water level types studied	109
55	Relationship between annual radial growth of conifers in type I-A swamps and water level indices, 1930-1957	111
56	Relationship between annual radial growth of conifers in type II-A swamps and water level indices, 1930-1957	111
57	Relationship between annual radial growth of conifers in type II-B-1 swamps and water level indices, 1930-1957	112
58	Relationship between annual radial growth of conifers in type I-B swamps and water level indices, 1930-1957	112
59	Relationship between annual radial growth of conifers in type II-B-2 swamps and water level indices, 1930-1957	113
60	Interception of rainfall by the forest at plot CC-1 as related to storm size, summers of 1956 and 1957	121
61	Ground water levels and use at plot CC-1 in part of 1956 and 1957	125
62	Daily ground water use at plot CC-1 as related to water levels, summer of 1956 and 1957	126
63	Cumulative water use by source at plot CC-1, summers of 1956 and 1957	136
64	Cumulative evapo-transpiration in Cedar Creek swamp and evaporation from a nearby standard U. S. Weather Bureau pan during the growing season of 1957	138
65	Soil moisture storage deficits in trenched and untrenched subplots, plot CC-1, summer of 1957	142

CHAPTER I

INTRODUCTION

A swamp forest is one in which a high water table affects the tree roots during a part or all of the growing season. These effects may be either adverse or beneficial to the trees. Ground water may restrict root development, respiration of the roots, and the rate of decomposition of organic materials; or it may benefit the trees by providing a supply of water in addition to rainfall.

Although no quantitive data are available to show the relative proportion of upland and swamp forests in the northern Lake States, observations indicate that at least 10 per cent of the forest land would fall into the swamp category.

These swamp forests range in character from poorly stocked, slow growing spruce and tamarack bog forests to well stocked, vigorous stands of several types growing on mineral soils. Their value for the production of timber and wildlife is commensurate with their range in character. In the Lake States, the influence of swamp forests upon the ground water has not been clearly defined.

Swamp forests have been the subject of considerable research. The results, however, have not always been in agreement, perhaps because differences between swamp types were not clearly recognized.

The research upon which this dissertation is based was undertaken with the idea that the position, movement, and other character-

istics of ground water might help to explain differences in composition and site quality of swamp forests as well as the influence of swamp forests upon the ground water.

Review of previous work

Although there has been no work published which specifically attempts to cover the complex interrelationships between ground water and swamp forests in a comprehensive way, there is a considerable amount of literature which bears directly upon several major aspects of the problem.

The influence of water levels upon swamp forest quality and composition varies. A very high water table, less than two feet from the surface throughout most of the year, often has a deleterious effect upon forest growth. When well aerated, however, conditions for plant growth are improved (Hesselman, 1910; Bergman, 1920; Wilde, 1933; Conway, 1940; Lutz and Chandler, 1946; Tamm, 1950; Spurr, 1952; Wilde et al., 1954; Troedsson, 1955). In addition, lateral water movement has been thought to favor forest growth through enrichment of the water by oxygen, removal of toxic materials and by supplying nutrients to plant roots (Harlow, 1927, Bruckner, 1932; Donahue, 1940; Tamm, 1950; Troedsson, 1952, 1955; Rutter, 1955). Substantiating data of a definitive nature on water movement, however, are largely lacking.

Deeper water levels, which are from two to five feet below the soil surface are generally believed to favor forest growth (Wilde, 1933; Stoeckler and Sump, 1940; Chandler et al., 1943; Stoeckler, 1948; Wilde and Pronin, 1950; Spurr, 1952, 1955; Wilde et al., 1954;

Thames et al., 1955). Water tables which lie deeper than five feet from the soil surface are not considered in this paper, as they seldom occur in swamps except in periods of extreme drouth.

In addition to the depth of water table, degree of aeration, and amount of lateral movement of the ground water, the concentration of dissolved nutrient ions in the ground water may influence forest growth (Pierce, 1953; Troedsson, 1952, 1955). The effect of the latter, however, may be difficult or impossible to assess (Gorham, 1956; Gorham and Pearsall, 1956).

The reactions of the forest upon the ground water situation are likewise significant, modifying its effects upon the forest in several ways. For example, the forest tends to reduce extremes of both high and low water levels by creating soil conditions conducive to rapid infiltration of precipitation so it is released to streamflow more slowly. The forest also intercepts precipitation and transpires vast amounts of water, thus depleting the supply of soil moisture above the water table and lowering the level of the ground water. On the other hand, it reduces evaporation of water from the soil, and by protecting it from erosion enhances desirable conditions (Zon, 1927; Kittredge, 1948; Lassen et al., 1952; Colman, 1953; and many others). However, these influences have seldom been investigated as they apply to swamps.

The coactions within the swamp biota which result in the development of a forest community of specific composition and quality have been related to the actions and reactions mentioned in the previous paragraphs only in general terms (Weaver and Clements, 1938).

In addition to work bearing directly on interrelationships between ground water and swamp forests, a vast amount of knowledge has

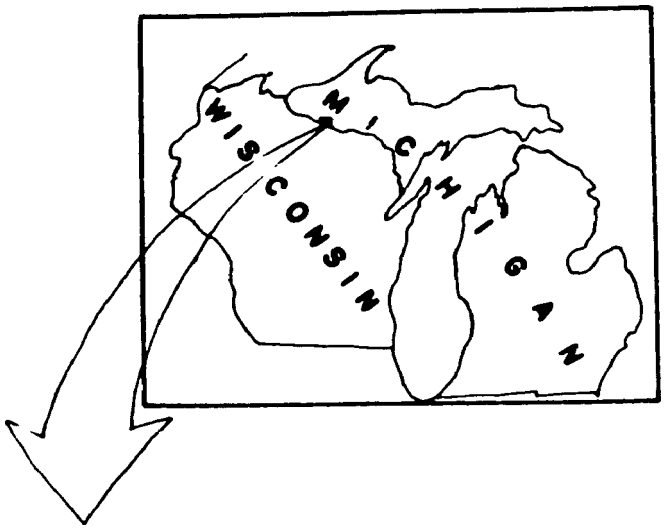
been collected in cognate fields; plant physiology, hydrology, geology, limnology, ecology and forestry. It is, however, beyond the scope of this paper to review all this literature. Instead, when published information from these fields is drawn upon in the development of this dissertation, references will be cited.

The locality studied

This dissertation is based upon field work conducted in the Ottawa National Forest, in the western end of the Upper Peninsula of Michigan. Plots were located in Iron and Gogebic counties, which lie adjacent to the northern border of Wisconsin (Figure 1).

The western half of Michigan's upper peninsula varies from level to almost mountainous upland. Lands in western Iron county and eastern Gogebic county are moderately rolling uplands, with elevations ranging from 1500 to nearly 1800 feet above sea level. They are underlain by acid igneous and metamorphic rocks. The region is rich in minerals, particularly iron. A thick mantle of glacial drift, deposited during the repeated glaciations of the Pleistocene epoch covers this base rock. Few rock outcrops are found. The drift was apparently derived from the underlying material and similar rock formations to the north.

The last advance of the glacier probably occured during the Valders substage in late Wisconsin time. There is doubt concerning the exact location of the southern border of the ice sheet during the last advance in the locality studied, but it is believed to have reached near the northern boundary of Wisconsin (Zumberge, 1956). The Valders ice sheet melted less than 11,000 years ago. Thus geologically, the terrain is youthful, with poorly developed drainage and numerous lakes and swamps.



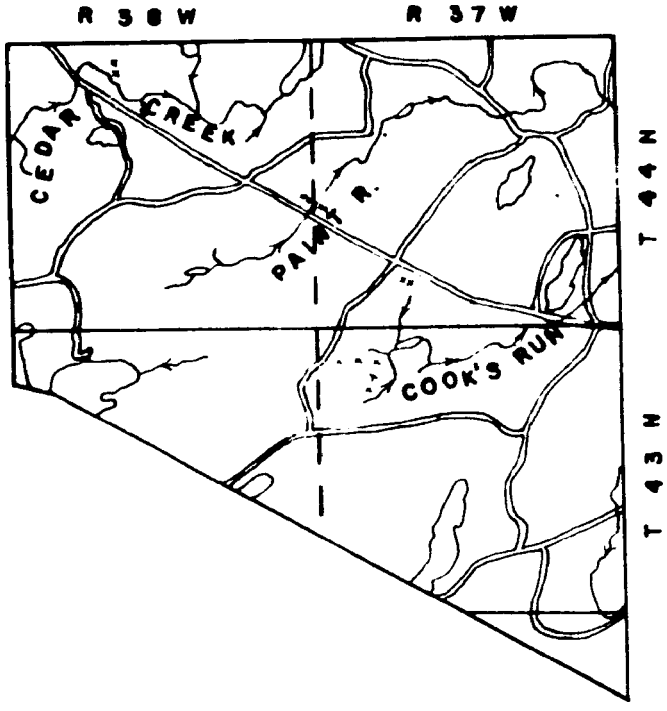


FIGURE 1. Map of study area. Each plot marked by x.

The soils on the uplands, however, exhibit well developed profiles of both the true podzol and grey-brown podzolic groups. The sandy soils are mostly podzols, and are covered with a variety of forest types ranging from intolerant aspen, birch and pine to hardwood-hemlock. The heavier soils are mostly grey-brown podzolics, predominantly occupied by the northern hardwood-hemlock type.

Swamp soils are extremely variable, ranging from wet mineral soils to organic soils differing considerably in composition and in depth.

The climate of the area is humid and cool. The mean annual precipitation is 31.5 inches, two-thirds falling from May through October in the form of frequent rains. The remainder falls mostly as winter snow. The ground is usually snow covered from mid-November until mid-April. The mean annual temperature of the area is 40.8° F., that of the hottest month, July, being 66.8° F., and that of the coldest month, January, being 14.8° F. Extreme temperatures have ranged from 103° F. in the summer to -40° F. in the winter. However, maximum temperatures exceeding 90° F. usually do not occur on more than four or five days during the summer. Frost may be expected during any month of the year except July, but the usual frost free season in the swamps is about 85 days (U. S. Weather Bureau, 1930-1957).

CHAPTER II

METHODS OF STUDY

General considerations

Despite the fact that all swamp forests are characterized by conditions of excess water for greater or lesser periods throughout the year, they are not uniform in terms of species composition, quality or productivity. Therefore an understanding of the variations in the swamp environment may help to explain differences in the character of the forests thereon.

In the review of past work it was indicated that several characteristics of ground water may have important influences upon the forest, among them the level of the ground water. The water level in any given swamp, however, is controlled in large degree by the prevailing weather, so water levels must be related to weather phenomena during the period of investigation.

Although ground water may influence the germination and establishment of forest trees in swamps, it acts upon the established tree mainly through its actions on tree roots. The effect may be modified by soil characteristics. Several characteristics of the ground water such as water levels, degree of stagnation, rate of seepage and nutrient content may be important in this respect. Equally important are the abilities of individual tree species to adapt themselves successfully

to varying ground water conditions. These adaptations may be of the nature of the development of a strong root system in a wet environment, capable of withstanding either long periods of submersion or rapid reductions in water levels.

In order to discover some of the interrelationships between swamp forests and ground water, sixteen one-tenth acre plots were laid out in five different swamps which exhibited noticeable differences in the character and quality of the swamp forest. A wide range of forest sites ranging from a non-commercial spruce-tamarack bog to the transition zone between mixed-conifer swamps and upland northern hardwoods were sampled, including soil types ranging from raw moss peat through wood peats and mucks to wet mineral soils. The following factors were investigated on each plot.

1. The depth of the water table.
2. The "freshness" of the ground water.
3. The rate of lateral movement (seepage) of the water.
4. The total base nutrient content of the ground water.
5. Soil moisture and temperature above the water table.
6. The soil profile.
7. Root penetration and distribution of the stand.
8. The structure of the forest stand.
9. Site quality.
10. Annual radial growth.

In addition, a weather station was set up in a forest opening in Sec. 9, T. 44 N., R. 38 W., Gogebic county, Michigan near swamp plot CC-1, where an investigation of interception of precipitation and transpiration and evaporation in the swamp forest was conducted.

A description of the methods used to measure the above factors follows.

The water factor

1. Weather.- Observations of the weather were taken at least twice weekly at the weather station set up in the forest opening. They consisted of the measurement of rainfall in a standard rain gage after every storm, measurement of evaporation from a standard U. S. Weather Bureau evaporation pan located near the rain gage, and maximum and minimum temperatures which occurred in the intervening period. During the season of 1957, a hygrothermograph was operated at the weather station.

2. Water levels.- Water levels were measured in observation wells located on each plot. A wooden scale was used to measure the water level below a reference point at the top of the well pipe. Displacement of the water level upward by the insertion of the rule was minimized by inserting the rule only to the depth necessary to establish a water mark.

A Leupold and Stevens model "F" water level recorder was installed at the well located in Cedar Creek Swamp near the weather station. A continuous record of the water levels in well CC-1 was thus obtained for the periods from July 5, 1956 to September 5, 1956 and from May 10, 1957 to October 1, 1957.

3. "Freshness" of the ground water.- The freshness of the water was measured by means of its oxidation-reduction potential, hereafter referred to as redox potential. The redox potential is expressed in millivolts of current at a given pH. It is a function of the

logarithm of the ratio of reduced to oxidised products in the saturated soil. The redox potential is much more sensitive as a measure of the oxidizing power of the water than the content of dissolved oxygen, according to Conway (1940). A Beckman model N pH meter was used for this measurement following the method used by Pearsall (1938) in moist soils.

4. Lateral movement of the ground water.- The movement of ground water was measured using common table salt using the method developed by Slichter (1905). Two wells were driven along the course of water movement and the apparatus, consisting of wire leads, an electrode, batteries and a milliammeter, was set up as shown in figure 2. The procedure was as follows.

First the normal conductivity of the ground water was measured and recorded. Then salt was placed in the upper well, and the time of insertion recorded. Thereafter, readings of conductivity were taken at frequent intervals, recording both the time and the ammeter reading, until a rise in conductivity showed that water containing salt had reached the lower well. The length of time required for the salt to reach the lower well, divided by the distance between the two wells was the rate of water movement. The rate of movement measured by this method was that of the most rapidly moving thread between the two wells.

5. Total base nutrient content of the ground water.- According to Pierce (1953), the degree of enrichment of the ground water in nutrient elements, particularly bases, is reflected directly in the specific conductance of the ground water. Troedsson (1952, 1955) found that the specific conductance is almost constant in any given area

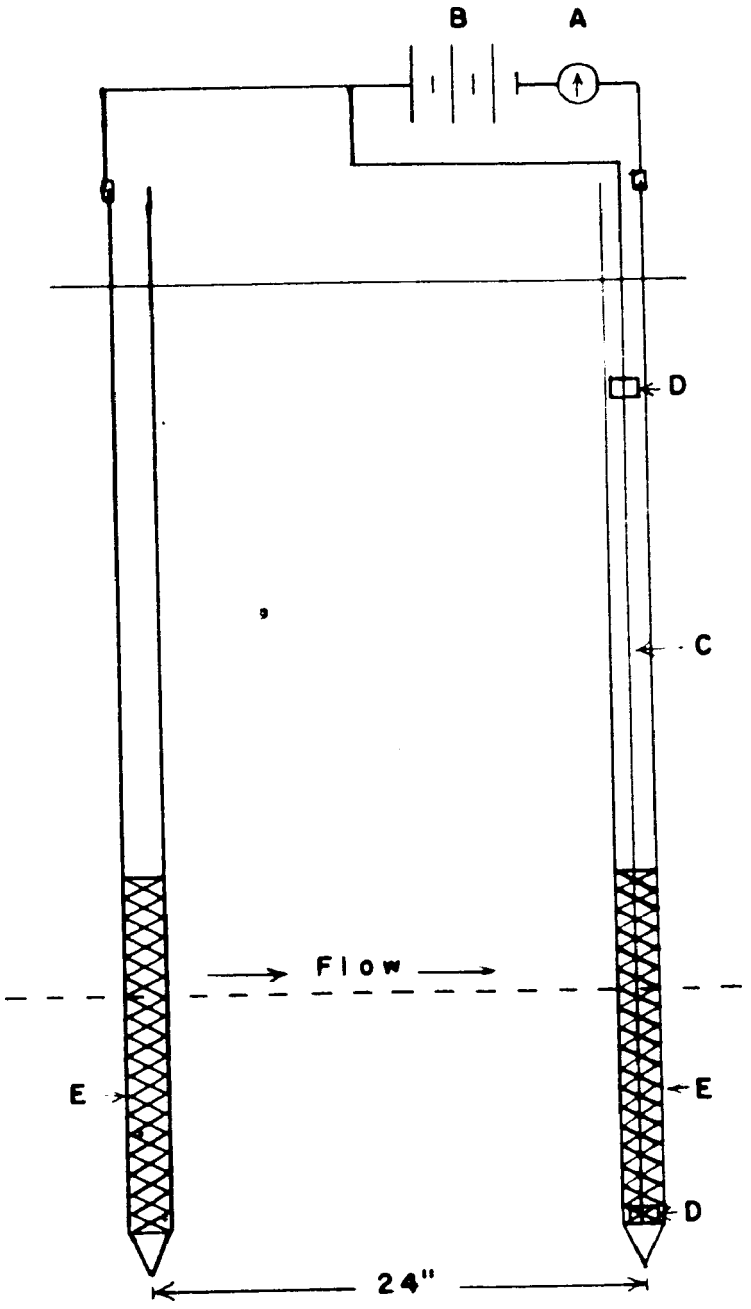


FIGURE 2. Diagram of apparatus used to measure seepage flow. A- Ammeter, B- Batteries, C- Electrode, D- Insulator, E- Well point.

throughout the year, and postulated that this is the direct result of the attainment of an ionic equilibrium between the ground water and the available solutes in the aquifer through which it flows. Therefore, the specific conductivity of the ground water was used as a measure of its total nutrient content. It was measured by the use of an Industrial Instruments Co. resistivity bridge.

6. Interception of precipitation.- Four rain gages, 3 inches in diameter, were placed on swamp forest plot CC-1 near the weather station. The precipitation was measured after each rain in all gages, and the four small gages moved to a new location within the plot. The average of all catches in the four small gages subtracted from the catch in the standard gage indicated the amount of interception by the forest canopy. No measure of stemflow was obtained.

7. Evaporation and transpiration from the ground water.- An examination of the hydrograph obtained from the water level recorder located in Cedar Creek Swamp revealed that regular diurnal fluctuations in the water level took place. Such fluctuations have been observed by other investigators, and methods of analyzing them to determine the daily amount of evaporation and transpiration, collectively termed evapo-transpiration, have been presented by Kittredge (1948). A modification of these methods, described below, was developed to analyze the fluctuations recorded on the hydrograph in terms of daily evapo-transpiration.

The water levels in a forested swamp, as indicated by the hydrograph, exhibit a characteristic daily rhythm; ie., a marked fall during the day and early evening, and a slower fall or even a rise during the night and early morning (Figure 3). It is assumed that

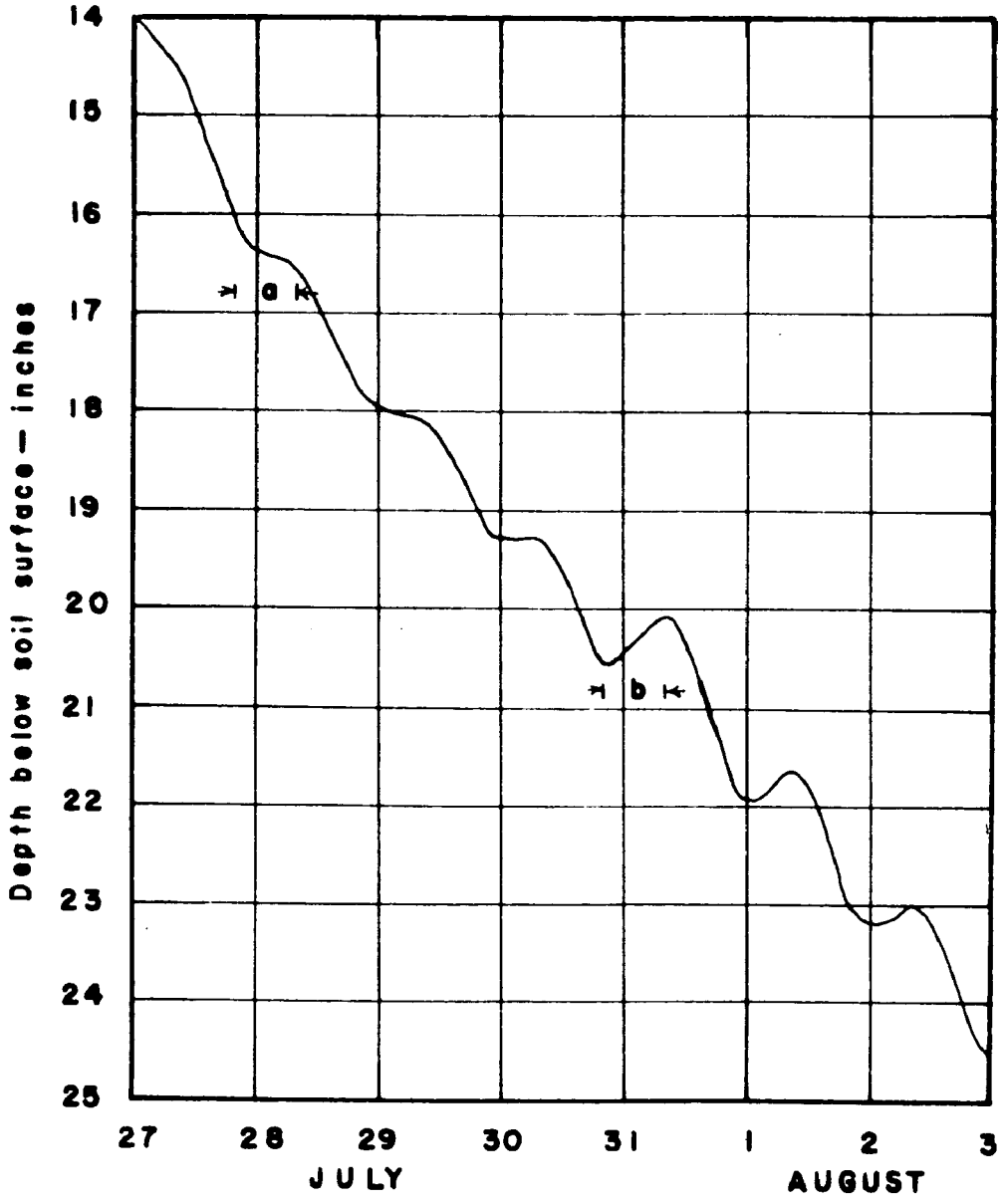


FIGURE 3, Hydrograph of ground water level at well CC-1, July 27 to August 3, 1956. a - negative recharge, b - positive recharge.

this fluctuation is due to the loss of ground water by evapo-transpiration during the daylight hours, and to the recharge of the ground water during the night when evapo-transpiration is negligible. Recharge may be either positive or negative; positive if the rate of seepage into the area exceeds the rate of seepage out of the area, thus causing the water level to rise, or negative when the rate of seepage into the area is exceeded by the discharge or rate of seepage out of the area, indicated by a continued fall in water level.

Since evapo-transpiration is negligible at night, the slope of the hydrograph during the period between midnight and dawn is a direct expression of the rate of recharge. A straight line extension of this slope for a period of 24 hours represents the position the water level would assume if evapo-transpiration were eliminated and the recharge rate maintained. (Line R_1 in figure 4.) During the daylight hours, however, evapo-transpiration occurs at a rate which usually exceeds the rate of recharge. The combined effects of evapo-transpiration and recharge result in the diurnal rhythm previously described, with the actual water level being somewhat lower than the potential water level would be in the absence of evapo-transpiration. The difference between the actual and potential level represents the fall in water level due to evapo-transpiration. (Line T_1 in figure 4.)

However, when the slope of each daily period of recharge is extended, it can be seen that the recharge rate often changes during the period of evapo-transpiration. In order to correct for this change in rate of recharge, the slope of the recharge rate the night following is extended backward to represent the potential position of the water

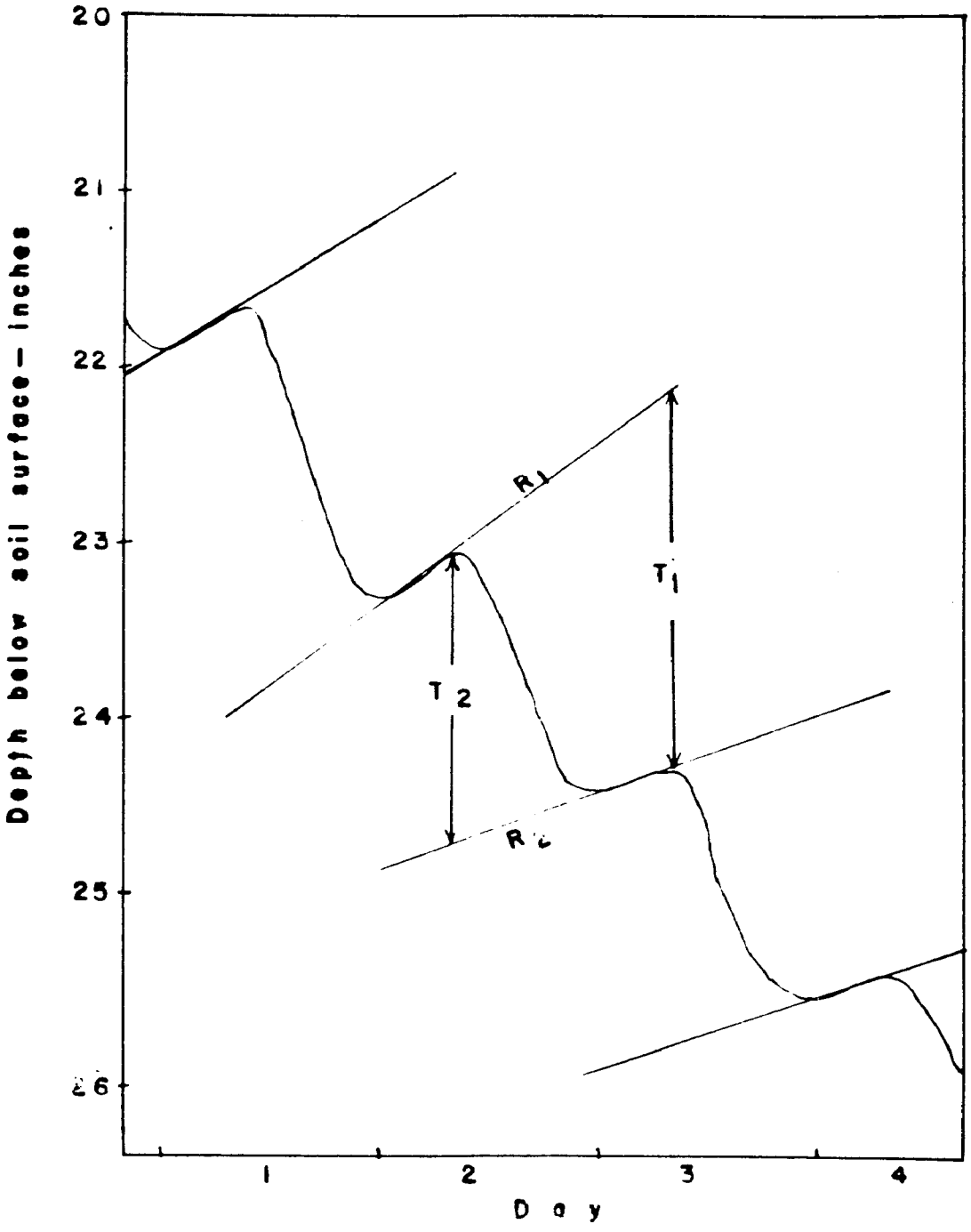


FIGURE 4. Method of estimating transpiration from ground water levels. See text for explanation.

table 24 hours earlier. The difference between this level and the actual level 24 hours earlier represents the amount of fall in water level due to evapo-transpiration during the day at the different rate of recharge. (Line T_2 in figure 4.) Assuming the change in recharge rate is constant during the intervening period, an average of the differences represents the amount of fall in water level due to evapo-transpiration during the day, corrected for the change in recharge rate which occurred during the same period.

The distance the water level falls, however, does not represent the actual depth of water removed from the soil, as only the water which drains freely from the pores in the soil immediately above the water table is removed when the water level falls. This amount of water which the soil will yield under the influence of gravity is the specific yield of the aquifer, and must be determined in order that the equivalent depth of water lost can be known.

In this study, the specific yield of the aquifer was determined from cores of soil removed from the field in an undisturbed condition at six inch intervals to a depth of 60 inches below the soil surface. The cores were soaked in water for a 48 hour period until they were saturated. Each core was removed from the water, weighed immediately, and placed to drain for 24 hours. They were covered by a wet cloth to prevent evaporation. Each core was weighed again at the end of the 24 hour period. The volume of water lost was also determined by converting the loss in weight of the soil during the period of drainage into units of volume of water. The specific yield was then obtained by dividing the volume of water lost from the soil core by the total volume of the core.

When the distance of fall of the water level in the well due to evapo-transpiration was multiplied by the specific yield expressed as a decimal, the net result was the actual depth of water used in evapo-transpiration during the day. Daily evapo-transpiration from the ground water in the Cedar Creek Swamp was thus calculated except during periods of rainfall when the hydrograph showed a constant rise and could not be used for this purpose. During such periods, however, the contribution of the ground water to evapo-transpiration in the swamp was negligible.

8. Soil moisture above ground water.- Unless the capillary fringe above the water table extends to the soil surface only part of the water used for evapo-transpiration in the swamp forest is supplied by the ground water, or reflected in ground water fluctuations. The soil above the level of the fringe contains a certain quantity of water which is available to plants, and from which evaporation may occur. Measurements of changes in moisture level due to evapo-transpiration and precipitation over a period of time provide a base for estimating the amount of water used from this layer. These measurements also give an indication of the height of the capillary fringe and the depth of wetting from precipitation.

Soil moisture was measured in the upper 21 inches of all swamp soils studied, except where the water level remained so high that soil moisture changed appreciably only at a lesser depth. Measurements were taken at depths of 1, 6, 12, and 18 inches, as deeply as necessary. In Cedar Creek swamp, measurements were also taken at the 3 inch level.

Fiberglas soil moisture units containing thermistors were placed

in auger holes, and the holes refilled. Measurements were made with a Berkely portable ohmeter. The moisture units were calibrated in the laboratory by the method outlined by Colman (1947). Only one unit was placed at each level. On plot U-?, all the moisture units were stolen, and could not be replaced.

From the quantity of soil water indicated by frequent readings of the units, it was possible to estimate moisture losses at the two plots in Cedar Creek Swamp in the following manner.

Soil moisture was measured approximately 24 hours following each period of rain. By that time the excess water in the soil had drained away. Measurements were continued at least bi-weekly during the following rainless period, and the amount and approximate rate of moisture loss calculated. When precipitation again raised the soil moisture content, the process was repeated. Thus the amount of water withdrawn from the upper soil layer by evapo-transpiration was determined.

On all other plots, only a record of the moisture content was kept, for limitations of time precluded the possibility of taking measurements after every rain. Therefore, evapo-transpiration of the swamp forest, from both the ground water and the overlying soil above, was estimated only on the plot containing the water level recorder.

Up to this point, evapo-transpiration has been discussed as if it were a single factor. However, the approximate role played by evaporation from the soil was separated from transpiration at the Cedar Creek plot where the water level recorder was installed.

To do so, the following assumptions were required: First, evaporation from the soil took place almost entirely at the soil

surface. The humidity of the air in the lower soil interstices was so high that evaporation was practically nil, although vapor movement did occur. Second, that the ground water did not contribute significantly to evaporation when its level was so low that the capillary fringe did not reach to the soil surface (Keen, 1928). Therefore, the soil moisture held in the layer of soil above the capillary fringe contributed practically all of the moisture removed from the swamp soil through evaporation except when the capillary fringe reached the soil surface.

If the above assumptions are correct, the differences between the loss of soil moisture from a trenched plot cleared of vegetation and an adjacent vegetated untrenched plot indicated the relative amount of moisture loss from the upper soil layers due to transpiration and evaporation separately.

These measurements were made. The trenched plot was made by cutting all roots and preventing their reentrance by placing a metal shield extending below the root zone around the plot and keeping it clear of all invading vegetation. Fiberglas units were placed in both the trenched and untrenched plots, and simultaneous readings were made throughout the summer of 1957.

Soil characteristics

The soil profile.- Excavations were made on each plot, and the soil profile was described. In addition, a mechanical analysis was made for each horizon of mineral soil profiles below the A1 horizon. The fine fractions were measured by the hydrometer method of Bouyoucos (1936), and the sand fractions were separated using standard sieves

and a mechanical shaker.

Organic soils were examined in the laboratory with a microscope, and the recognizable constituents were listed and described.

Root characteristics

1. Profile cross section studies.- In all soil profile pits, the woody roots exposed were mapped in the position in which they were found. They were classified in the following diameter classes: 1.01 inches or greater, 0.51 to 1.0 inches, 0.31 to 0.50 inches, 0.11 to 0.30 inches and 0.05 to 0.10 inches. Roots less than 0.05 inches in diameter were not mapped or counted. The number and size of tree roots in each square foot of stone free soil in each horizon or depth interval were calculated (Coile, 1937; Donahue, 1940).

2. Individual root excavations.- The vertical root development of individual swamp forest trees was also observed in a variety of situations. The number of observations made on individual root systems was limited by the absence of several species and size classes in close proximity to the observation wells, as well as the time consuming procedures involved. Line drawings of the form of vertical root development of 41 trees, ranging in size from 3 inches to 82 feet in height, were made. Species examined, and the number of observations were: balsam fir, 10; black spruce, 2; white spruce, 3; white cedar, 6; yellow birch, 4; hemlock, 2; black ash, 1; tag alder, 2; red maple, 3; and hard maple, 8. In addition, many qualitive observations were made of the root systems of windthrown trees.

Structure of forest stands

A map of each plot was constructed showing the location of each tree, stump or windthrown tree, crown coverage and micro-topography. Individual trees were numbered and the following descriptive data were listed on a standard form: total height, d.b.h. to the nearest 0.1 inch, age (when determinable), crown length, average crown diameter, crown class, crown condition, and special remarks pertaining to the condition of the tree.

On each plot, a sub-sample consisting of eight milacres, arranged in the form of a cross, was examined to determine the abundance of tree seedlings, shrubs, and herbaceous vegetation.

Site quality and growth

The site quality of spruce and fir, expressed in terms of total height at age 50 years for sound dominant and codominant trees was determined. The site quality for white cedar was estimated on the basis of total height at maturity for the same crown classes.

Increment cores were extracted from all sound coniferous trees to provide data on radial growth on each site.

In 1957, general phenological observations were made. These included the time of leafing in the spring, and dates when leaf coloration and leaf fall began in the autumn. These observations were made in both the swamps and on adjacent uplands. The time when leader growth began in coniferous species, except white cedar and hemlock, was also noted.

As might be expected, some of the factors investigated proved

to be important in contributing to an understanding of swamp forests, while others were of minor consequence or showed no relation to water, soil or tree conditions. The results of this investigation are presented and analyzed in the chapters that follow.

CHAPTER III

ACTIONS OF GROUND WATER UPON THE FOREST

Even a cursory examination of swamp forests reveals that water levels vary in depth from swamp to swamp. Further, during dry periods, water levels may remain constant in one swamp, while they fall markedly in another. The water level in a swamp may exert important influences on the forest. Therefore, a classification of water level types seemed necessary.

Classification of swamps by water level characteristics

It has been possible to classify swamps on the basis of water level characteristics from a study of measurements in 16 wells located in five swamps during the summers of 1956 and 1957. This classification is given below.

Water Level Characteristics of Northern Michigan Swamps.

I. Water Level essentially constant throughout the year.
   - A. Water level shallow. Within 18 inches of the soil surface during most periods of drouth.
   - B. Water level moderately deep. Below 18 inches in depth even during wet seasons.

II. Water level fluctuates with precipitation.
   - A. Fluctuations direct and immediate, amplitude large.
   - B. Fall in water level lags until an appreciable precipitation deficit develops.
     1. Thereafter fluctuates directly with precipitation.

2. Thereafter falls to a low level with little fluctuation until an appreciable precipitation surplus is built up.

During 1956, a wet year, the water level in all swamps was relatively stable, except in type II-A, which exhibited rapid changes in level. In 1957, water levels were low in all swamps except type I-A. Figure 5 illustrates the swamp types described during the dry summer of 1957. A discussion of each type follows.

In swamp type I the water level was maintained by water seeping from the groundwater reservoir which surrounded it. Except for short periods, such swamps were seldom flooded. Surface drainage was sufficiently developed to carry excess water rapidly away. During dry weather the rate of seepage into these swamps apparently was in equilibrium with the rate of water loss by evapo-transpiration and seepage outflow.

Swamps characterized by a relatively constant water level were sometimes surrounded by a zone which exhibited water level fluctuations of type II. In such cases they laid at a lower level than the surrounding type, and the high inflow of water during wet periods was removed by surface overflow, and the low inflow of water into the swamp during dry periods was sufficient to balance evapo-transpiration losses.

Water levels which fluctuated directly and immediately with precipitation, type II-A, were usually a peripheral type which surrounded those having more stable water levels in their interior. The rapid, direct fluctuations in water levels were due to storm runoff from the surrounding catchment area which raised the water level rapidly

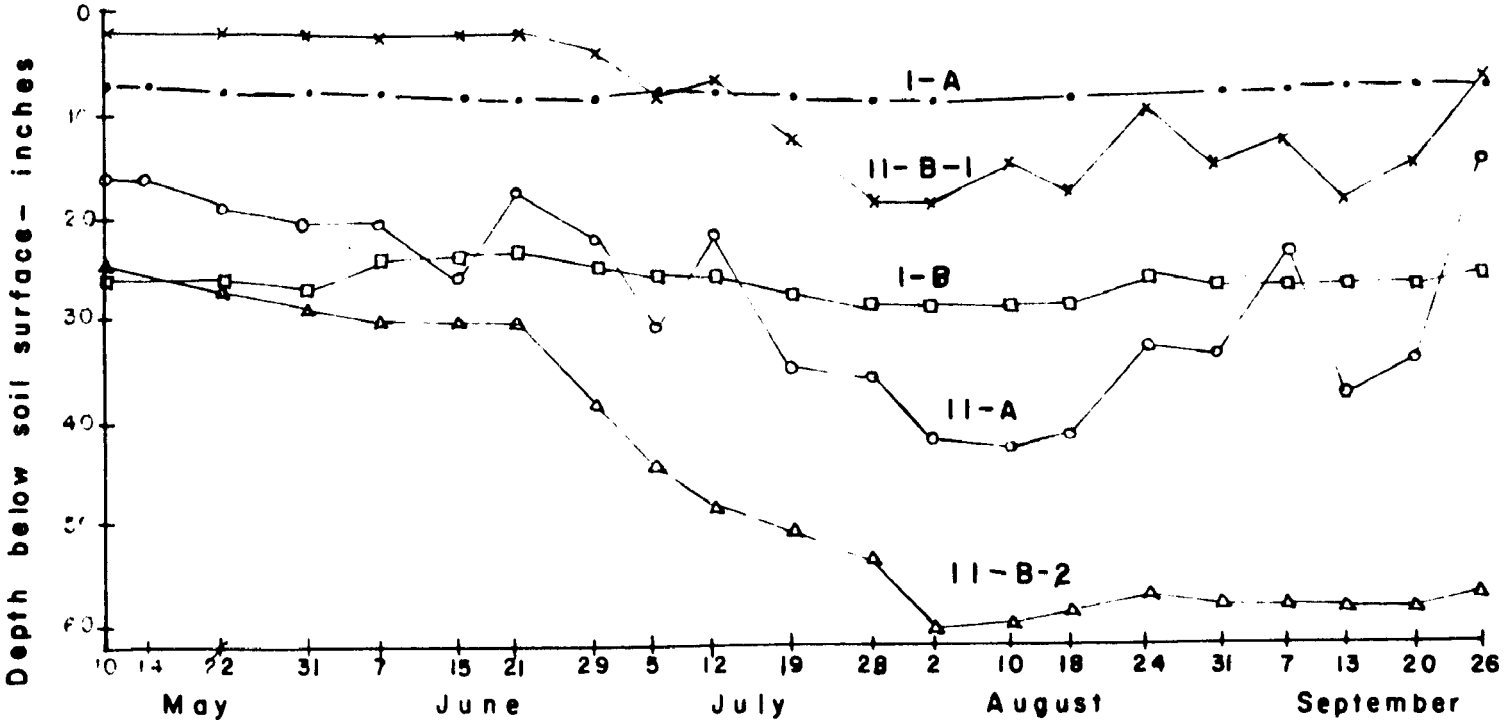


FIGURE 5. Water level types in different swamps during 1957.

following precipitation. At the same time, a moderately rapid seepage outflow allowed the water level to drop steadily after precipitation ceased. The detention of runoff near the swamp border and its rather steady release resulted in more stable water level conditions in the swamp interior. Where swamp type II-A did not surround another swamp type, it was restricted to rather narrow belts along permanent or intermittent streams. It is difficult to conceive of this type as other than a narrow belt, for the amplitude of water level fluctuations were dampened considerably with distance from the edge toward the center of the swamps.

Swamps of type II-B were characterized by a water table that remained high early in the growing season and fluctuated in level only after a considerable precipitation deficit developed. The groundwater reservoir surrounding this swamp type was apparently limited in its capacity to provide a uniform seepage inflow, and became depleted during periods of inadequate precipitation. As storage was exhausted, water levels began to fall. Thereafter, they either fluctuated directly with precipitation, but with a lower amplitude than in type II-A, or they continued to fall until a considerable precipitation surplus was again built up.

Swamp type II-B-1 is an example of the former type. Fluctuations in such a type were due to the same reasons as for type II-A. The lesser amplitude of fluctuation, however, was due to the lesser amount of storm flow reaching the swamp.

Swamp type II-B-2 continued to fall as the groundwater reservoir was depleted in spite of subsequent precipitation, probably due to the fact that the moisture storage capacity of the soil above the water

level was sufficient to retain most of the water falling thereon, and there was little storm flow from the surrounding area. Thus little recharge of the underground reservoir was possible until the storage capacity of the overlying soil was satisfied. With the high vegetative water use during the growing season, a considerable precipitation surplus would be necessary before the water level could be raised.

Either of the sub-types of type II-B may be found on swamp borders or throughout a swamp. On the swamp border, they were slightly elevated above the general level of the swamp, and even the wet season water level laid sufficiently deep to permit the normal development of a soil profile to the B horizon.

Precipitation falling upon this border was retained to a large extent in the surface soil above the water level, or flowed off into the lower swamp types before it percolated deeply enough to recharge the underground reservoir. Where precipitation flowed off as storm flow the lower lying type exhibited direct fluctuations with precipitation, at least after the initial depletion of the underground reservoir occurred. Any soil stratum with a low permeability could cause such superficial seepage. Even a slightly indurated B horizon may be sufficient.

That this was the case is suggested by the data in table 1, which were taken from observations at wells CC-1 and CC-2. Well CC-1 laid below well CC-2, and was characterized by type II-A water level fluctuations, immediate and direct with precipitation. Well CC-2 was in swamp type II-B-2, with a lag in water level fluctuation depending on an extended development of a precipitation deficit or surplus.

During periods of moderate to heavy precipitation in 1957, the

TABLE 1

FLUCTUATIONS OF WATER LEVEL FOLLOWING PRECIPITATION IN A SOURCE AREA (CC-2) AND A RECEPTION AREA (CC-1) OF SEEPAGE STORMFLOW

Date 1957	Ppt. ins.	Water level in wells CC-2 pre-ppt. inches	CC-2 rise ins.	CC-1 pre-ppt. inches	CC-1 rise ins.	Spec. yield CC-1 %	Water gained CC-1 ins.	Difference CC-1 rise minus ppt. inches
May 13-4	0.71	26.8	0.6	20.1	7.5	12.5	0.94	0.23
25-6	0.57	28.0	1.6	20.0	4.2	12.5	0.52	-0.05
June 6	0.39	33.3	0.7	25.0	7.0	11.7	0.82	0.43
17-8	1.27	34.42	3.8	19.8	11.6	9.4	1.09	-0.18
July 11	0.25	48.0	-0.1	37.0	2.0	14.3	0.29	0.04
21	0.59	51.5	-0.2	33.5	7.2	9.7	0.70	0.11
Aug. 14	0.42	58.4	0.2	43.7	1.9	14.3	0.27	-0.15
Sept. 3	0.30	57.2	0.0	23.3	2.6	9.7	0.25	-0.05
13	0.34	58.3	0.1	31.8	4.1	9.7	0.40	0.06
21-4	1.84	58.1	0.1	25.3	15.4	12.5	1.92	0.08

water level in well CC-2 showed little or no response, while in the lower lying well CC-1, the rise in water level often equaled or exceeded that which could be attributed to direct precipitation, even assuming that all precipitation penetrated to the ground water. Such most certainly was not the case. Some was retained in the soil above the water level or intercepted by the forest canopy. At the same time, there was no evidence of surface runoff. Therefore the additional moisture must have been due to superficial seepage from the area lying above.

The amount of seepage stormflow probably varies with numerous factors such as the amount, intensity, duration and season of precipitation; the antecedent soil moisture conditions and the depth and permeability of soil strata which impede percolation. Certainly the length and amount of slope, perhaps even the aspect exerts an influence. None of these factors were studied in detail and therefore the only conclusion that can be justified is that seepage stormflow does occur, causing rapid fluctuations in ground water levels in lower lying areas.

From the above discussion of water level characteristics, it is readily apparent that the types grade into one another, with no sharp line of demarcation between. Furthermore, different swamp types may exist within the same swamp as well as between different swamps, with each type grading into the other. As in forest type mapping, however, it may be useful to draw type boundaries through transition zones even though such boundaries be somewhat arbitrary. The above classification of swamp types based on water level characteristics can be similarly applied.

Swamp soils

The relationship of soil development to ground water characteristics is shown in table 2. It may be readily seen that the depth and persistence of the high water level was a major influence. The relation was modified slightly by the effect of water movement.

Wherever the water level was high and persistent, the soil developed was organic, except at plot C-5, where the rather well-aerated water rapidly seeping through the stony sands permitted rapid decomposition of the litter deposited. Where water movement was restricted, a very raw sphagnum moss peat developed, but where water movement was more rapid the peats were more woody, and better decomposed.

The degree of decomposition of the organic material may presumably be related to the character of the prevailing vegetation as well as depth and persistence of high water levels and the rate of seepage of ground waters. This is, however, not unusual, for among the many species that can successfully withstand the site restrictions imposed by excessive water are those which exhibit wide differences in ability to remove base minerals from the soil and concentrate them in their litter, thus modifying the rate of litter decomposition (Lutz and Chandler, 1946).

The effect of base-rich litter may be especially important at the edge of swamps, for many of the adjacent upland species such as red and hard maple, basswood, and trembling aspen have a rich litter which was dropped on the swamp edge.

TABLE 2

SWAMP SOIL DEVELOPMENT IN RELATION TO GROUND WATER CHARACTERISTICS

Plot	Ground Water Characteristics				Soil Development		
	Mean depth of high water inches	Persistence of high water	Rate of water movement ft./day	Redox of water Eh	Soil Organic Depth Inches	Organic Type*	Mineral Type*
E-1	3	high	0.07 or less	-252	48+	M.P.	-
P-2	3	high	14.0	-174	7	Muck/ W.P.	Sand
U-2	4	moderate	5.0	18	14-26	M.P./ W.P.	S.L.
C-1	8	high	7.0	- 60	48+	Muck/ W.P.	-
CC-1	8	very low	0.3	192	½-4	Mull	S.L.
C-5	10	high	16.0	264	2-5	Mull	Stony Sand
C-3	11	high	3.5	- 36	48+	Muck/ W.P.	-
E-3	11	very low	0.5	300	1-2	Mull	L.S.
C-4	12	high	3.5	- 6	48+	Muck/ W.P.	-
P-3	12	high	2.0	- 12	38	W.P.	S.L.
E-2	12	moderate	0.3	67	2-5	Mull	S.L.
C-2	13	high	8.0	- 96	48+	W.P.	-
CC-2	25	moderate	0.3	294	1-2	Mor	S.L.
U-1	30	moderate	8.0	168	2-5	Mull	S.L.
P-1	34	high	0.2	69	1-3	Mor	S.L./ Sand
P-4	34	moderate	0.2	186	3-7	Mull	Sand

*M.P. is moss peat, W.P., woody peat, S.L., sandy loam and L.S. loamy sand.

Wherever water levels were high, but the high level did not persist continuously, both mineral and organic soils were found. In these swamps the effect of the water level was weak, and the soil type may have been determined by other factors.

When the high water level was deeper than one foot below the surface of sandy soils, organic decay rates appeared to be unrelated to ground water conditions.

The redox potential of the ground water was closely related to the soil type and degree of decomposition. In every case in this study, the redox potential of the ground water decreased from the edge into the interior of each swamp. It appeared as if ground water seeping into swamps was depleted of its oxygen in decaying organic material, resulting in more completely decomposed plant material on the swamp margin than in the interior. This condition was pronounced where the ground water showed little mobility, as in the sphagnum bog E-1, characterized by a raw sphagnum peat in the center, but marked by an obvious marginal ditch in which the organic material was decomposed to a black muck. See table 3.

Ground water and tree roots

The major action of ground water upon swamp forests is exerted directly upon tree roots. The water level in a swamp is certainly of major importance, for as will be shown, the depth of root penetration is largely dependent upon the depth of the ground water. Since water levels vary not only in depth, but also in the nature of fluctuation with precipitation, root development must be related to the different water level types.

TABLE 3

RELATION OF REDOX POTENTIAL OF GROUND WATER TO STATE OF DECOMPOSITION OF ORGANIC SOIL AND LOCATION IN SWAMP

Swamp Series	Swamp Edge		Intermediate		Interior	
	Eh	Soil	Eh	Soil	Eh	Soil
E	300	Sandy loam	67	Sandy loam	-252	sphagnum moss Peat
CC	294	Sandy loam	-	-	192	Sandy loam
P-1,2	69	Sand	-	-	-174	Muck and sphagnum over Wood Peat
P-3,4	186	Sand	-	-	-12	Muck over Wood Peat
U	168	Sandy loam	-	-	18	sphagnum over Wood Peat
C-3,4,5	264	Sandy loam	-6	Muck over Wood Peat	-36	Muck and sphagnum over Wood Peat
C-1,2	-60	Muck	-	-	-96	Wood Peat

During periods of high water levels the freshness and the rate of movement of the ground water may also affect the root development of swamp trees. The results of investigations on these ground water characteristics will be shown below.

Root development in swamp type I-A.- Root distribution was examined during late August, 1956 in soil profiles dug on eight different plots where the ground water level was shallow and essentially stable. The weather during 1956 was very wet and water levels were high in this swamp type throughout the summer. Soils ranged from raw moss peat of great depth through wood peat and muck to a sandy loam mineral soil. Table 4 presents a brief description of each plot.

The soil profile in the moss peat was located in bog E-1, a stagnant bog poorly stocked with slow growing black spruce and tamarack. The water level was 4 inches beneath the bog surface. The maximum depth of tree roots over 0.05 inches in diameter was 4½ inches, although finer roots may have penetrated somewhat deeper. Root density, as would be expected, decreased rapidly with increasing depth, there being 0.84 square inches of cross sectional root area per square foot of peat in the upper 3 inches of the profile and only 0.21 square inches per square foot in the 3 to 4½ inch level. During the dry summer of 1957 the water level fluctuated between 2 to 7 inches below the bog surface. Thus only a small portion of tree roots in this bog were flooded even during a wet year, and almost all roots were above the water level during a dry year (Figure 6).

Five soil profiles were dug in woody peat. Of these the surface was well decomposed to a muck on four plots, and consisted of a well-decomposed moss peat interspersed with muck on the other. Soil profiles are shown in figures 7-11.

TABLE 4

CHARACTERISTICS OF SAMPLE PLOTS IN SWAMPS WITH A SHALLOW, ESSENTIALLY STABLE WATER LEVEL (TYPE I-A)

Plot	Water depth 1956 inches*	Range in level 1957 inches*	Soil		Tree species adjacent to soil pit
			surface	subsoil	
C-1	9	8-11	muck	woody peat	white cedar, balsam fir, black ash
C-2	13	12-14	muck	woody peat	white cedar, balsam fir
C-3	11	10-14	moss peat and muck	woody peat	white cedar, black spruce, balsam fir
C-4	13	12-18	muck	woody peat	black spruce, trembling aspen
P-3	14	11-23	muck	woody peat	white cedar, black spruce, balsam fir
E-1	4	2-7	moss peat	moss peat	black spruce, tamarack
P-2	4	2-6	muck over woody peat	sand	white cedar, balsam fir
C-5	9	9-14	mull humus	sandy loam	t. aspen, w. spruce, balsam fir

*From top of highest level on soil profile pit. Water levels do not agree with well measurements, as wells were located at an intermediate elevation between the hummocks and depressions.

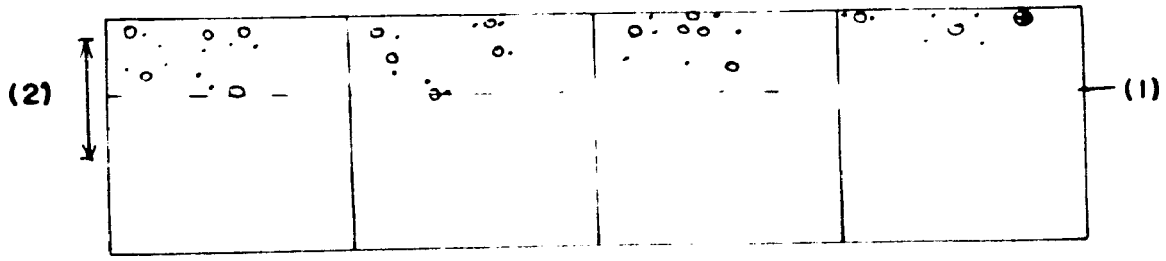


FIGURE 6. Soil profile and root distribution, plot E-1. (1)- Water level, August, 1956. (2)-Range in level, summer, 1957. Soil is poorly decomposed, loose sphagnum peat. Root size classes shown as follows: · = 0.05 - 0.10 inches, ° = 0.11-0.30 inches, ⊕ = 0.31 - 0.50 inches, ◑ = 0.51 - 1.00 inches and ○ = larger than 1.00 inches.

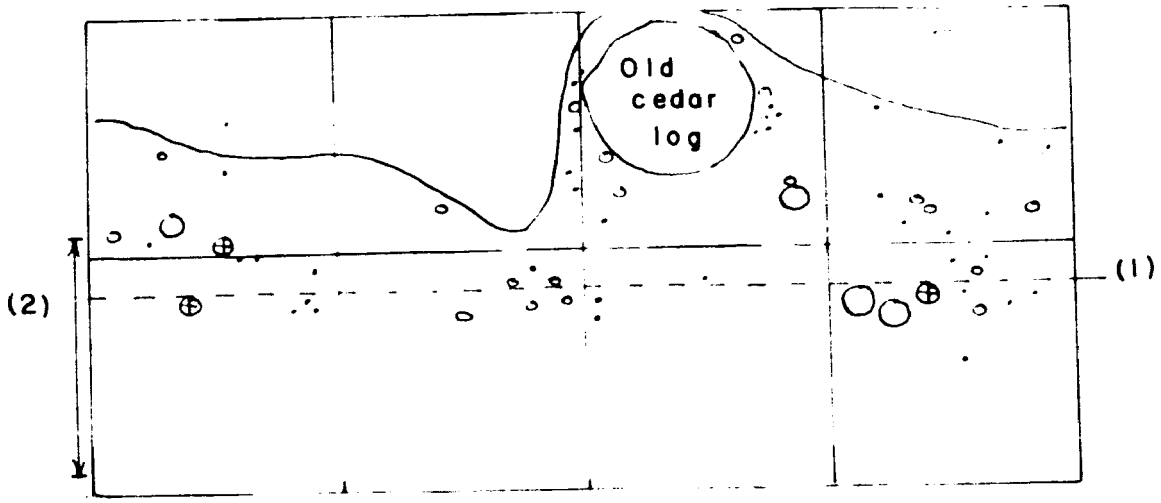


FIGURE 7. Soil profile and root distribution, plot P-3. (1)- Water level, August, 1956. (2)-Range in level, summer, 1957. Soil is mucky wood peat to 32 inches, over organic clay to 38 inches, all over a yellow-grey mottled sand. Root sizes as in figure 6.

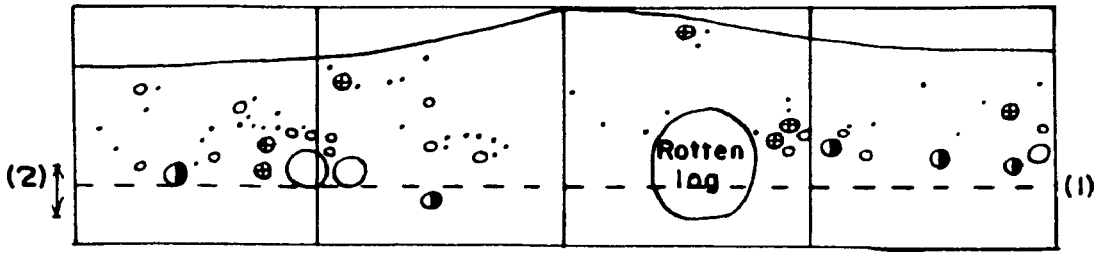


FIGURE 8. Soil profile and root distribution, plot C-1.
(1)-Water level, August, 1956. (2)-Range in level, summer, 1957.
Soil is well decomposed woody peat, with a muck surface.
Root sizes as in figure 6.

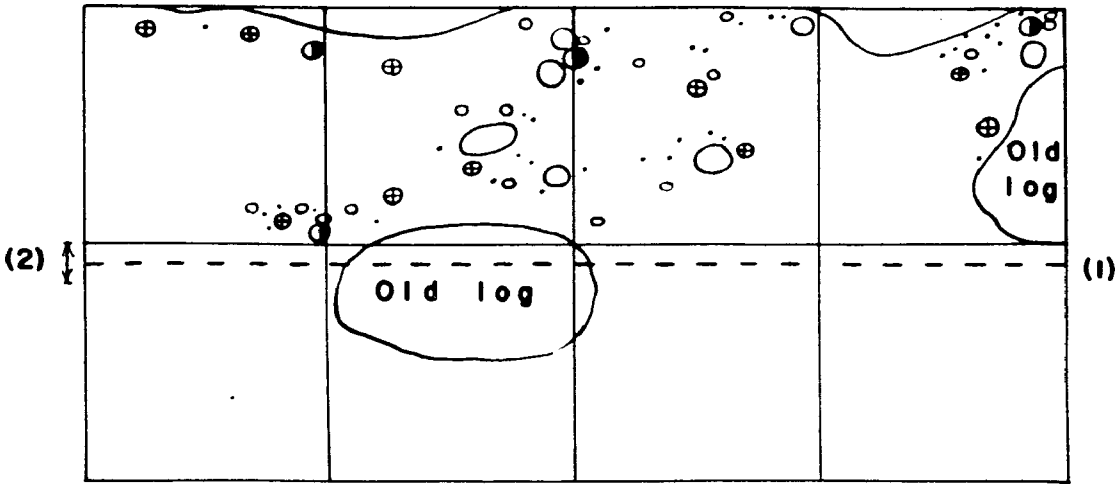


FIGURE 9. Soil profile and root distribution, plot C-2.
(1)-Water level, August, 1956. (2)-Range in level, summer, 1957.
Soil is slightly decomposed woody peat, with a muck surface.
Root sizes as in figure 6.

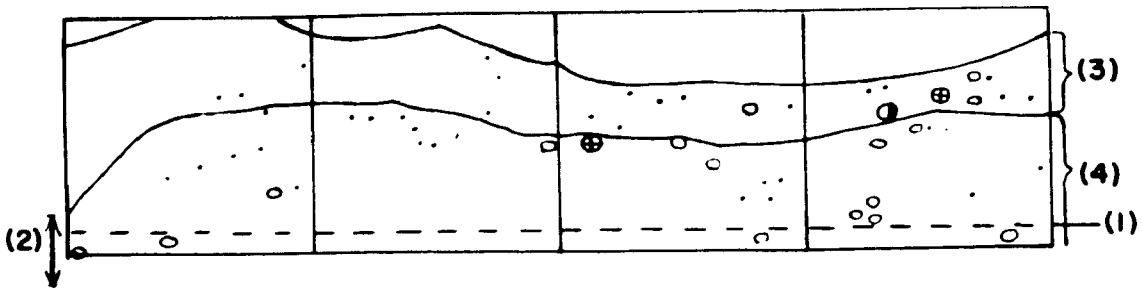


FIGURE 10. Soil profile and root distribution, plot C-3. (1)-Water level, August, 1956. (2)-Range in level, summer, 1957. (3)-Sphagnum in muck. (4)-Well decomposed woody peat. Root sizes as in figure 6.

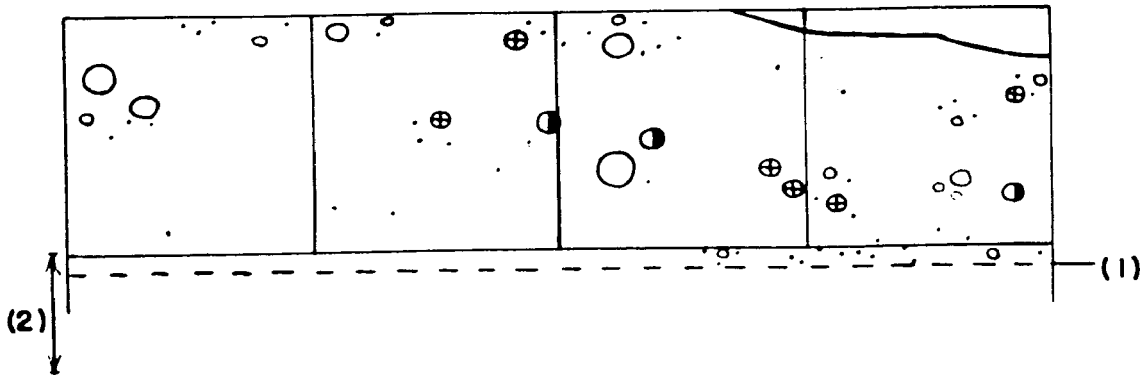


FIGURE 11. Soil profile and root distribution, plot C-4. (1)-Water level, August, 1956. (2)-Range in level, summer, 1957. Soil is mucky, well decomposed woody peat. Root sizes as in figure 6.

It will be noticed that the soil surface in many plots showed considerable micro-relief. For this reason, the depth to ground water varied considerably over even a small plot.

In these woody peats, it was apparent that the depth of rooting was restricted by the high water level. During times of high water level, such as in the entire summer of 1956, a small portion of the roots were submerged for long periods. In dry seasons such as 1957, the roots were submerged for shorter periods. Following a slight drop in water level, all roots laid completely above the saturated peat. Although the tree roots studied did not penetrate deeply below the water level, a small proportion did extend an inch or two beneath the water during most of the year.

The density of roots throughout the soil profile was nearly uniform in peats underlaid by a shallow, essentially stable water table, although there was a slight decrease with depth to and slightly below the water, where root density abruptly decreased to zero (Figure 14).

In the uppermost layers of the peat a few large laterals and a great many fine roots (0.05 to 0.10 inches in diameter) occurred. Below the large laterals and above the water the roots were mostly fine, whereas those submerged throughout most of the year although not of large diameter, were more coarse than the upper roots, practically none being smaller than 0.10 inch in diameter (Figure 15).

The remaining two soil profiles in swamp type I-A were sandy mineral soils. One was covered by a relatively thick organic layer consisting of 7 inches of sphagnum moss and muck (P-2), the other was a very stony sand containing clay inclusions (C-5), covered by an organic horizon varying widely in thickness. This organic layer was

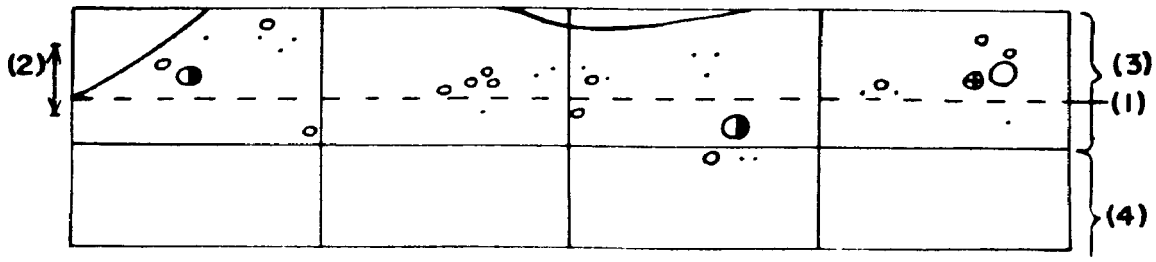


FIGURE 12. Soil profile and root distribution, plot P-2. (1)-Water level, August, 1956. (2)-Range in level, summer, 1957. (3)-Sphagnum in muck. (4)-Grey sand. Root sizes as in figure 6.

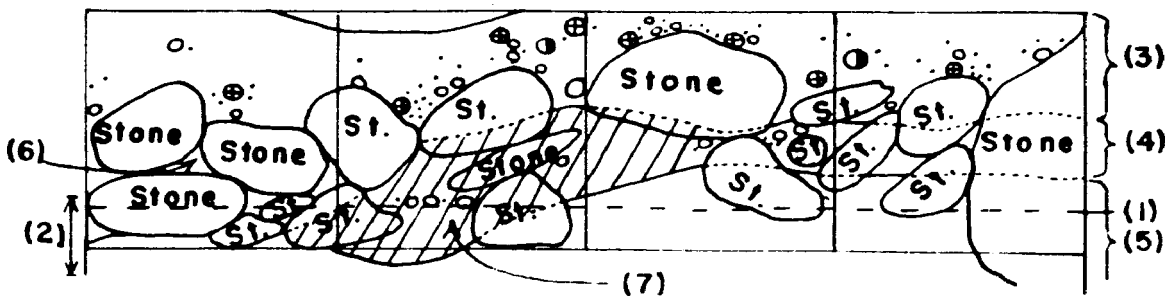


FIGURE 13. Soil profile and root distribution, plot C-5. (1)-Water level, August, 1956. (2)-Range in level, summer, 1957. (3)-Mull humus. (4)-Grey sandy loam. (5)-Brown sandy loam. (6)-Open spaces between stones. (7)-Clayey lens. Root sizes as in figure 6.

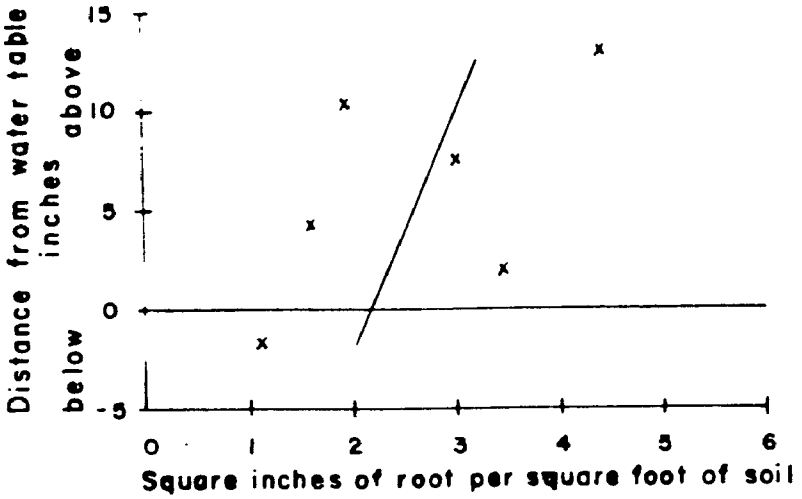


FIGURE 14. Mean root density in relation to water levels, organic soils, swamp type 1-A. Independent variable on vertical axis for visual convenience.

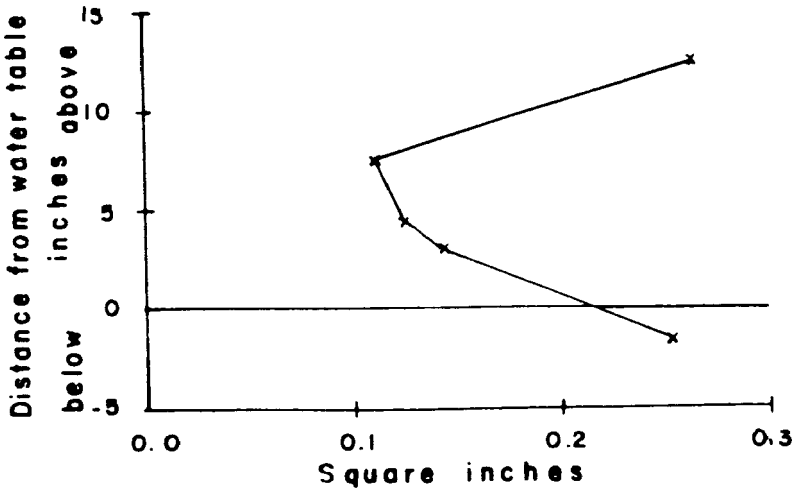


FIGURE 15. Mean cross-sectional area of roots in relation to water levels, organic soils, swamp type 1-A. Independent variable on vertical axis for visual convenience.

a well-decomposed humus thoroughly mixed with mineral soil except in stony depressions where the humus was a laminated leaf layer only partially decomposed (Figures 12 and 13).

Tree roots of balsam fir and white cedar were rather uniformly distributed throughout the muck on plot P-2, and extended into the surface of the underlying grey sand. On the profile examined the water level ranged in depth between 2 and 5.5 inches during 1957. Thus nearly one half of the roots exposed on the face of the pit were submerged almost continuously, a phenomenon not observed elsewhere.

On plot C-5, roots of trembling aspen, balsam fir and white spruce were similarly concentrated in the organic layer. The deepest root penetration was in a clayey lens within the sand, but none were found below the highest water level observed in 1956 and 1957.

In addition to the examination of root size and distribution across the face of soil pits, the vertical root penetration of 10 individual trees over a shallow, essentially stable water table was studied by excavation. Three species were excavated; six balsam firs ranging in height from $2\frac{1}{2}$ to 12 feet, two black ash, one 3 feet and the other 14 feet tall, and two small white spruce about $1\frac{1}{2}$ feet tall. Line drawings of each root system except for the larger black ash were made. In every case roots of the trees penetrated below the high water of 1956.

The young balsam firs typically had a short stubby tap root growing into the ground water. Below the water surface the tap root grew in an irregular manner, bending and twisting much like a corkscrew and ending abruptly (Figure 16). Root penetration was deeper by one to two inches than that observed in the soil pits.

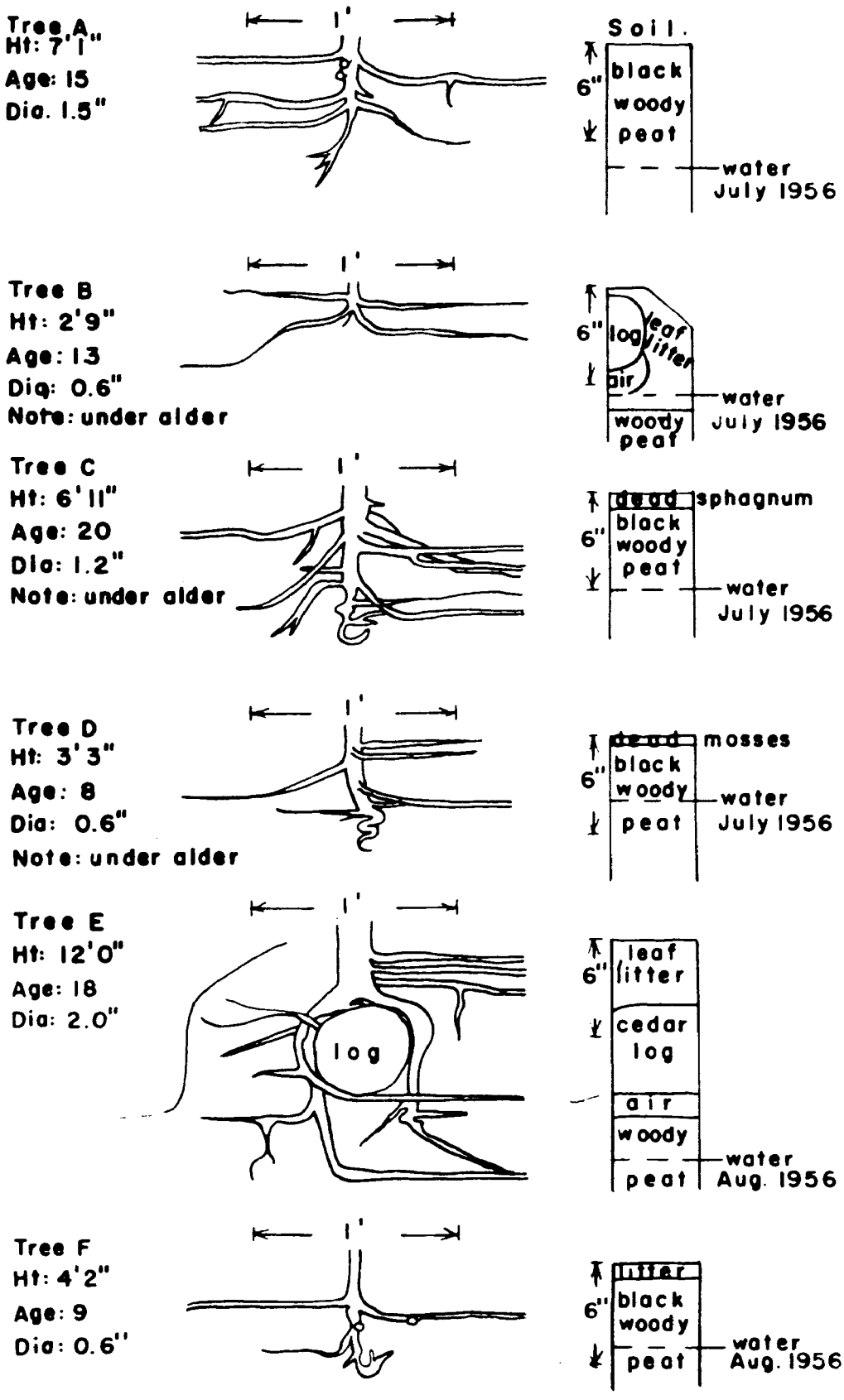


FIGURE 16. Vertical penetration and form of balsam fir roots in type I-A swamps. Note twisted, gnarled roots of trees C, D and F below the water. Fine rootlets not drawn.

The roots of black ash and white spruce that extended below the water were, as a rule, finer than those of the balsam fir, and were rather fibrous. The fibrous roots of ash penetrated as much as 4 inches below the water, but white spruce roots were always near the water surface. (Figures 17 and 18).

The larger black ash tree excavated was transplanted during early July, 1956 with the root system entirely submerged on the edge of Golden Lake. Throughout the dry winter and spring of 1957 the lake level fell below the tree roots, but the submergence during 1956 apparently did not injure the tree, as it appeared vigorous throughout the period. The tree roots were again examined in the fall of 1957. They all appeared to be healthy and were still growing at that time indicating a high degree of resistance to flooding.

Root development in swamp type I-B.- One soil pit was dug on a plot where the ground water level remained at a depth of 23 + or - 3 inches throughout the summers of 1956 and 1957 (Figure 19). Tree species adjacent to the soil pit were large white cedar, white and black spruce; and yellow birch and red and hard maple seedlings. The maximum depth of root penetration was 20 inches, or just above the weakly developed gley horizon, present at that depth. The root density decreased rapidly with depth, being 1.12, 0.72, 0.16, and 0.00 square inches of cross sectional root area per square foot of stone free A_1, A_2, B and G horizons, respectively. The A_1 horizon was rich in incorporated humus. No individual tree excavations were made on this swamp type.

Root development in swamp type II-A.- The water level on two swamp plots fluctuated directly with rainfall. A gley horizon was

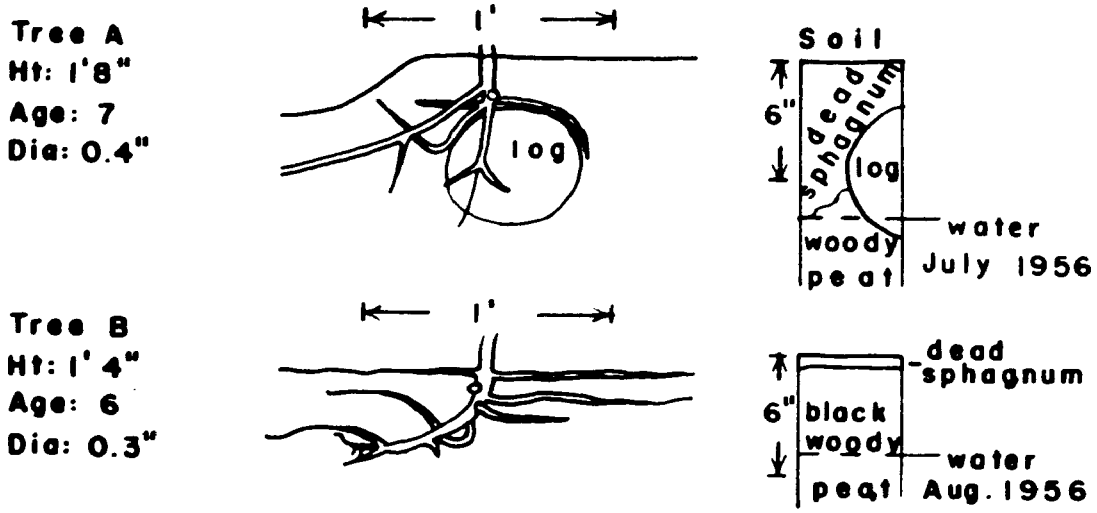


FIGURE 17. Vertical penetration and form of white spruce roots in type I–A swamps. Fine rootlets not drawn.

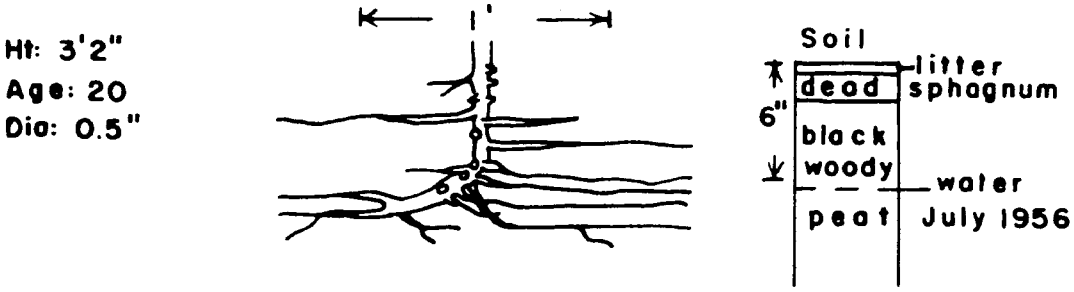


FIGURE 18. Vertical penetration and form of black ash roots in a type I-A swamp. A great mass of fine, fibrous rootlets at and below the water not drawn. Adventitious roots arise from lenticels.

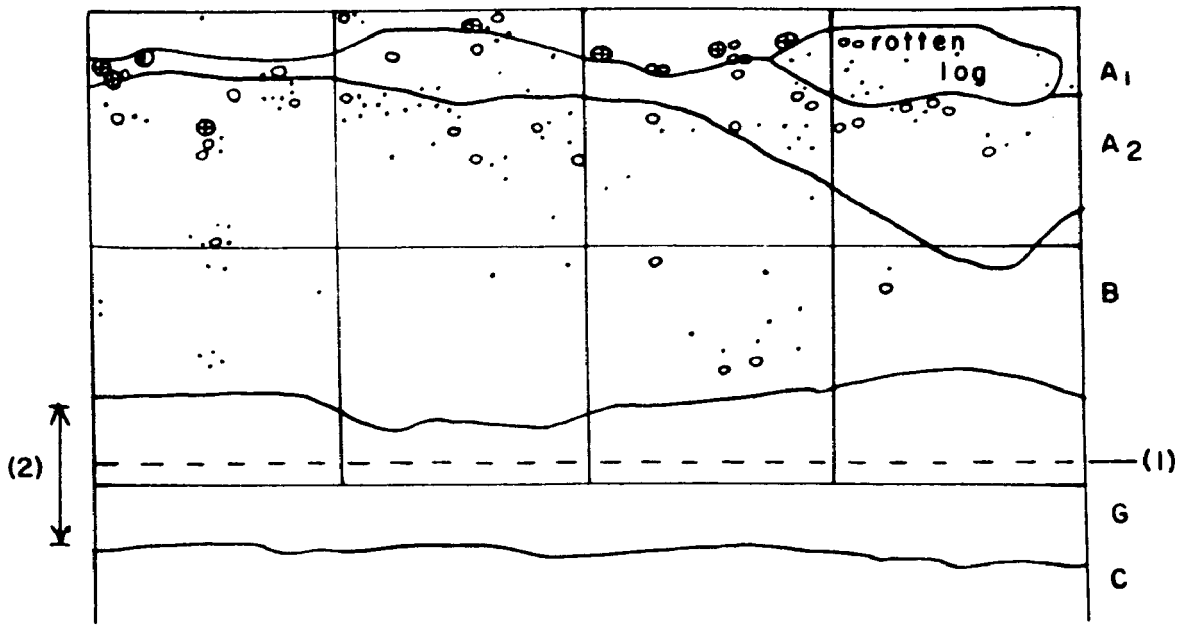


FIGURE 19. Soil profile and root distribution, plot P-1. (1)-Water level, August, 1956. (2)-Range in level, summer, 1957. A_1 horizon is slightly incorporated humus, A_2 is grey sandy loam, B is yellow sand, G is yellow-brown sandy loam, strongly mottled with grey, C is gravelly, yellow-red sand. Root sizes as in figure 6.

present in each of the soil profiles examined, but it was not uniform, varying in intensity of mottling, thickness, and extent. This was probably due to the heterogeneous character of the soil, which ranged from loamy sand to almost a loam in texture. The humus layer at each profile was a granular black mull, incorporated with mineral soil.

Tree roots of balsam fir, white cedar and yellow birch were concentrated in the humus enriched A1 horizon of both plots, and root density decreased rapidly with depth, being 9.25, 0.93, 0.57, and 0.00 square inches per square foot of stone free soil in the A1, A2, B and G horizons, respectively. The maximum depth of root penetration was restricted to the upper limit of the gley horizon, which probably represents the position of the ground water surface for the greater part of each year. In these areas of rapidly fluctuating water levels, however, the ground water frequently rose above the gley horizon, and during extended dry periods dropped considerably below it. The root distribution and soil profile in plots CC-1 and E-3 are shown in figures 20 and 21.

Most of the individual trees excavated for examination of vertical root penetration were in swamp type II-A. Eighteen trees, including three hard maples, four white cedars, two hemlocks, two yellow birches, two black spruces, two balsam firs, one white spruce, and two red maples were examined.

The examination of the root systems of hard maple was quite revealing. All root systems were shallow. There was little evidence of tap root formation and lateral development was sparse. The maximum depth of root penetration appeared to be limited by the high water levels of spring. All roots that had penetrated below that level were

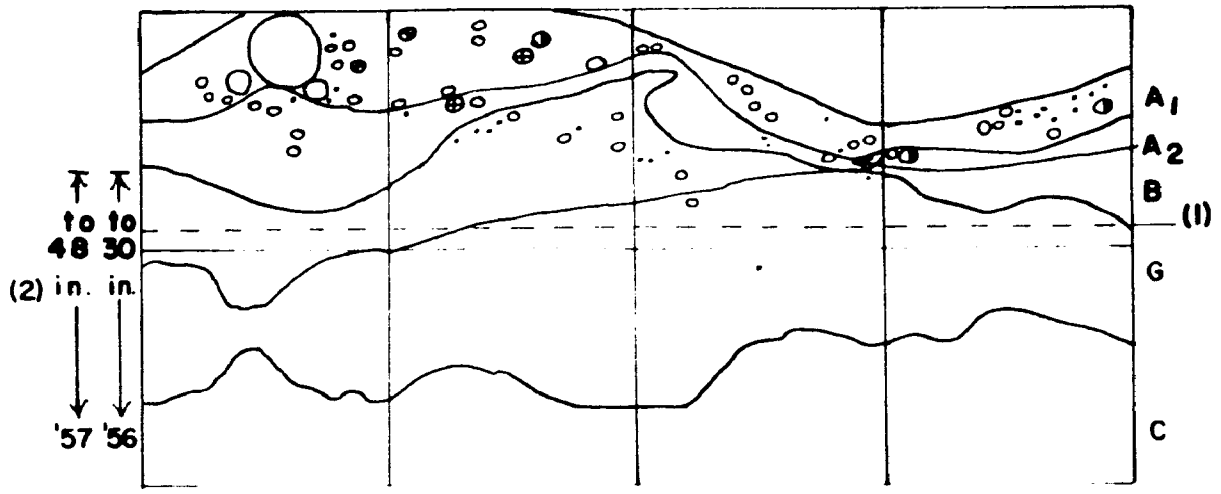


FIGURE 20. Soil profile and root distribution, plot CC-1. (1)-Water level, August 23, 1956. (2)-Range in level, summers of 1956 and 1957. A_1 horizon is mull humus, A_2 is weakly leached, grey sandy loam, B is rusty-grey sandy loam, G is grey-green mottled sandy loam, C is rusty-yellow loamy sand. Roots as in figure 6.

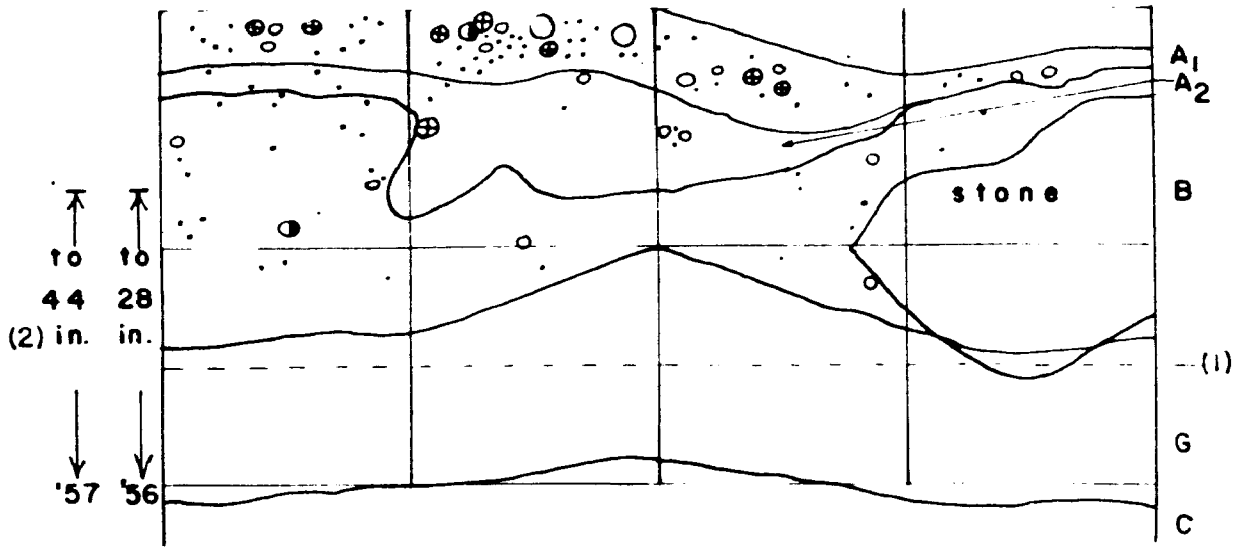


FIGURE 21. Soil profile and root distribution, plot E-3. (1)- Water level August 20, 1956. (2) Range in level, summers of 1956 and 1957. A_1 horizon is mull humus, A_2 is weakly leached, grey sandy loam, B is rusty-yellow loamy sand, G is weakly mottled yellow-grey sandy loam, C is reddish brown sandy loam. Root sizes as in figure 6.

dead (Figure 22). No evidence of adventitious rooting was found.

The roots of white cedar were found entirely above the level of the gley horizon. The root system consisted mainly of laterals, with a weakly developed tap root on very small trees. Many adventitious roots were present near the root crown of a young tree located in an accumulation of litter (Figure 23).

Hemlock roots extended into the ground water during high water levels. There was a strong lateral development, with vertical sinker roots branching downward, abruptly separating into a brush-like mass at or near the high water levels (Figure 24). Adventitious roots were found on the small hemlock. Excavation of the hemlock shown in figure 24B. revealed that roots from an adjacent red maple extended eight inches deeper than the deepest hemlock penetration.

The two yellow birch root systems in figure 25 showed no evidence of tap root development or adventitious rooting. Almost the entire root system of the larger tree was submerged during most of 1956. Observation of a large yellow birch and a large white cedar tree which were windthrown together in this area showed the yellow birch root system to be nearly one foot deeper than that of the cedar, although the smaller roots were not observed, having been torn off and partially decayed since the trees had been uprooted.

Black spruce roots barely penetrated the gley horizon, although they apparently withstand frequent flooding for short periods, as evidenced by the presence of a small spruce growing in a depression created by windthrow of a balsam fir. The spruce had its roots completely submerged for several weeks in 1956 without apparent damage, and a small adventitious root had arisen into wet litter at the base of

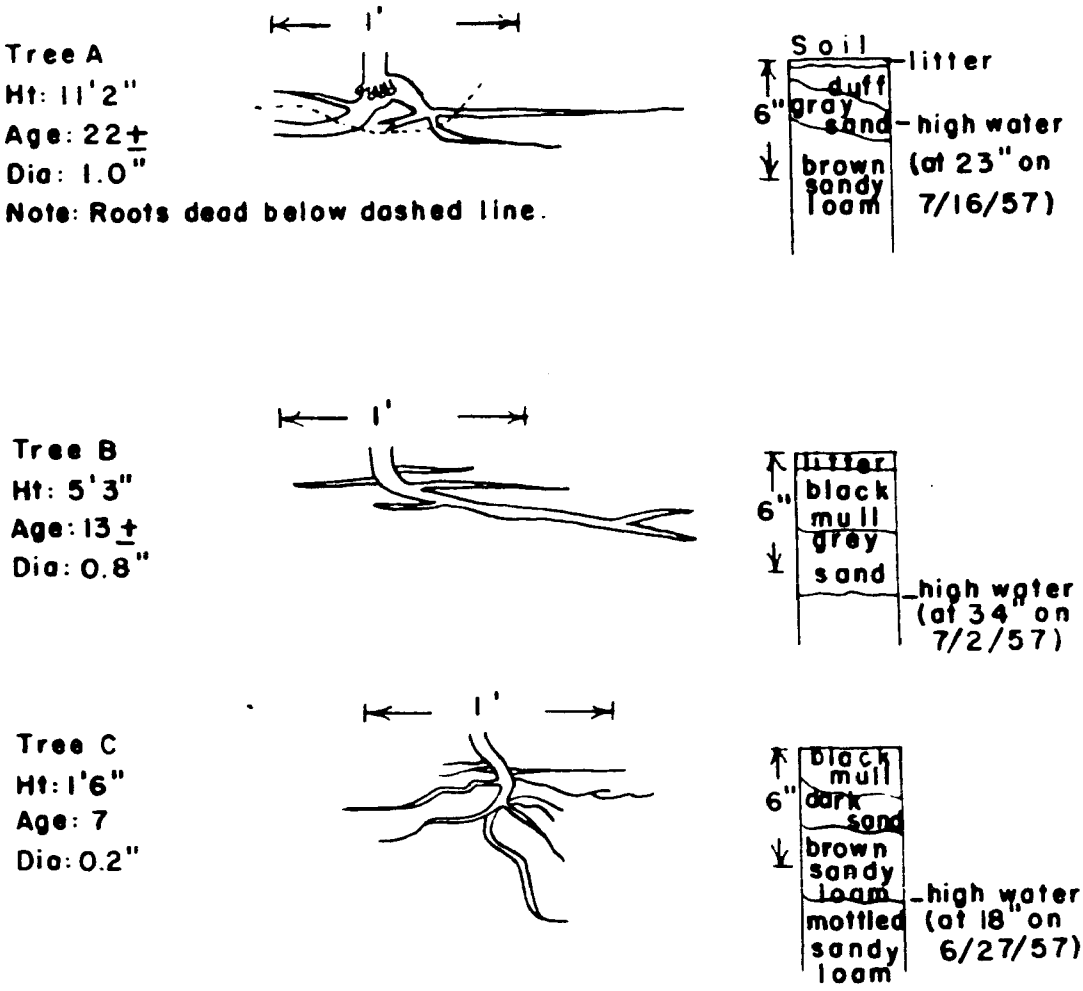


FIGURE 22. Vertical penetration and form of hard maple roots in type II-A swamps. Note that live roots are found only above the high water level. High water level established from well observations. Fine rootlets not drawn.

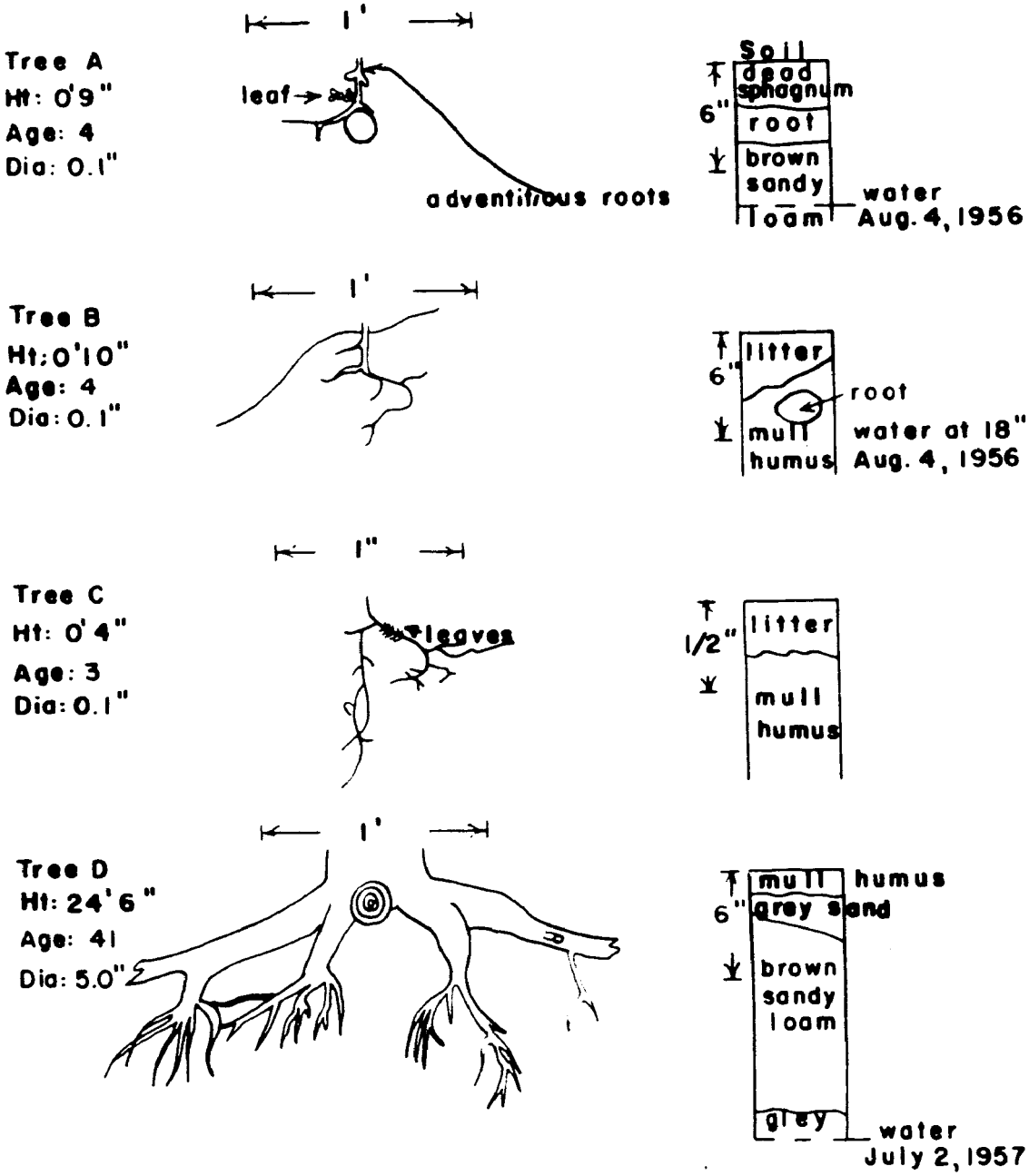


FIGURE 23. Vertical penetration and form of white cedar roots in type II-A swamps. No trees of intermediate size found on this type. Fine rootlets drawn only on tree C to show adventitious root development.

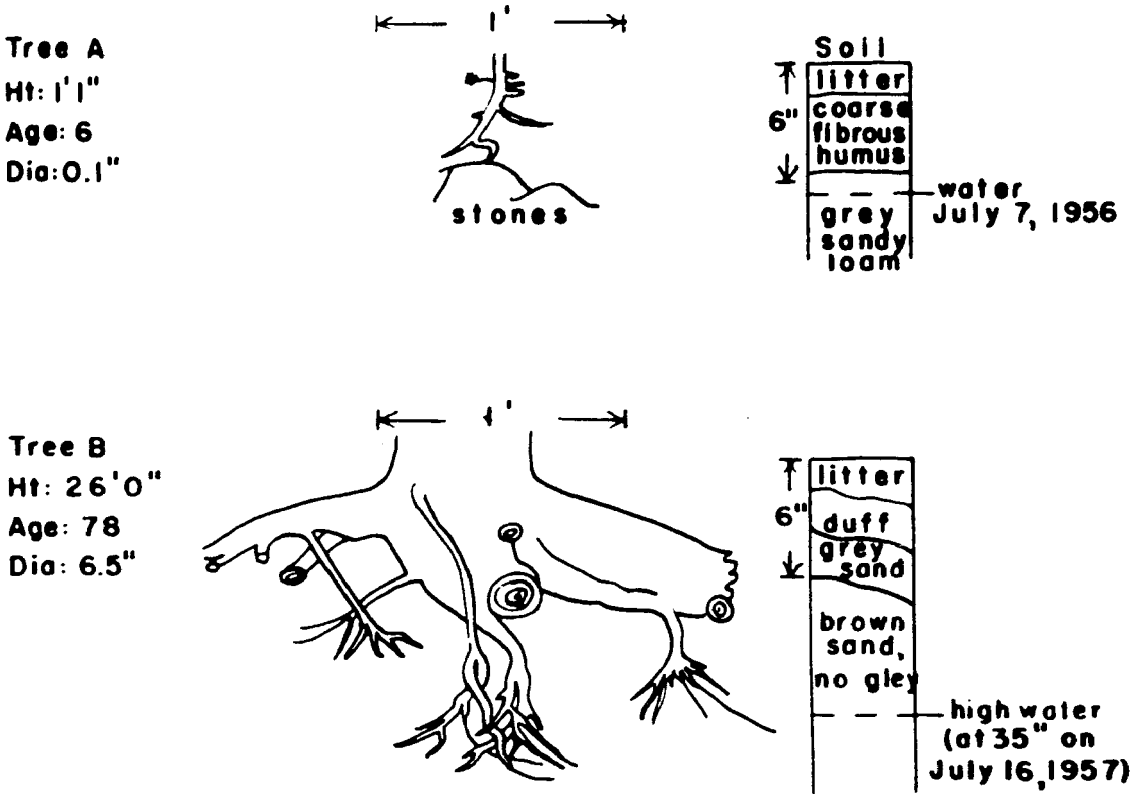


FIGURE 24, Vertical penetration and form of hemlock roots in type II-A swamps. No trees of intermediate size found on this type. Fine rootlets not drawn.

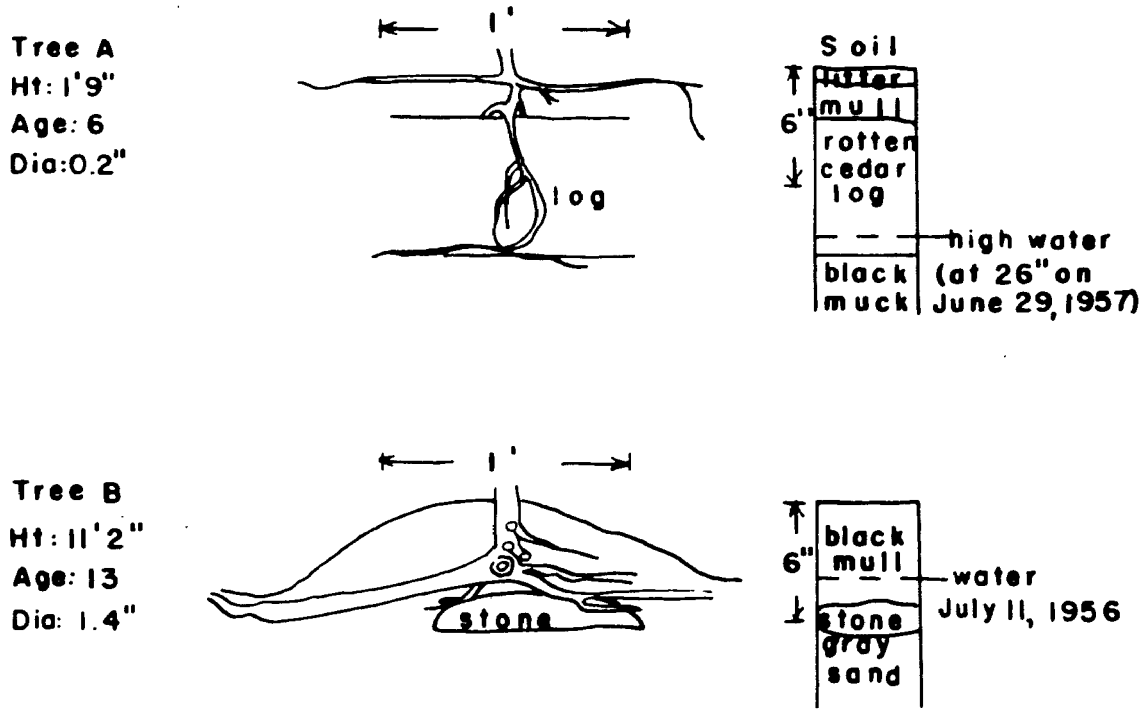


FIGURE 25. Vertical penetration and form of yellow birch roots in type II-A swamps. Fine rootlets not drawn.

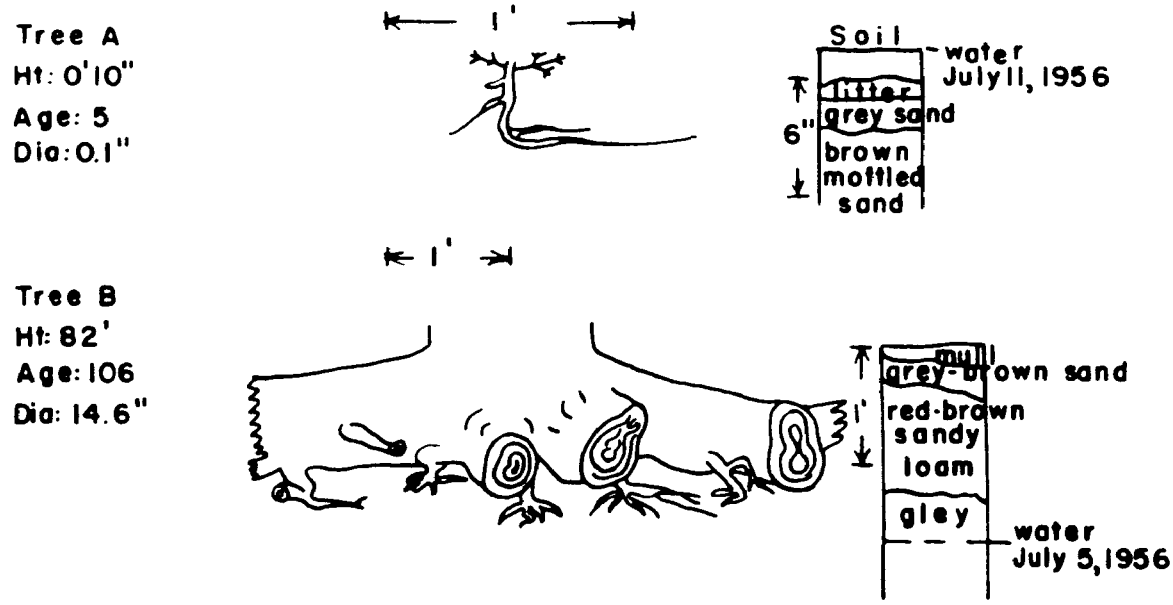


FIGURE 26. Vertical penetration and form of black spruce roots in type II-A swamps. Roots of tree A often flooded, tree B roots are mostly above high water levels.

the lowermost branch, fully one inch above the original soil level (Figure 26).

The development of the weak tap root of young balsam fir evidently ceases soon after it penetrates into the gley horizon in swamps with widely fluctuating water levels. Older trees such as the two excavated and shown in figure 27 were characterized by a relatively shallow lateral root system from which sinker roots penetrated downward below the higher water levels. Each of the sinker roots ended rather abruptly by dividing into a brush-like mass within the soil layer frequently saturated by ground water. No adventitious roots were observed.

The single white spruce excavated was shallow rooted. Two poorly developed sinker roots penetrated into a weakly gleized horizon at a depth of 26 inches and ended abruptly with little branching. The lower 6 inches of the larger sinker root were dead (Figure 28).

Roots of a red maple tree penetrated into the gley horizon and were nearly completely submerged during high stages of the fluctuating water level (Figure 29). In spite of this fact, the main root divided into three strong laterals almost at the level of maximum penetration. Adventitious rooting in the moist humus at the root crown was evident.

Root development in swamp type II-B-1.- During a wet year, ground water levels in this type remained relatively high and stable. It was only after a considerable precipitation deficit developed that the water level fell appreciably. Thereafter the water table fluctuated directly with precipitation.

Two soil pits were dug in this type (Figures 30 and 31). Plot E-2 was located on a very stony sandy loam characterized by large

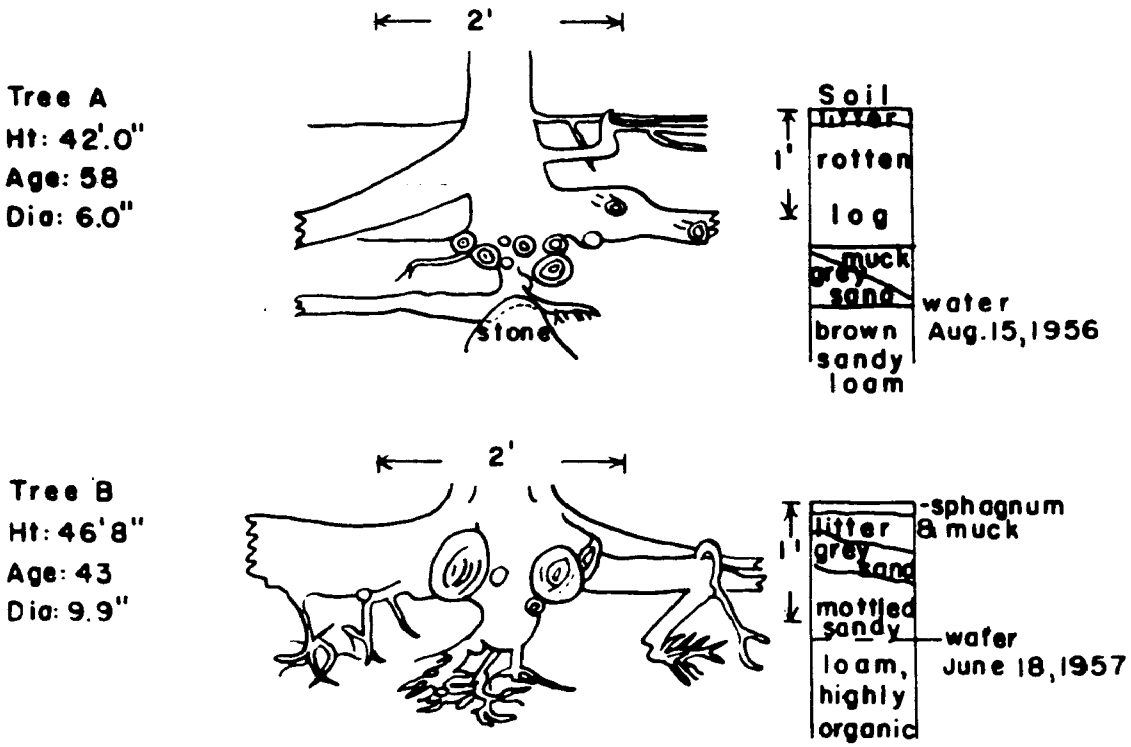


FIGURE 27. Vertical penetration and form of balsam fir roots in type II-A swamps. The short, stubby roots of tree B are typical in form of those found frequently below the water level.

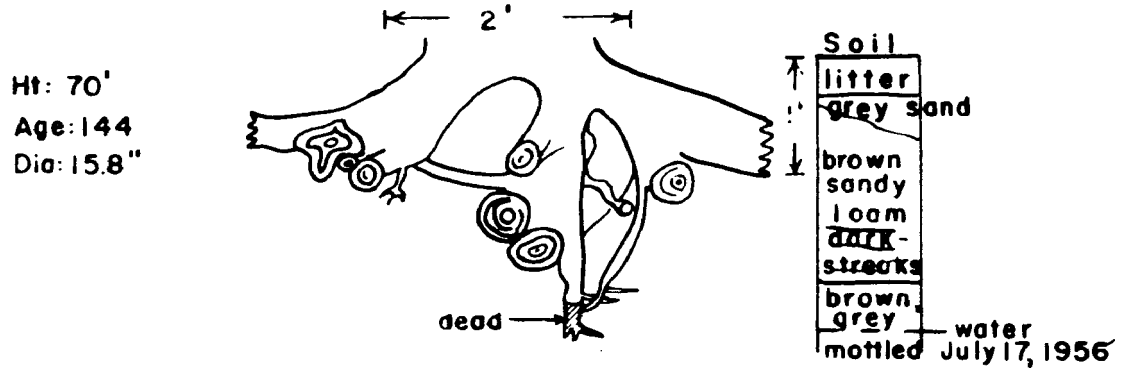


FIGURE 28. Vertical penetration and form of white spruce roots in a type II-A swamp. Tree infested with root rot.

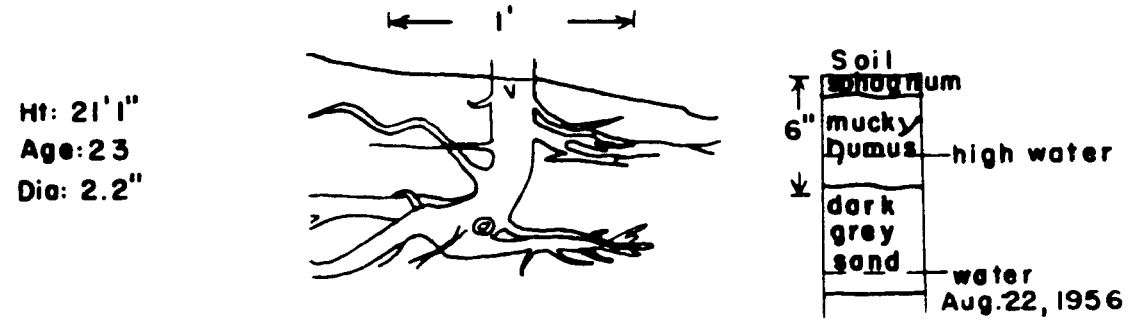


FIGURE 29. Vertical penetration and form of red maple roots in a type II-A swamp. Most of root system flooded during wet periods.

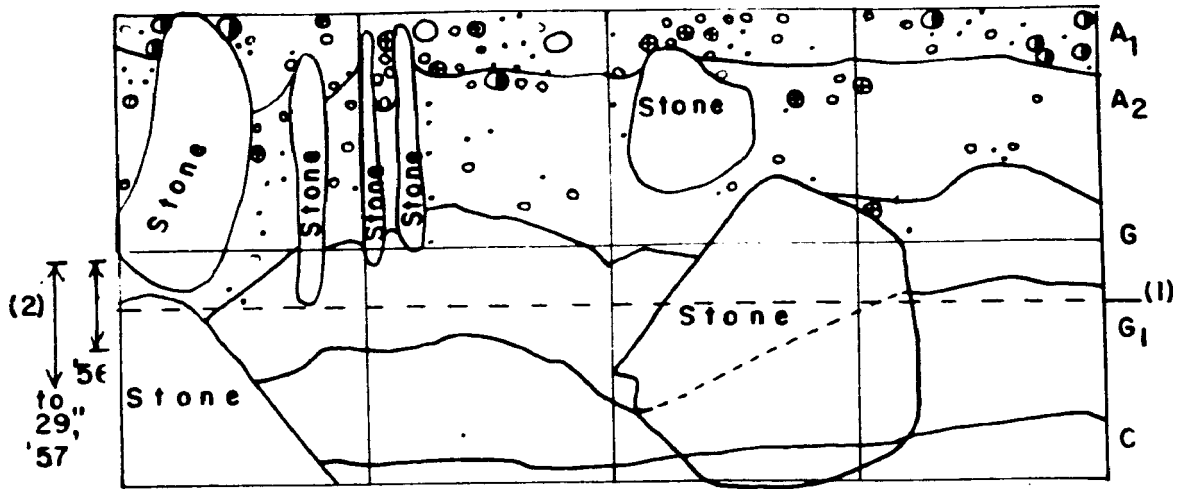


FIGURE 30. Soil profile and root distribution, plot E-2. (1)-Water level, August, 1956. (2)-Range in level, summers of 1956 and 1957. A_1 is mull humus, A_2 yellow-brown sandy loam, G grey, sticky sandy loam, G_1 black gley containing charcoal, C greyish-pink, platy sandy loam. Root sizes as in figure 6.

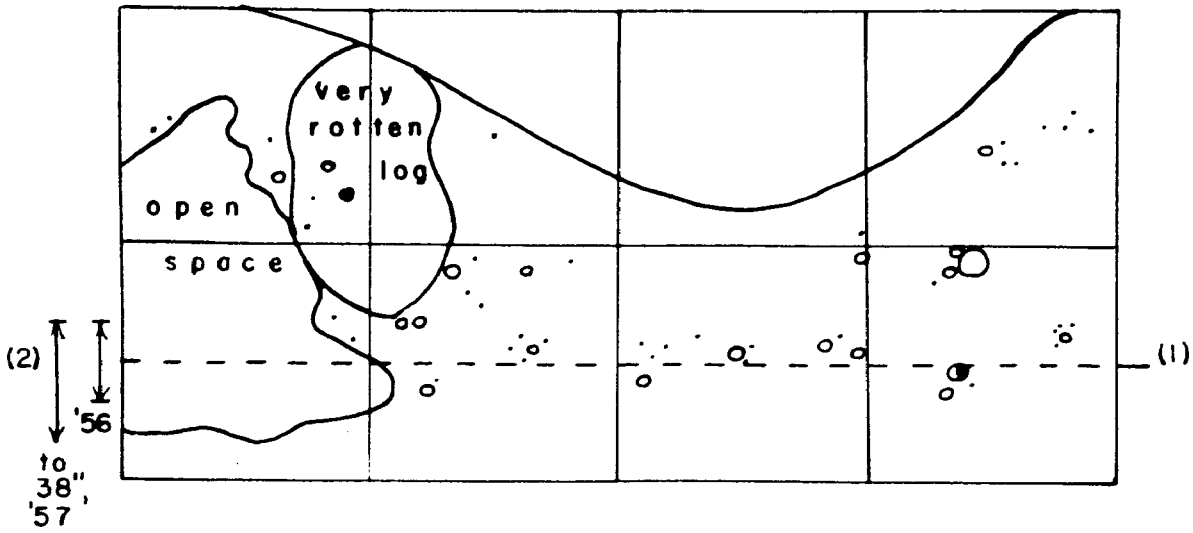


FIGURE 31. Soil profile and root distribution, plot U-2. (1)-Water level, August, 1956. (2)-Range in level, summers of 1956 and 1957. Soil grades from a mossy, fibrous peat at the surface into woody peat, over an extremely gravelly sandy loam at 27 inches depth. Root sizes as in figure 6.

hummocks and depressions. The hummocks were characterized by an organic layer of well incorporated granular mull humus, whereas the depressions supported a luxuriant growth of sphagnum moss. All of the yellow birch, white cedar and balsam fir grew upon the hummocks.

Tree roots in plot E-2 were concentrated in the A_1 horizon of the hummock examined, being 10.72 square inches of cross sectional root area per square foot of stone free soil. At lower levels, root density decreased rapidly to 0.93 square inches of root per square foot in the A_2 horizon and only 0.06 square inches per square foot at a maximum depth of 15 inches in the weak gley horizon. The depth of the water surface remained a little deeper than 12 inches from the top of the hummock throughout 1956, but dropped to 30 inches by late 1957. Most of the roots were above the water surface even during wet periods.

Plot U-2 was located on an organic peat soil of a similarly hummocky nature over a coarse gravelly and stony rubble embedded in sandy loam soil. A mossy fibrous peat at the surface graded into a black wood peat. Root penetration was restricted entirely to the peat layer. The water level in wet periods remained at approximately 18 inches below the top of the hummocks, or within a few inches of the surface in the depressions. During late 1957, it fell 2 feet below 1956 levels.

The distribution of tree roots in the hummock was unusual. There were no roots in the upper 6 inches. Below this depth, root density increased to the wet weather water level at about 18 inches beneath the hummock tops. The maximum depth of root penetration was 20 inches. A possible reason for the lack of roots near the hummock tops was the

extreme dryness of the hummocks during dry periods. During a dry period in 1957, sphagnum moss on several hummocks was so dry that it shattered underfoot when trod upon.

Root systems of three small white cedars, 9, 30, and 33 inches tall were excavated in this swamp type. Two alder trees were also excavated (Figures 32 and 33). All trees were shallow rooted, depth of penetration being limited by the high water level. Both of the alder and one of the cedars unmistakeably arose by layering. A dense mass of short fibrous roots arose from stems which were covered by organic material. The small cedar seedlings were similarly shallow rooted, and both showed evidence of adventitious rooting.

Root development in swamp type II-B-?.- This swamp type was characterized by a moderately deep water table that was stable for a period during the spring, but fell rapidly and remained low following a precipitation deficit. This type often marked the transition from swamp to upland. No well defined gley horizon was present in these border soils, but where lenses of heavy soils existed mild gleization was evident.

The three soil profiles dug in this type were all characterized by a wet weather water level between 25 and 34 inches below the soil surface, and all were in mineral soil. The water level on plots CC-2, U-1, and P-4 dropped below a depth of 5 feet during the dry summer of 1957. The profiles and root distribution are shown in figures 34, 35 and 36.

The humus layer of each profile contained the greatest concentration of roots of the larger white spruces, balsam firs and white cedars. Yellow birch, hard maple, and red maple seedlings were also concentrated

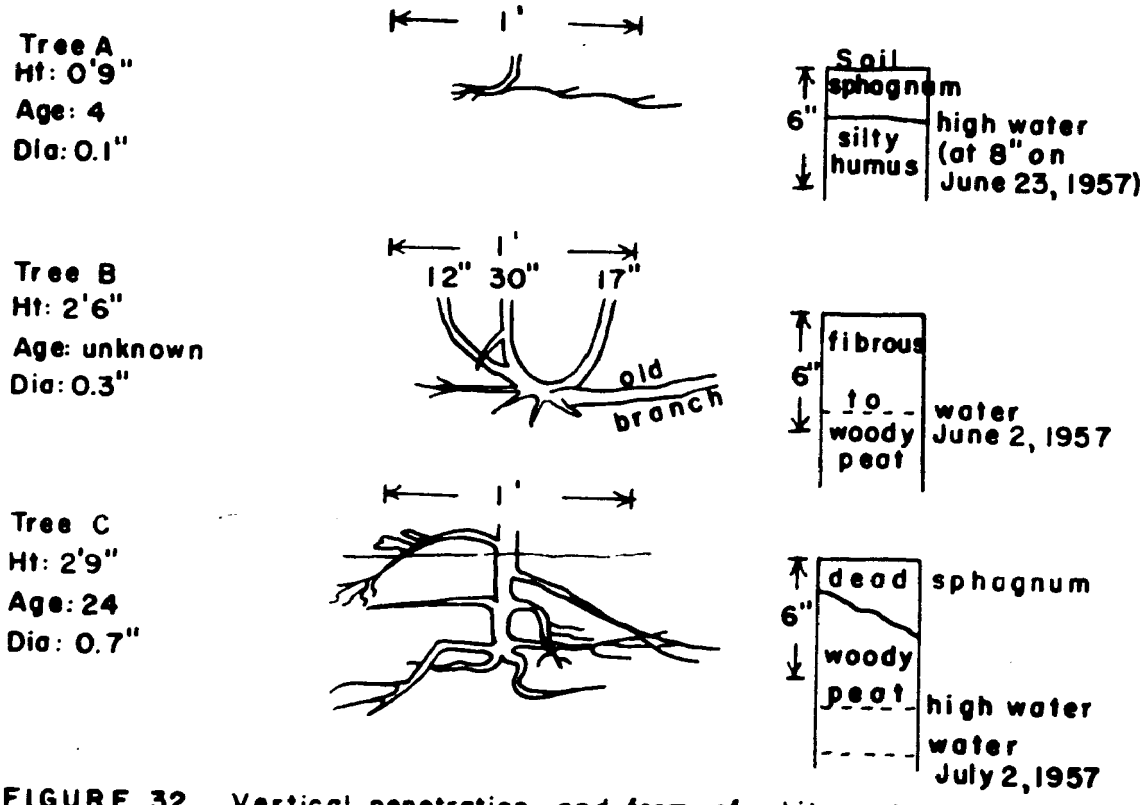


FIGURE 32. Vertical penetration and form of white cedar roots in a type II-B-1 swamp. Masses of fine rootlets not drawn.

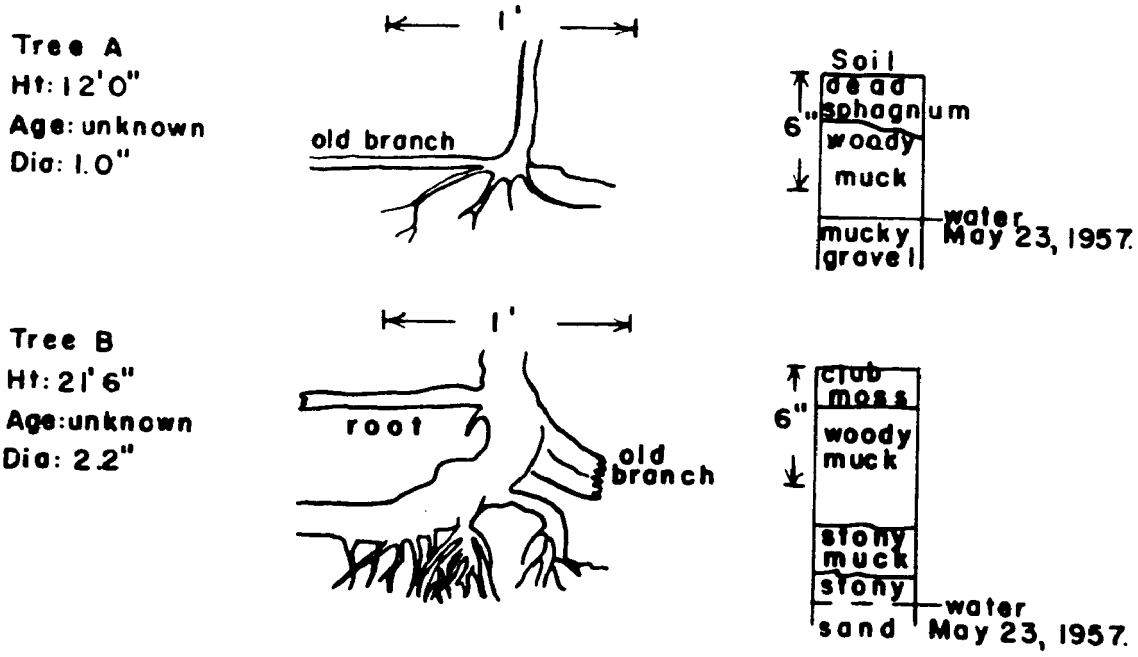


FIGURE 33. Vertical penetration and form of tag alder roots in a type II-B-1 swamp. Fine rootlets not drawn.

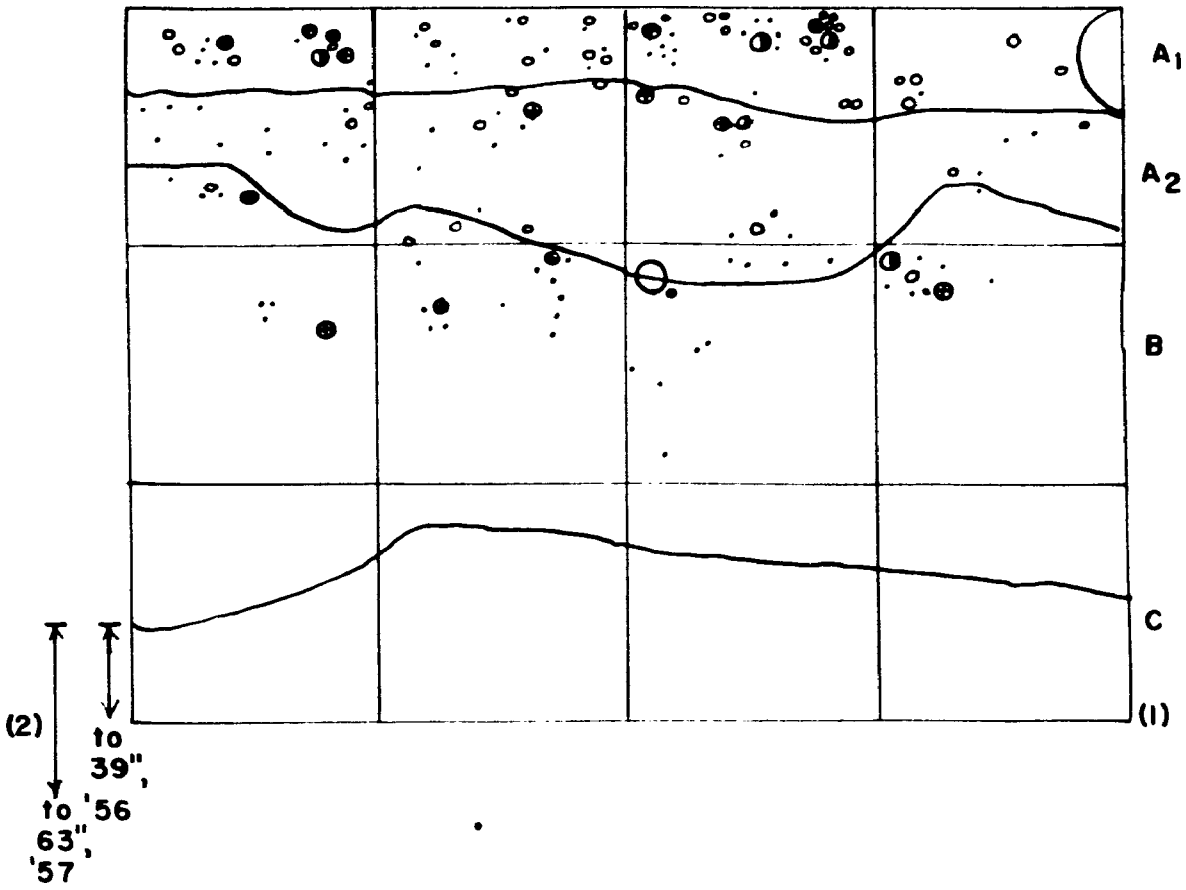


FIGURE 34. Soil profile and root distribution, plot U-1. (1)-Water level, August, 1956. (2)- Range in level, summers of 1956 and 1957. A_1 is block silty loam humus, A_2 dark grey sandy loam, B rusty-yellow sandy loam with clayey lumps, C stony loamy sand, no mottling evident. Root sizes as in figure 6.

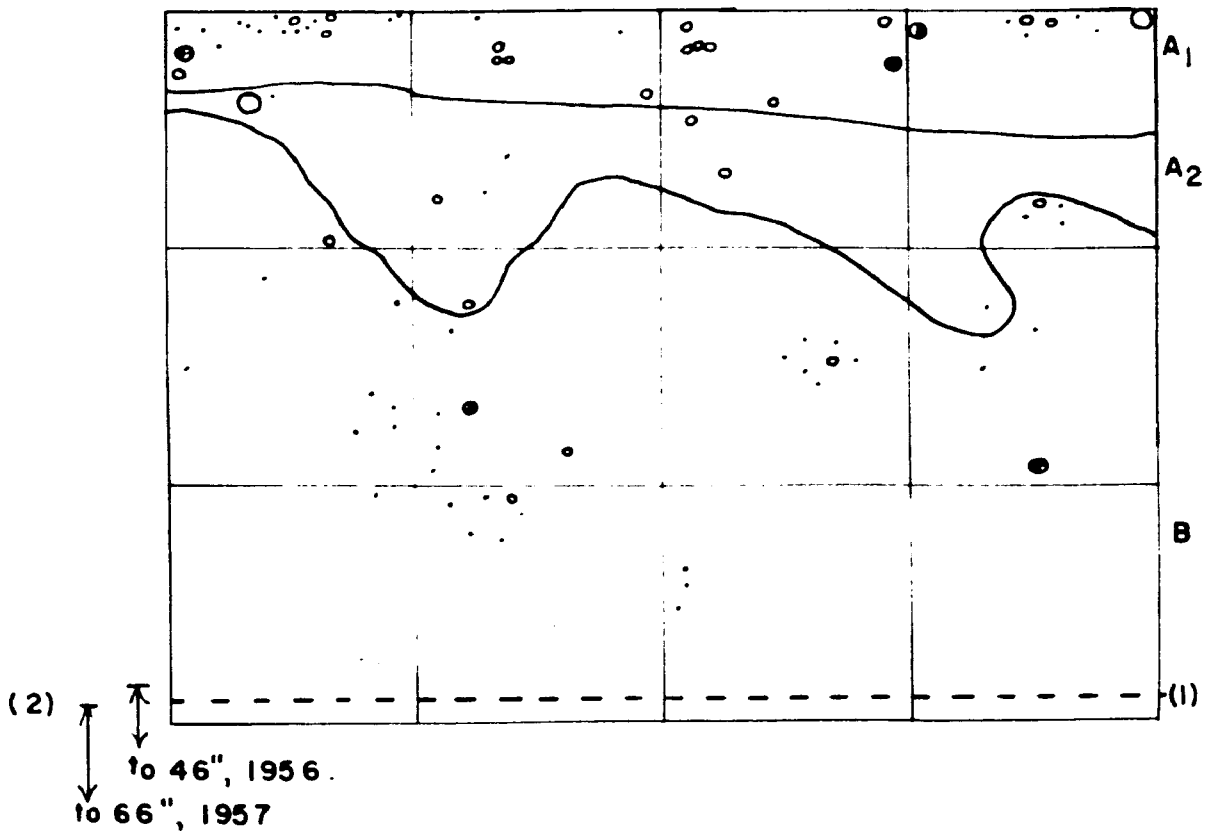


FIGURE 35. Soil profile and root distribution, plot P-4. (1)- Water level, August, 1956. (2)- Range in level, summers of 1956 and 1957. A_1 is sandy block humus, A_2 grey sand, B yellow-brown sand, dark brown splotches, no gley. Root sizes as in figure 6.

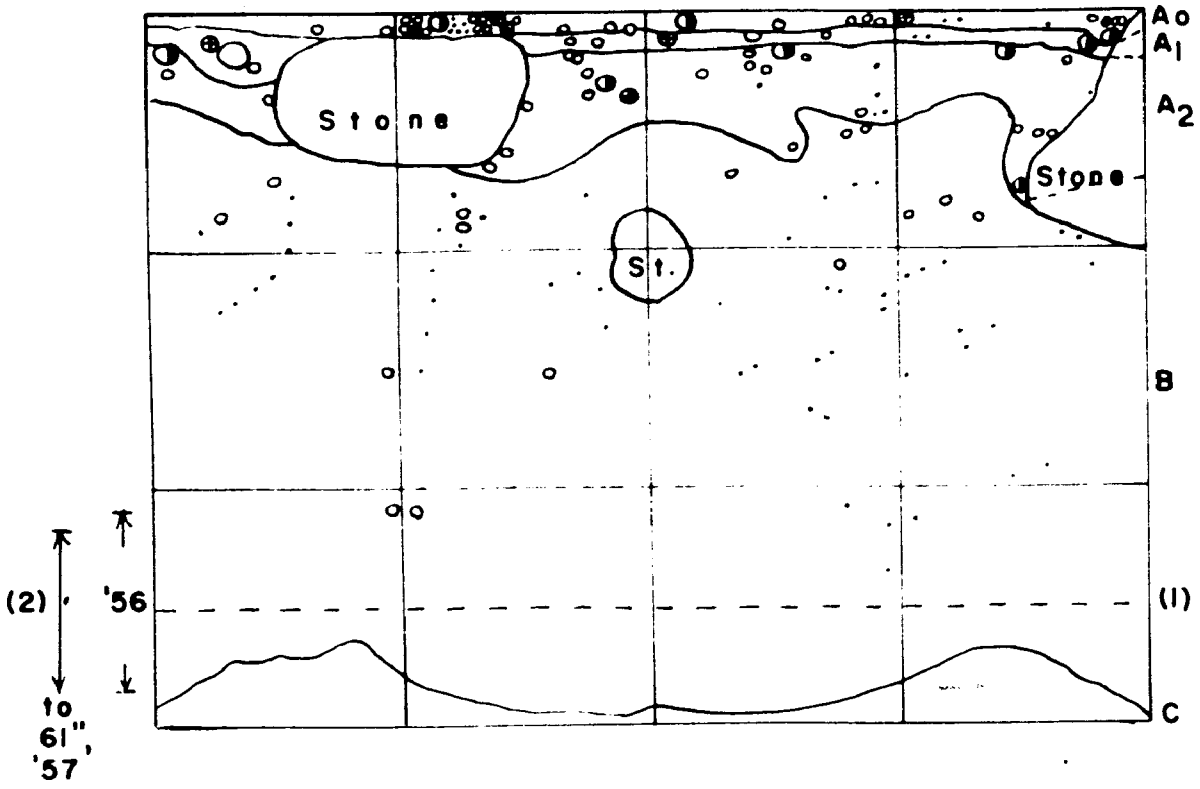


FIGURE 36. Soil profile and root distribution, plot C C-2. (1)-Water level, August, 1956. (2)-Range in level, summers of 1956 and 1957. Ao is black organic material, A_1 sandy humus, A_2 pink-grey loamy sand, B rusty-brown, blocky loamy sand, C hard, platy pink sandy loam. Root sizes as in figure 6.

there. None of the roots were below 30 inches. None penetrated below the high water level. From the standpoint of tree root penetration, these sites are more like uplands than swamps. As was true in the other swamps, roots were concentrated near the surface, decreasing rapidly with depth. There were 6.88, 1.87, and 0.52 square inches of cross sectional root area per square foot of stone free soil in the A_1, A_2 and B horizons, respectively.

Excavation of the root systems of individual balsam firs, yellow birches, hard and red maples showed that root penetration was practically unrestricted on the swamp border sites and root form and penetration were similar to that on uplands (Figures 37, 38, 39 and 40).

From the foregoing it appears that the high ground water level restricts the depth of rooting in all swamp types except in the swamp-upland transition where the upper surface of the ground water is below the B horizon. Individual species, however, appear to differ in their capacity to penetrate into the saturated soils. Balsam fir, black ash, yellow birch and red maple roots often penetrated to a depth of nearly permanent saturation. Black and white spruce, hemlock, white cedar and alder roots penetrated to depths that may be saturated for extended periods, especially during wet years.

In contrast, hard maples appear extremely sensitive to submersion and are shallow rooted when growing in swamps. All living roots of swamp grown saplings were restricted to levels only briefly or never flooded. In two specimens, the lower roots had been killed by high water.

Where ground water levels were high and relatively stable the roots of all species seemed to penetrate to a more uniform depth than

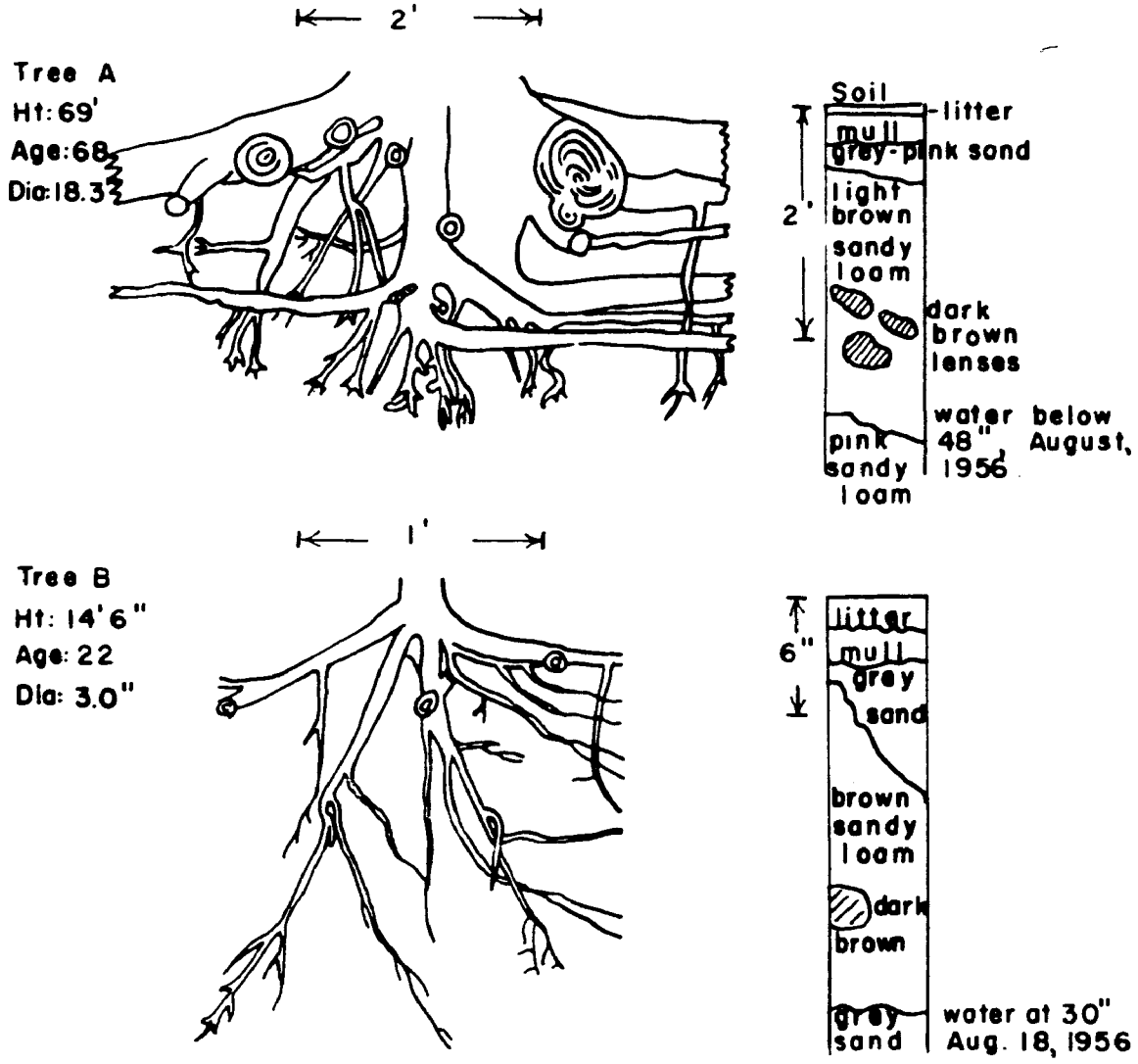


FIGURE 37. Vertical penetration and form of balsam fir roots on upland (A) and swamp border, type II-B-2 (B). Root systems are similar despite age and site differences.

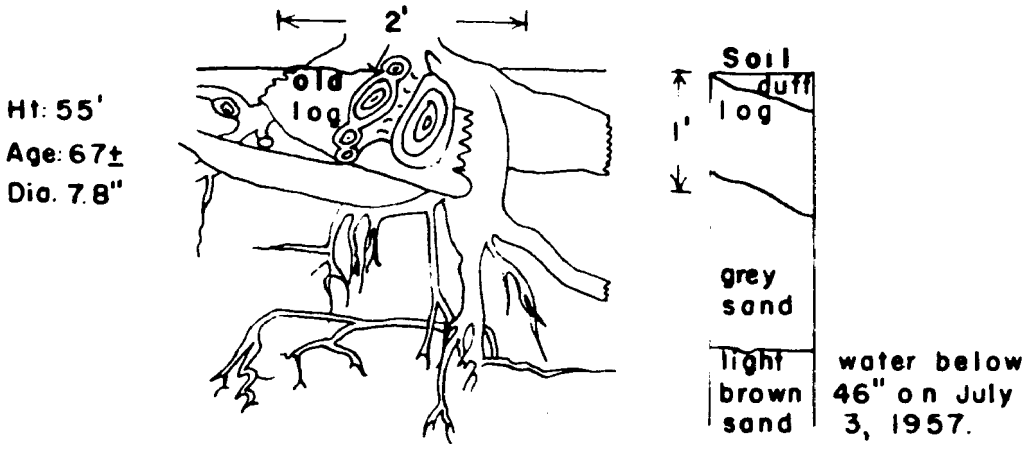


FIGURE 38. Vertical penetration and form of yellow birch roots in a type 11-B-2 swamp. Near plot CC-2.

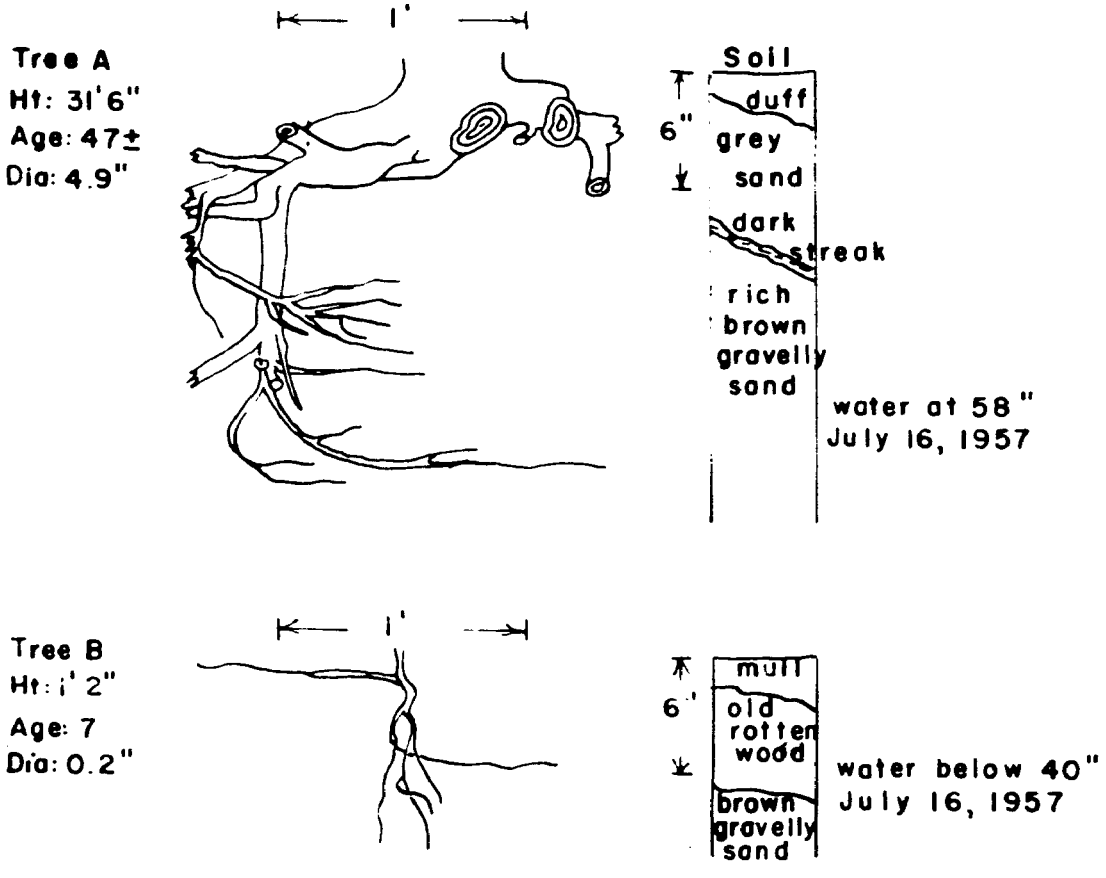


FIGURE 39. Vertical penetration and form of red maple roots in a type 11-B-2 swamp. Near plot P-4.

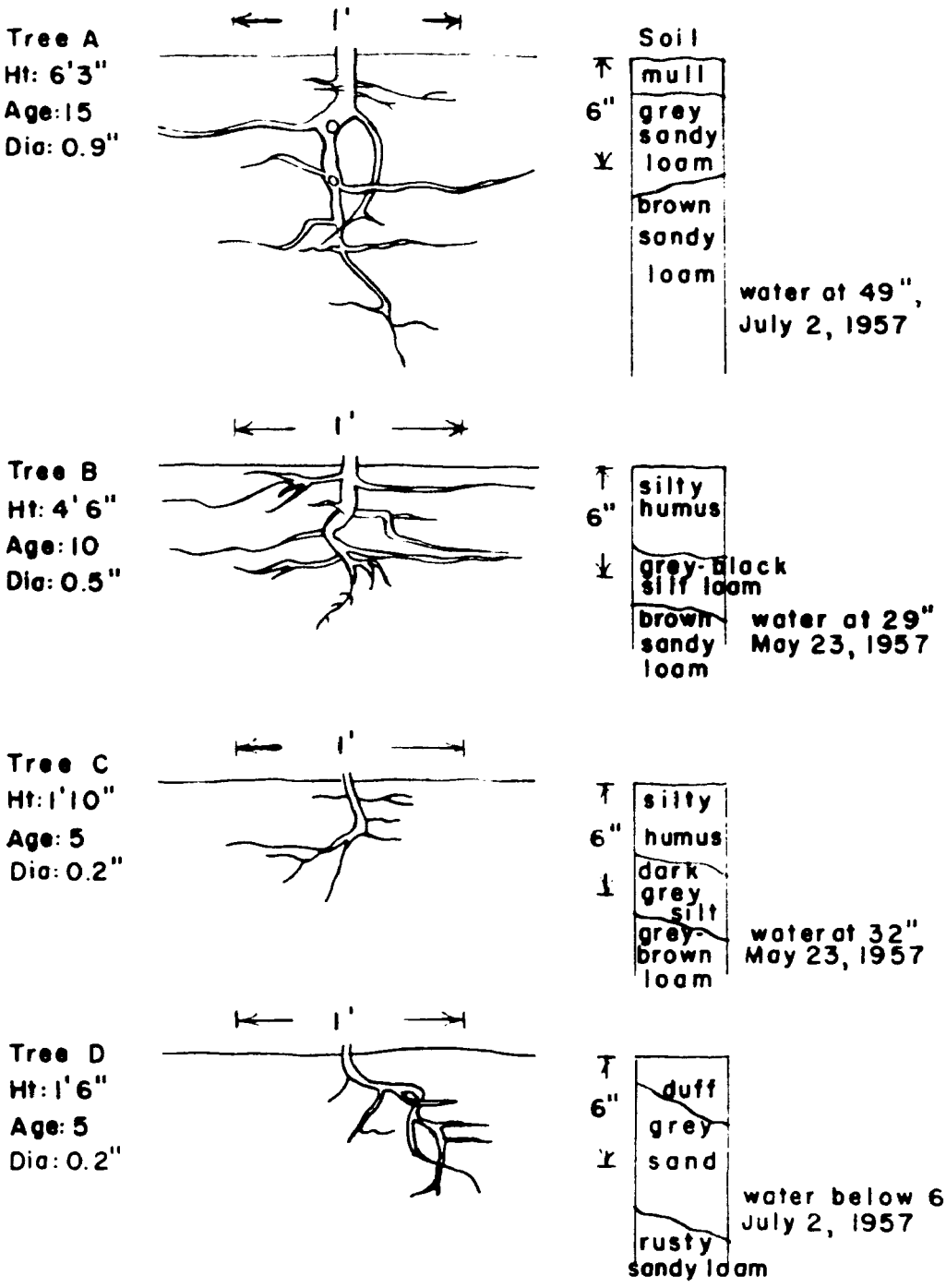


FIGURE 40. Vertical penetration and form of hard maple roots on upland and swamp border, type II-B-2. Tree A on plot CC-2, trees B and C on plot U-1, tree D on upland above CC-2.

they did where ground water levels fluctuated.

Root development and redox potentials.- Several writers have indicated that increasing freshness of the ground water in swamps is correlated with improved tree growth (Hesselman, 1910; Pierce, 1953). Since the ground water affects the tree through its root system, one might expect that the extent of penetration into the ground water by tree roots would be directly related to the redox potential of the ground water.

This assumption is not supported by the observations made in this study. In seven soil pits where roots were observed below the ground water, the redox potential of the ground water (adjusted to pH 7) ranged from -252 to 18 millivolts, with a mean value of -87 millivolts. In five other profiles where the ground water was periodically so high as to restrict root penetration, roots were not found below the high water level of 1956. Redox potentials on the latter plots ranged from -6 to 300 millivolts, with a mean value of 148 millivolts. In addition, the roots of trees excavated individually on plots exhibiting high water levels penetrated into ground water of both high and low redox potentials.

These observations on root development in relation to redox potential are inconclusive. If any relationship does exist, it is obscured by water level fluctuations, variations in soils and other factors. Only by controlled experiments can the significance of redox potential be established with confidence.

Root development and seepage.- On all plots in type I-A and II-B-1 swamps the ground water remained close to the soil surface for extended periods. The influence of lateral water movement on root

growth was considered to be most important under such conditions. Root development in relation to seepage on these plots is shown in Table 5.

TABLE 5

ROOT DEVELOPMENT ON PLOTS CHARACTERIZED BY PERSISTENT HIGH GROUND WATER LEVELS IN RELATION TO RATE OF SEEPAGE

Plot	Water level 1956 inches[1]	Seepage ft/day	Maximum root depth inches	Root density in upper 3" of ground water Sq. in. root/Sq.ft. soil
E-1	4	0.1	4.5	0.07
E-2	15	0.3	14.5	0.00
P-3	14	2.0	17.5	3.82
C-4	13	3.5	13.0	0.00
C-3	11	3.5	12.0	0.12
U-2	18	5.0	19.5	0.66
C-1	6	7.0	7.0	0.53
C-2	13	8.0	13.5	0.79
P-2	5	14.0	8.0	0.63
C-5	9	16.0[2]	8.5	0.00

[1]Depth may differ from well observations due to variations in micro-topography at the two locations within each plot.

[2]Rate may not be representative due to heterogeneous character of substratum.

On the plots where tree roots exposed on the face of the soil pits extended into the ground water, the rate of seepage exceeded 2 feet per day, except on plot E-1. On this plot, only a single root was found below the water, and that one was barely below the surface.

Elsewhere, tree roots commonly penetrated into the ground water. Plot C-5 represents a unique case, for the rate of water movement through the large openings in the stones was very rapid, but tree roots were unable to reach the rapidly moving stream due to the air space above the water (cf. figure 13). The rate of water movement through the clayey lens and sandy loam soil was not determined, but in all other similar soils studied, seepage rates less than 1 foot per day were measured.

These results indicate that seepage movement through swamp soils may ameliorate the unfavorable effects of high water levels. Several writers have suggested that such may be the case (Donahue, 1940; Tamm, 1950; Troedsson, 1952, 1955). The favorable effect of moving water is usually attributed to better aeration in moving than stagnant waters, a conclusion which remains open to question, as no distinct relationship between redox potential and the rate of ground water movement could be detected (Figure 41).

Nevertheless, despite low redox potentials in the ground water, tree roots are able to penetrate and survive in such water when it is actively seeping through the soil. Several writers have noticed the favorable effect of moving water on plant growth and have suggested that reasons other than oxygen supply may be important, such as the removal of toxic materials and the presence of greater amounts of plant nutrients in moving than in stagnant water (Huikari, 1954; Gorham, 1953; Troedsson, 1952). Huikari (1954) further suggests that roots of birches, pine and spruce in Finland may penetrate into stagnant water and receive the necessary oxygen for respiration from a supply transported downward in the sap of the tree. The possibility of an internal aerating system

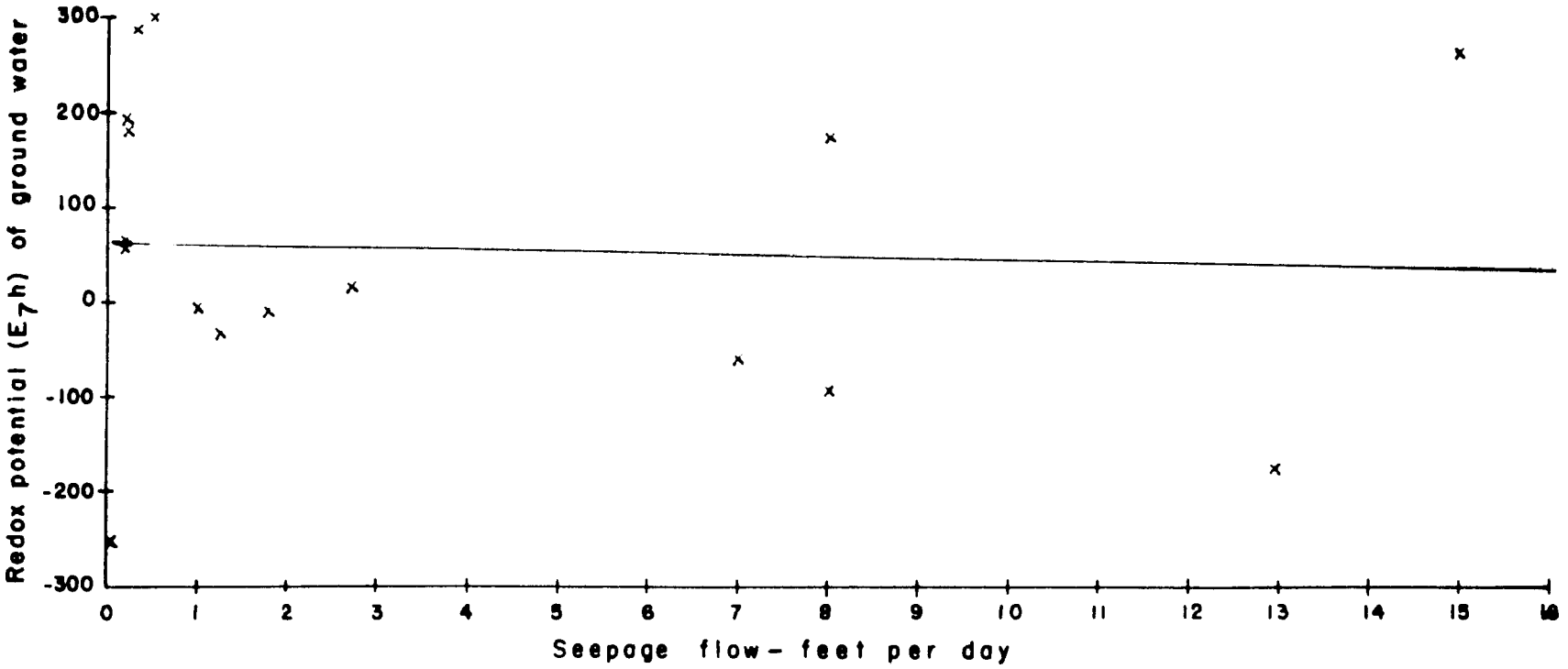


FIGURE 41. The relation between redox potential and rate of ground water seepage in several swamps.

in the xylem of Alnus glutinosa is propounded by McVean (1956).

Such possibilities help to explain root penetration into ground water, but still fall somewhat short of explaining the greater extent of root penetration in moving, yet poorly aerated ground water as opposed to stagnant, poorly aerated ground water. It seems that an additional factor related to water movement may also be important, along with the reasons mentioned above.

Oxygen dissolved in water is chemically very active; much more active than oxygen contained in more or less dry air, as evidenced by the rapid oxidation of a piece of iron submerged in water containing small quantities of dissolved oxygen. When water is moving past a substance, a considerable amount of dissolved oxygen may come into contact with it even at very low concentrations. Thus the actual supply of oxygen to a root may be as much a function of the rate of water movement as to the concentration of the oxygen itself in the ground water. Therefore, seepage water may exert a favorable effect in supplying oxygen for the respiration of tree roots even though the water may be rather poorly aerated as evidenced by the redox potentials seen in this study. This may be the explanation to the apparent inverse relation shown between root penetration and redox potentials shown earlier.

A further examination of redox potentials in the ground water will be made in relation to site quality of spruce and fir.

The moisture supply in the root zone

Quantity.- It is evident from the foregoing that high water levels restrict the depth of rooting by swamp trees. Furthermore, in the

several swamp types, water level fluctuations do not vary synchronously by season or amount and distribution of precipitation. At any given time ample moisture may be available in one swamp, while in another the moisture content in the root zone may be very low.

Several factors affect the moisture supply within the root zone in any swamp. The amount and distribution of precipitation, and the position of the water table are especially important. In a given swamp type either may be the dominant factor.

Observations during the dry summer of 1957 indicated that no important soil moisture deficit below field capacity developed at any time in swamp type I-A, where the water level was shallow and essentially stable. This statement holds regardless of the soil type. Figure 42 shows the mean soil moisture deficit in the root zone in this swamp type in relation to precipitation and the mean depth of the water table.

In swamp type I-B, where the water level was moderately deep and stable the moisture content of the soil varied with precipitation, but the range of variation was considerably reduced by the moisture moving upward from the water table in the capillary fringe (Figure 43).

Where the water level fluctuated directly with precipitation as it does in swamp type II-A, and in type II-B-1 following the drop in level subsequent to the appearance of a precipitation deficit, the depth of the water table was closely related to the moisture deficit in the soil. In the loamy sand and sandy loam soils examined in these swamps a moisture deficit below field capacity did not appear in the soil until the ground water fell deeper than one foot from the soil surface. Thereafter, the moisture deficit in the soil rose approximately 1 inch per foot of drop in the water level when the ground water

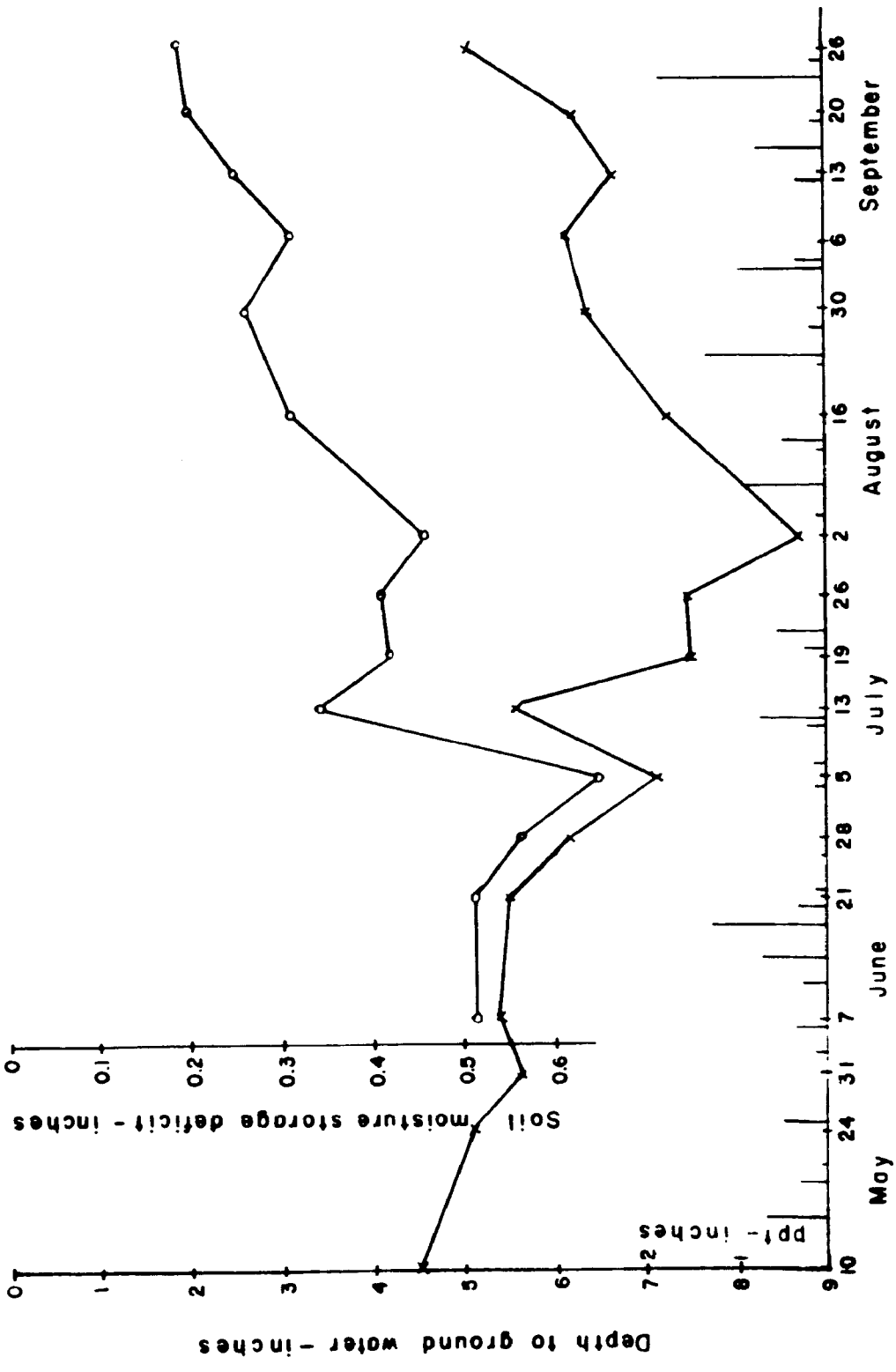


FIGURE 42. Mean soil moisture storage deficit in relation to water levels in type I-A swamps, summer of 1957.

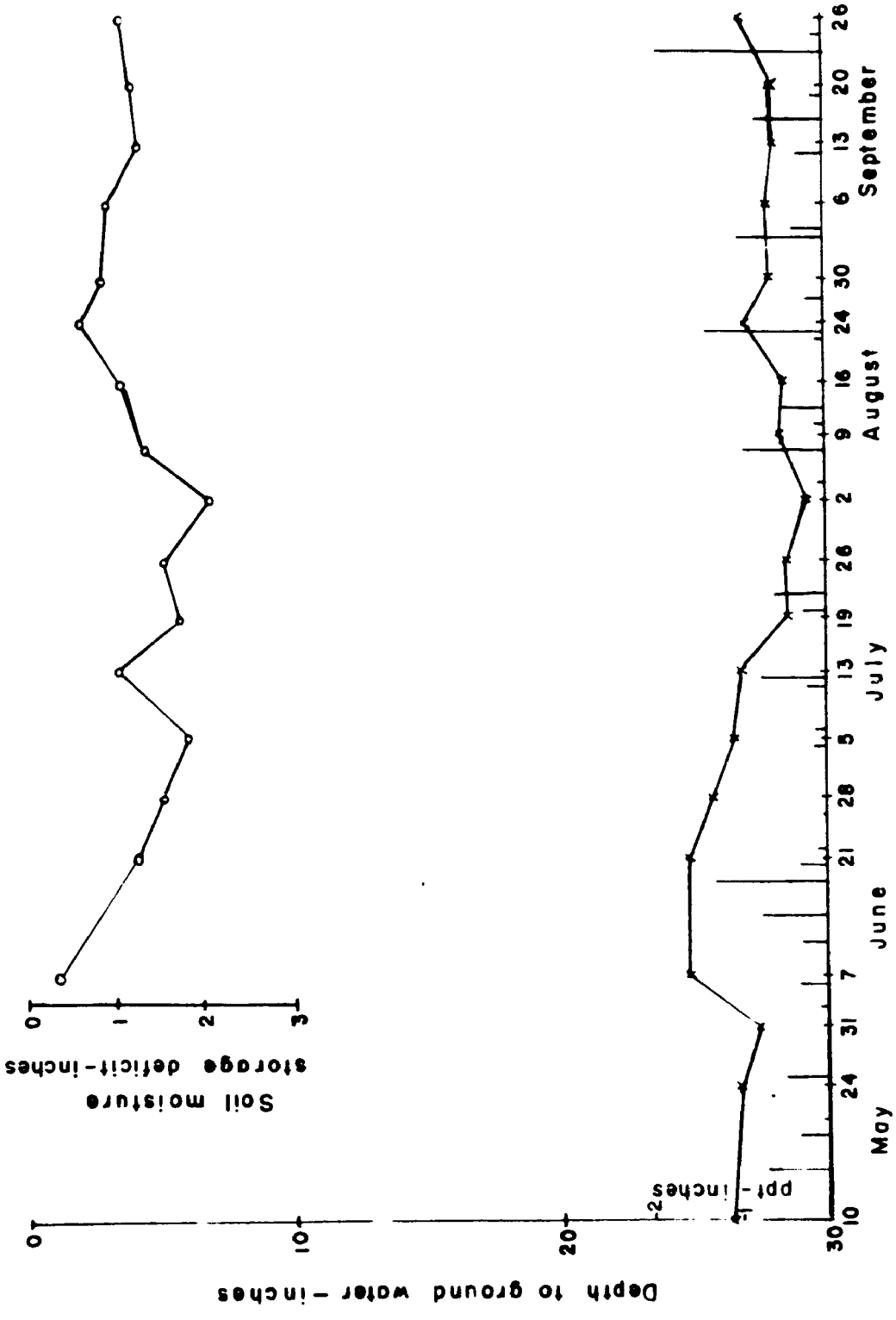


FIGURE 43. Soil moisture storage deficit in relation to water level in a type 1-B swamp, summer of 1957.

level was between 1 to 4½ feet below the soil surface (Figures 44 and 45).

In the remaining swamp type, II-B-2, where the ground water fluctuated only after a considerable precipitation deficit or surplus, there was little relation between the depth of the ground water and the moisture content of the soil in the root zone. Early in the growing season the moisture content varied with precipitation within limits determined by the depth of the ground water as in type I-B swamps. Following the major drop in water level the moisture content again varied with precipitation, but the limit in variation imposed by a deeper water level was less marked. Thus, little relation between ground water level and soil moisture content in the root zone existed in this swamp type (Figure 46).

Of all the swamp types there was only one type wherein the moisture content of the root zone was closely related to the depth to the ground water. Wherever the water level fluctuated immediately and directly with precipitation such a relationship existed. In all other swamp types the depth to the ground water at a given time at best only indicated the amplitude of variation in moisture content which is possible. As the depth to ground water from the soil surface increased, the amplitude in variation of soil moisture content increased until it approached that of upland soils.

Distribution.- The moisture content of swamp soils lying above ground water varied most in the upper 4 inch soil layer, except on plot CC-1. The soil moisture variation at plot CC-1 is unusual in that the range in variation increased with depth. Such a phenomenon is entirely unexpected. There are two closely related explanations

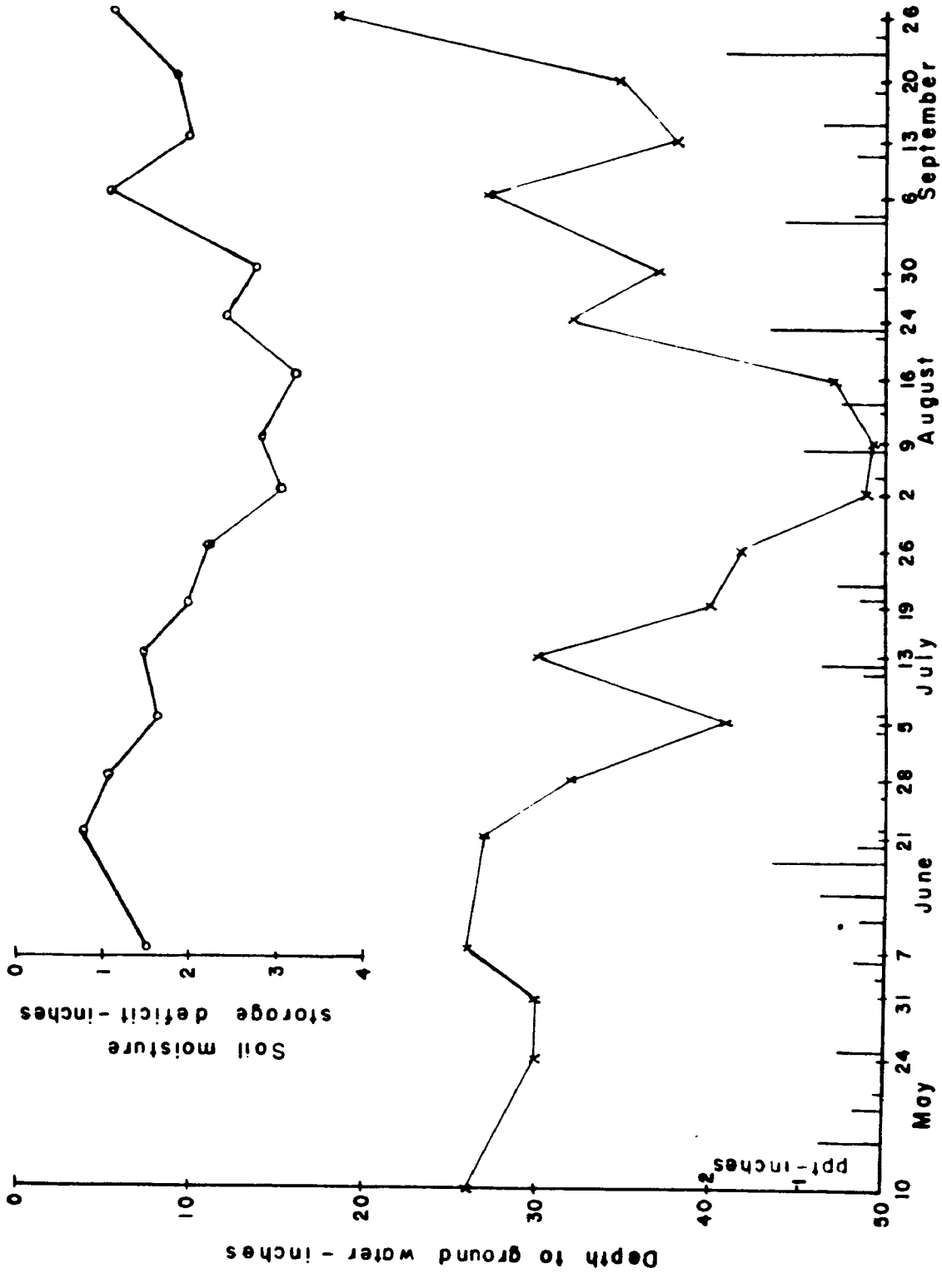


FIGURE 44. Mean soil moisture storage deficit in relation to water levels in type II-A swamps, summer of 1957.

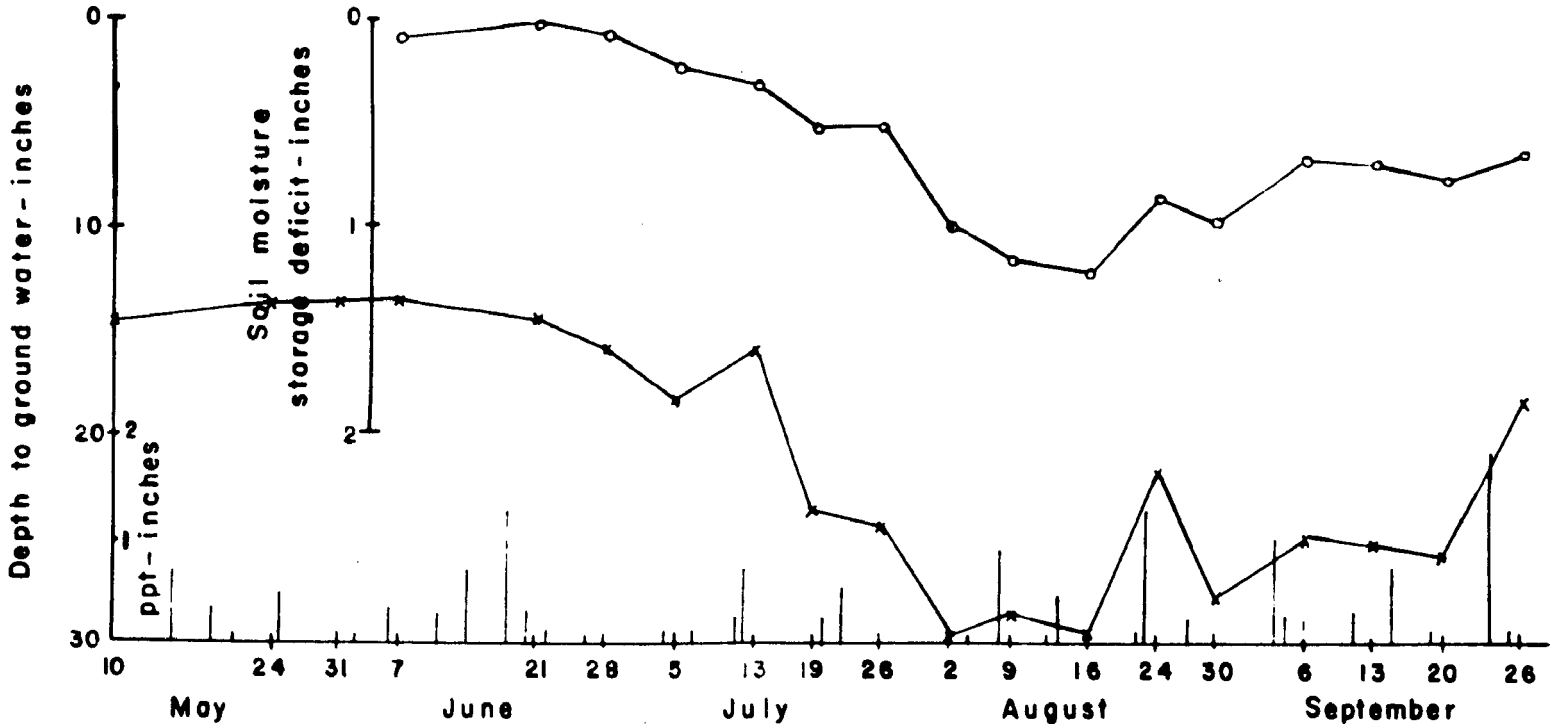


FIGURE 45. Soil moisture storage deficit in relation to water level in a type II-B-1 swamp, summer of 1957.

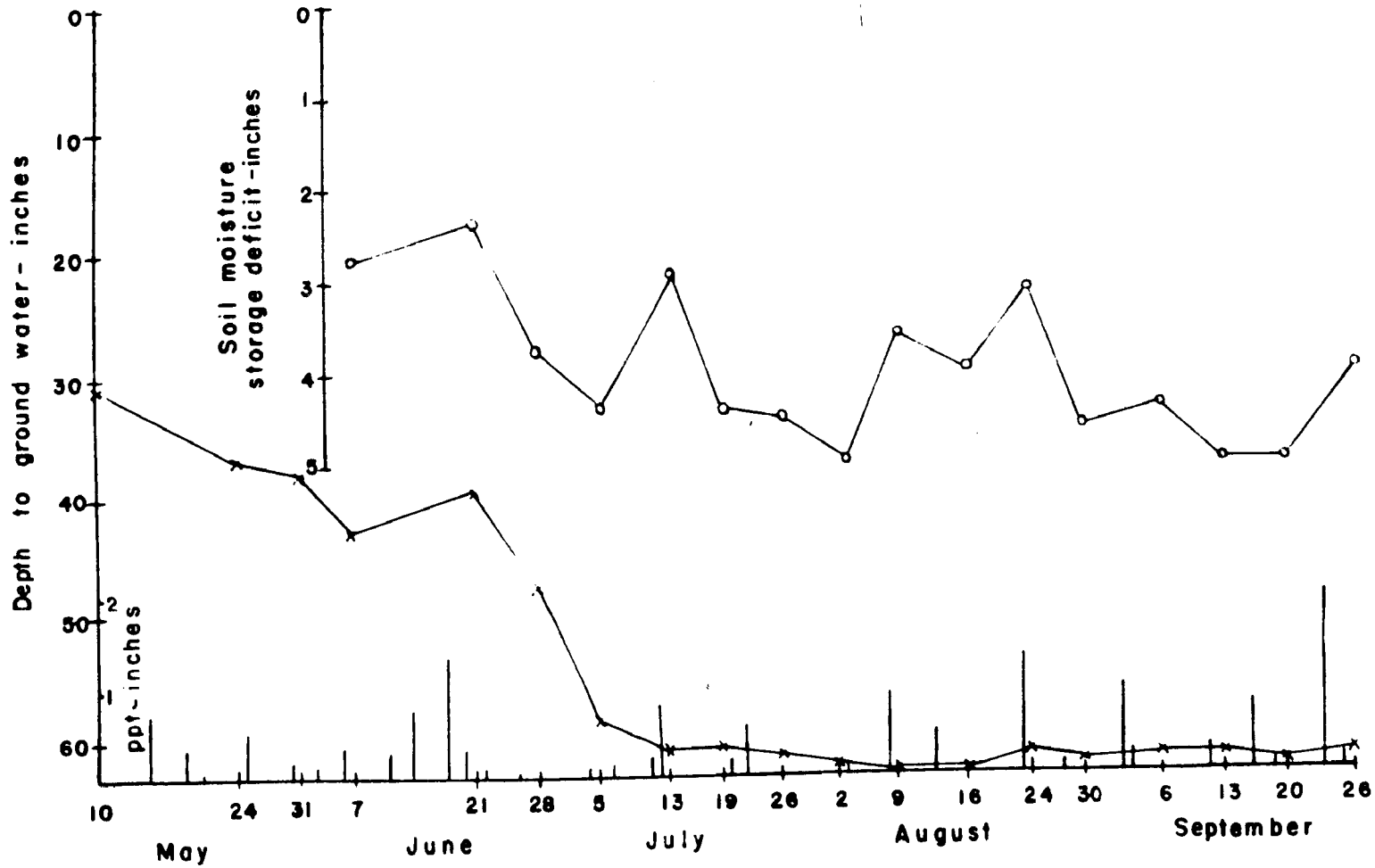


FIGURE 46. Mean soil moisture storage deficit in relation to water levels in type II-B-2 swamps, summer of 1957.

that may help clarify this inconsistency. First, in digging the trenched plot, the roots near the soil moisture units may have been killed back sufficiently to prevent normal moisture absorption in the upper soil layers. Second, the normal root distribution may not have been present, there being more absorbing roots near the lower moisture units than the upper ones. An examination of the root distribution across the face of the soil pits indicates that heterogeneous root distribution might well be expected frequently enough to cause such a result as herein shown.

Either killing back of roots or erratic distribution would affect soil moisture extraction. Aldrich et al (1935) indicated that soil moisture extraction by pear roots is directly proportional to root concentration, suggesting that moisture movement in soils at less than field capacity is so slow as to be practically unavailable to trees when it is more than a short distance from the absorbing roots.

Generally speaking, the soil moisture content increased with depth. The greatest range of seasonal variation occured near the soil surface with the least seasonal variation in moisture content at lower levels, except where the ground water laid at a depth exceeding 4 feet in late August, 1957. A heavy rain of 1.33 inches on August 23, 1957 moistened the soil to a depth of 12 or more inches, raising moisture contents considerably above that level, but it had little effect below. The moisture content in the lower soil levels continued to fall slightly after this rain, and spring moisture contents were greater, so the range in moisture content at the 15.1 to 21.0 inch level exceeded that of the 9.1 to 15.0 inch level (Table 6).

TABLE 6

VARIATION IN SOIL MOISTURE CONTENT BY DEPTH IN SWAMP SOILS INFLUENCED BY GROUND WATER - SUMMER OF 1957

Plot	Swamp type	Inches Depth to groundwater High Low	Ratio of maximum to minimum observed moisture content in inches of water by depth below soil surface. Soil depth (inches) 0-4.0	4.1-9.0	9.1-15.0	15.1-21.0
CC-2	II-B-2	25-61	4.10	3.69	1.83	2.36
P-4	II-B-2	34-66	2.95	2.71	1.58	2.05
U-1	II-B-2	30-63	2.24	2.99	1.34	1.41
E-2	II-B-1	13-29	1.82	1.51	1.05	1.00
U-2	II-B-1	4-26	No record moisture units stolen			
E-3	II-A	9-44	2.81	2.14	1.13	1.02
CC-1	II-A	8-48	1.57	1.67	2.04	2.06
P-1	I-B	31-37	2.39	1.43	1.30	1.12
P-2	I-A	4-8	1.44	1.09	No units deeper	
C-2	I-A	8-10	1.22	1.15	" "	"
C-3	I-A	6-10	1.34	1.03	" "	"
C-4	I-A	6-12	1.43	1.09	" "	"
C-5	I-A	9-13	1.31	1.14	" "	"
C-1	I-A	3-6	1.62	No units deeper		
P-3	I-A	3-15	1.41	" "	"	
E-1	I-A	2-7	1.29	" "	"	

In spite of the fact that the uppermost soil layer dried sufficiently to cause mortality of seedling hard maple, yellow birch and elm on several plots in 1957, available moisture was present in the root zone of the larger trees throughout the entire summer of 1957 on all plots. It may well be that the lower moisture contents observed in the upper soil layers were due to moisture extraction by shallow rooted seedlings, forbs and shrubs, as well as the loss due to direct evaporation. The tops of sphagnum hummocks on plot U-2 were also observed to dry so severely that the moss shattered underfoot during the dry periods in 1957. Surface moisture conditions were sufficiently dry to impede seedling development in all swamp types except type I-A, where the water moving upward from the shallow water table kept the soil moist to the surface throughout the season.

Nutrients in ground water

In addition to the effect of ground water characteristics such as water level and redox potential, the ground water may provide a supplementary source of nutrient ions to forest tree roots. In this study, however, the ionic content of the ground water was extremely low at all plots, the specific conductances measured varying between 2.5^{10-6} and 13.2^{10-6} units. See table 7. In comparison with the total nutrient supply in the root zone, the quantity of nutrients in the ground water is considered insignificant.

TABLE 7

SPECIFIC CONDUCTANCE OF GROUND WATER ON SWAMP PLOTS

Plot	Spec. Conductance (10^{-6} units) Mean	Range	No. of Samples
P-1	2.5	2.3-2.9	4
E-2	2.8	2.2-3.6	4
U-2	2.9	2.6-3.1	4
E-3	3.5	3.0-4.5	4
E-1	3.6	2.9-4.0	4
CC-2	3.8	3.3-4.4	4
P-4	4.2	3.0-5.4	4
U-1	4.7	3.1-7.0	4
C-1	4.9	3.8-6.1	5
CC-1	5.0	3.8-6.1	4
C-5	5.3	4.0-7.3	4
C-2	6.2	4.7-7.2	5
P-2	7.2	5.3-9.0	4
C-3	7.8	5.3-10.0	5
C-4	9.0	7.3-9.8	5
P-3	13.2*	8.9-15.6*	4

*Possibly contaminated by table salt on high reading.

Ground water and forest composition

The development of the forest vegetation in the swamps of the western Upper Peninsula of Michigan closely parallels the development of swamp soils. The character and composition of the present forest, however, was modified by disturbances such as fire, windthrow and cutting which were not of sufficient magnitude to change the soil. Nevertheless, the characteristics of the ground water are largely associated with the ultimate forest type.

Where water levels are shallow and stable, the present swamp forest is largely coniferous, except on two plots where a severe fire burned in the 1890's, and the dominant cover is trembling aspen (Table 8). On all such areas, conifers are maintaining themselves as advance reproduction. In the stagnant bog, on the raw moss peat, only black spruce and tamarack are present as reproduction. Where the organic matter is increasingly well decomposed, the hardwood component becomes stronger, although most of the hardwoods are relatively intolerant species such as black ash, black cherry, trembling aspen, mountain ash, and white birch. More tolerant hardwoods, such as yellow birch, red and hard maple, and elm are present only in the smaller size classes.

Of the conifers, white cedar and balsam fir comprise most of the overstory, but the advance reproduction consists mostly of balsam fir. In the very small size class, white cedar is well represented, but heavy browsing by deer and snowshoe hare keeps this species from developing (Table 9). In the absence of disturbances such as fire and heavy windthrow which severely open the stand, the evidence indicates

TABLE 8

COMPOSITION OF SWAMP FORESTS WHERE WATER LEVEL IS SHALLOW AND STABLE

Plot	Soil Type	Size Class	Stocking[1] Conifers	Hardwoods	Both
E-1	Moss Peat	Upper Crown	4	0	4
		36" ht.-3" dbh	63	0	63
		12-35" ht.	13	0	13
		0-11" ht.	25	0	25
C-3	Moss Peat	Upper Crown	52	0	52
	over	36" ht.-3" dbh	25	0	25
	Wood Peat	12-35" ht.	0	12	12
		0-11" ht.	100	38	100
C-2	Wood Peat	Upper Crown	45	0	45
		36" ht.-3" dbh	38	0	38
		12-35" ht.	50	12	50
		0-11" ht.	75	12	75
P-2	Moss Peat	Upper Crown	41	5	46
	and Muck	36" ht.-3" dbh	25	0	25
	over	12-35" ht.	38	50	88
	Wood Peat	0-11" ht.	100	100	100
P-3	Muck over	Upper Crown	38	0	38
	Wood Peat	36" ht.-3" dbh	88	25	88
		12-35" ht.	88	12	88
		0-11" ht.	100	88	100
C-4	Muck	Upper Crown	28	33	61
		36" ht.-3" dbh	25	0	25
		12-35" ht.	50	38	62
		0-11" ht.	100	50	100
C-1	Muck	Upper Crown	42	3	45
		36" ht.-3" dbh	63	88	100
		12-35" ht.	75	25	100
		0-11" ht.	100	38	100
C-5	Wet Sandy	Upper Crown	10	55	65
	Stony	36" ht.-3" dbh	13	12	25
	Loam	12-35" ht.	12	38	50
		0-11" ht.	100	88	100

[1]Stocking is per cent crown cover for upper crown level, and per cent milacre plots stocked for reproduction. Total may be less than sum of conifers and hardwoods when same plot is stocked by both.

TABLE 9

SPECIES COMPOSITION OF SWAMP FORESTS BY HEIGHT CLASS
WATER LEVEL SHALLOW AND STABLE

Species	Per cent representation by size class[1] Upper Crown	36" ht.-3" dbh	12-35" ht.	0-11" ht.
Conifers				
Balsam fir	33	48	40	34
White cedar	28	6	5	14
Black spruce	11	14	7	13
White spruce	2	0	7	4
Tamarack	0	3	0	0
Total	74	71	59	65
Hardwoods				
Yellow Birch	2	4	7	4
Red Maple	0	4	7	4
Trembling Aspen	24	0	2	1
Black Cherry	0	4	15	9
Mountain Ash	0	4	3	7
Hard Maple	0	0	2	7
Black Ash	0	9	2	0
Elm	0	4	0	0
White Birch	0	0	3	3
Total	26	29	41	35
Grand Total	100	100	100	100

[1] Per cent crown cover is per cent area occupied by each species in relation to total crown area. Per cent of height class represents per cent of milacre plots stocked by a given species in relation to the total number of milacre plots stocked by each species.

that conifers will continue to dominate where water levels are stable and shallow.

The softwoods also appear to be holding their own where water levels are shallow and stable in early summer and later fluctuate with precipitation in dry years. Balsam fir is replacing white cedar to a large degree, however, and the dominant hardwoods are the more persistent and moderately tolerant yellow birch and red maple (Tables 10 and 11).

Where water levels fluctuate directly with precipitation and reach high levels only for a short period after heavy rains, the hardwoods appear to be ascending to dominance. Even though the stands have been somewhat opened by windthrow and subsequent salvage, white cedar and spruce are poorly represented in the larger size classes of reproduction. The aggressive balsam fir, while present in all size classes, is failing to maintain its present position (Tables 12 and 13). On the other hand, yellow birch and red maple reproduction are rapidly filling the openings in the forest stands. Even heavy browsing by deer and snowshoe hares has failed to prevent their ascendancy.

The development of hardwood reproduction is even more marked wherever high water levels are deeper than one foot below the soil surface, regardless of the type of water level fluctuation. In the stands studied on these types, the crown canopy is largely closed. Balsam fir is the only conifer that appears destined to survive while hard maple, red maple and yellow birch reproduction takes over the future stand (Tables 14 and 15).

Although yellow birch, red maple and elm appear to be well adapted to swamp conditions, and destined to occupy an increasing pro-

TABLE 10

COMPOSITION OF SWAMP FORESTS WHERE WATER LEVELS ARE SHALLOW AND STABLE IN SPRING, AND THEREAFTER FLUCTUATE WITH PRECIPITATION

Plot	Soil Type	Size Class	Stocking[1] Conifers	Hardwoods	Both
U-2	Moss Peat over Wood Peat	Upper Crown	47	0	47
		36" ht.-3" dbh	25	0	25
		12-35" ht.	0	50	50
		0-11" ht.	38	50	88
E-2	Sandy Loam	Upper Crown	18	49	67
		36" ht.-3" dbh	38	25	63
		12-35" ht.	50	75	88
		0-11" ht.	50	100	100

[1]Stocking is per cent crown cover for upper crown level, and per cent milacre plots stocked for reproduction. Total may be less than sum of conifers and hardwoods when same plot is stocked by both.

TABLE 11

SPECIES COMPOSITION OF SWAMP FORESTS BY HEIGHT CLASS.
WATER LEVELS SHALLOW AND STABLE IN SPRING, AND THEREAFTER
FLUCTUATE WITH PRECIPITATION

Species	Per cent representation by size class[1] Upper Crown	36" ht.-3" dbh	12-35" ht.	0-11" ht.
Balsam fir	0/	25	5	9
White Cedar	23	19	0	13
Black Spruce	34	2	7	14
White Spruce	0	13	9	0
All Conifers	57	59	21	36
Yellow birch	32	9	21	15
Red maple	11	15	39	30
Hard Maple	0	9	11	6
Black Cherry	0	8	8	3
Mountain Ash	0	0	0	10
All Hardwoods	43	41	79	64
Grand Total	100	100	100	100

[1]Per cent crown cover is per cent area occupied by each species in relation to total area covered. Per cent reproduction represents per cent milacre plots stocked by a given species in relation to the total number of milacre plots stocked by each species.

TABLE 12

COMPOSITION OF SWAMP FORESTS WHERE WATER LEVEL FLUCTUATES DIRECTLY WITH PRECIPITATION

Plot	Soil Type	Size Class	Stocking[1] Conifers	Hardwoods	Both
CC-1	Sandy Loam	Upper Crown	34	29	63
		36" ht.-3" dbh	12	50	50
		12-35" ht.	38	100	100
		0-11" ht.	100	100	100
E-3	Sandy Loam	Upper Crown	58	9	67
		36" ht.-3" dbh	0	62	62
		12-35" ht.	25	88	88
		0-11" ht.	75	100	100

[1]Stocking is per cent crown cover for the upper crown level, and per cent milacre plots stocked for reproduction. Total may be less than sum of conifers and hardwoods when same plot is stocked by both.

TABLE 13

SPECIES COMPOSITION OF SWAMP FORESTS BY HEIGHT CLASS.
WATER LEVEL FLUCTUATES DIRECTLY WITH PRECIPITATION

Species	Per cent representation by size class[1] Upper Crown	36" ht.-3" dbh	12-35" ht.	0-11" ht.
Balsam fir	21	7	9	11
White Cedar	37	0	0	18
Black Spruce	4	0	6	8
White Spruce	9	0	0	2
Hemlock	0	0	0	1
All Conifers	71	7	15	40
Yellow Birch	21	33	17	18
Red Maple	8	60	43	24
Hard Maple	0	0	15	10
Black Cherry	0	0	5	0
Mountain Ash	0	0	5	8
All Hardwoods	29	93	85	60
Grand Total	100	100	100	100

[1]Per cent crown cover is per cent area occupied by each species in relation to total area covered. Per cent reproduction represents per cent milacre plots stocked by a given species in relation to the total number of milacre plots stocked by each species.

TABLE 14

COMPOSITION OF SWAMP FORESTS WHERE HIGH WATER LEVELS ARE ALWAYS DEEPER THAN 18 INCHES FROM SOIL SURFACE

Plot	Soil Type	Size Class	Stocking[1] Conifers	Hardwoods	Both
P-1	Sand	Upper Crown	68	20	88
		36" ht.-3" dbh	13	12	25
		12-35" ht.	12	38	50
		0-11" ht.	100	100	100
P-4	Sand	Upper Crown	34	52	86
		36" ht.-3" dbh	0	25	25
		12-35" ht.	0	62	62
		0-11" ht.	50	100	100
CC-2	Sandy Loam	Upper Crown	42	24	66
		36" ht.-3" dbh	0	75	75
		12-35" ht.	0	100	100
		0-11" ht.	38	100	100
U-1	Sandy Loam	Upper Crown	44	25	69
		36" ht.-3" dbh	0	100	100
		12-35" ht.	0	100	100
		0-11" ht.	12	100	100

[1]Stocking is per cent crown cover for upper crown level, and per cent milacre plots stocked for reproduction. Total may be less than sum of conifers and hardwoods when same plot is tocked by both.

TABLE 15

SPECIES COMPOSITION OF SWAMP FORESTS BY HEIGHT CLASS
WATER LEVELS ALWAYS LOWER THAN 18 INCHES FROM SOIL SURFACE

Species	Per cent representation by size class[1] Upper Crown	36" ht.-3" dbh	12-35" ht.	0-11" ht.
Balsam Fir	22	6	3	17
White Cedar	7	0	0	5
Black Spruce	1	0	0	2
White Spruce	25	0	0	1
Hemlock	7	0	0	0
All Conifers	62	6	3	25
Yellow Birch	27	0	13	11
Red Maple	6	12	20	21
Hard Maple	3	72	45	29
Elm	0	0	2	2
Black Cherry	1	10	17	9
Trembling Aspen	1	0	0	1
Mountain Ash	0	0	0	2
All Hardwoods	38	94	97	75
Grand Total	100	100	100	100

[1] Per cent crown cover is per cent of area occupied by each species in relation to total area covered. Per cent reproduction represents per cent milacre plots stocked by a given species in relation to the total number of milacre plots stocked by each species.

portion of future stands, the future position of hard maple is not so clear. Hard maple was an aggressive invader in all swamps except the stagnant bog E-1, but was found in the upper crown canopy only in border types where the water level remained deeper than 18 inches even in wet weather.

The absence of large hard maples wherever the ground water frequently rises close to the soil surface may be a result of the inability of this tap-rooted species to adjust to the restricted root zone in such swamps. The root systems excavated where ground waters were shallow either failed to penetrate below high water levels, or where they did so during dry years, were apparently killed back by high water during wet years. Even above the ground water, lateral development of the root system was sparse. Hard maple apparently develops well as a seedling until the swamp site becomes limiting to root growth. Thereafter, its ability to develop and compete successfully with its associates is severely restricted by its inadequate root system, despite its well-known tolerance to shade.

Under most swamp conditions, therefore, hard maple appears to be unable to develop successfully throughout its life span. The presence of advance reproduction of the species is likely to be misleading as an indication of future forest composition. On swamp margins, however, where water levels are deeper, hard maple may largely replace even red maple, yellow birch and elm.

Ground water and the growth of swamp forests

Each of the several ground water characteristics, by their effect upon the tree roots previously mentioned, influences the productive

capacity as well as the forest composition on different swamp sites.

Site Quality. Bowman (1944) states that site index measurements based on the total height of dominant trees at age 50 years give a reliable indication of site quality for spruce and fir in Northern Michigan. Since all plots in this study contained spruce or fir or both species, this index was used, with one important modification: the total heights of both dominant and codominant trees were used in conjunction with the curves of Bowman, with the result that the site indices given are conservative.

An examination of table 16 indicates that water level characteristics, redox potential and species composition may be associated with site quality of spruce and fir. Figure 47 verifies the relationship of water level type to site index. In view of the previous relationship shown between root penetration and water level this relationship of increasing site index to decreasing root restriction by high water levels is not surprising.

Where water levels are high and relatively stable, however, the site index varies considerably. It is on these sites that some tree roots are in contact with or submerged in the ground water almost continuously. Trees in swamps characterized by other water level types also have their roots submerged for varying lengths of time, especially during wet years and in the early part of the growing season. In spite of the inconclusive relationship shown between root penetration and redox potential shown earlier, the relationship between site index for spruce and fir and redox potential was plotted in figure 48. Here it is seen that the redox potential does indeed bear a positive relation to site index even though the effect cannot be attributed to root restriction by stagnant water.

TABLE 16

SITE INDEX[1] OF SPRUCE AND FIR AS RELATED TO SITE CHARACTERISTICS IN SWAMP FORESTS OF WESTERN UPPER MICHIGAN

Water level type	Plot	Site index age 50	Soil[2] type	pH	E7h	Seepage rate ft/day	Associated species
I-A	C-4	48(10)[3]	Mu	6.7	-6	3.5	Aspen, w. cedar
	C-5	47(6)	S.L.	5.8	252	16.0	Aspen
	C-1	43(6)	Mu	5.8	-60	7.0	W. cedar, B. ash, Y.B.
	C-3	43(20)	Mu	6.6	-36	3.5	W. cedar
	P-2	39(10)	Mu/S.	6.5	-174	14.0	W. cedar, Y.B.
	C-2	38(7)	Mu/WP	6.3	-96	8.0	W. cedar
	P-3	36(6)	W.P.	6.5	-12	2.0	W. cedar
	E-1	26(6)	MP	4.4	-252	0.0	Tamarack
	Mean	40(71)					
II-B-1	E-2	55(1)	S.L.	5.6	67	0.3	Y.B., W. cedar, R.M.
	U-2	41(16)	MP/WP	5.5	18	5.0	W. cedar
	Mean	42(17)					
II-A	E-3	52(7)	S.L.	5.7	330	0.5	W. cedar, R.M.
	CC-1	40(3)	S.L.	5.7	192	0.3	Y.B., W. cedar
	Mean	48(10)					
I-B	P-1	49(13)	S.L.	5.7	69	0.2	W. cedar, Aspen, R.M., B. cherry
II-B-2	CC-2	55(5)	S.L.	5.7	294	0.3	Hemlock, Y.B., H.M.
	U-1	54(4)	SiL./ S.L.	5.1	168	8.0	Y.B., R.M., W. cedar
	P-4	53(3)	S.L.	5.5	186	0.2	Y.B., Hemlock, W. cedar
	Mean	54(12)					

Table 16 - Continued

[1]Site index based on curves presented in Bowman (1944).

[2]Mu-Muck, S.-Sand, S.L.-Sandy loam, WP-Wood peat, MP - Moss peat, SlL.-Silt loam.

[3](10) Figures in parentheses indicate number of trees in sample.

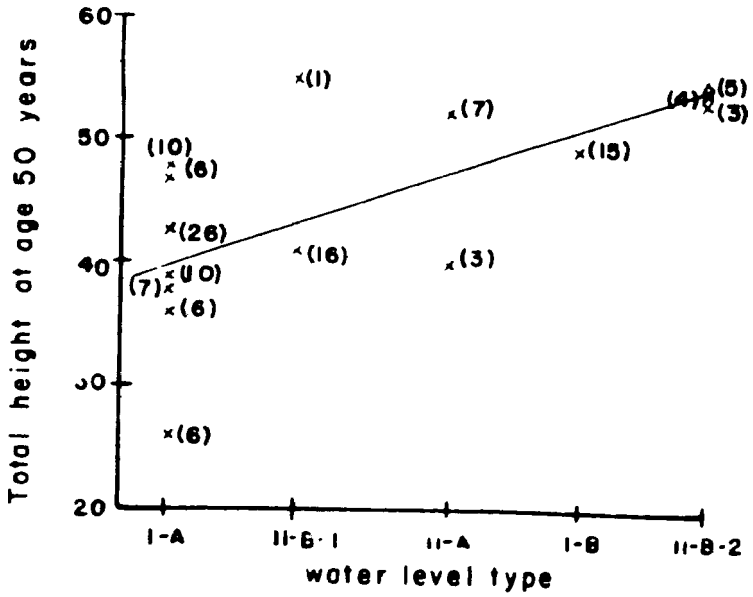


FIGURE 47. Site index of spruce-fir in relation to water level types. (10)=number of trees in each sample.

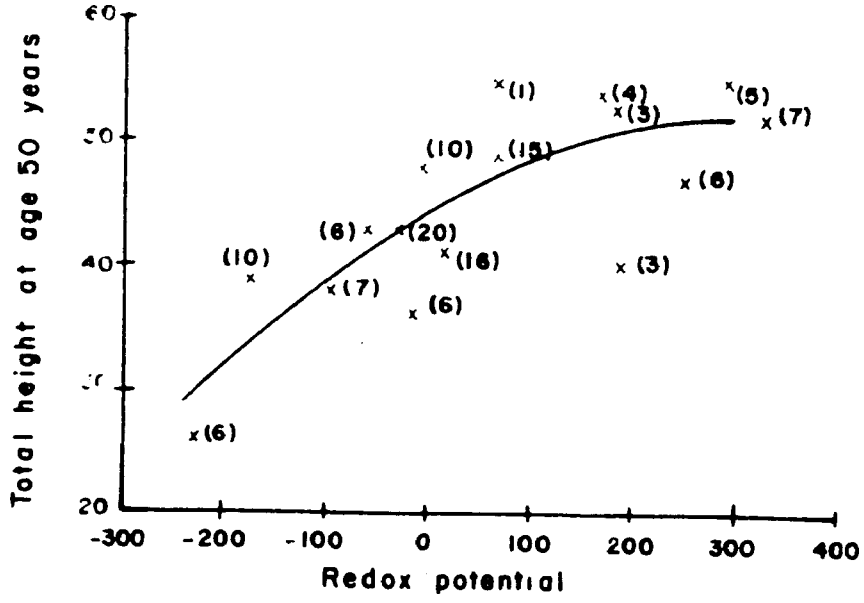


FIGURE 48. Site index of spruce-fir in relation to redox potentials of ground water. (10)=number of trees in each sample.

Although root penetration appears to be restricted by high water levels without regard to redox potentials, flooding of at least a part of the root system occurs frequently. When tree roots are flooded, the ability of a tree to absorb water and minerals is impaired, and its rate of transpiration and apparent photosynthesis is reduced, while its respiration rate increases. After flooding, the tree does not return to normal immediately. A period of several days may elapse before normal activity resumes (Childers and White, 1942; Parker, 1950; Kramer, 1951). In the laboratory studies upon which these statements are based, the water used was stagnant.

Hunt (1951) flooded loblolly, shortleaf and pond pine seedlings with standing and moving water and found after 7 months that the plants continuously flooded with standing water had a lower dry weight than those flooded with moving water. McDermott (1954) indicates that tolerance to flooding may vary with species. Further, it is common knowledge that frequent aeration of the water is necessary to insure good growth of plants in water culture. All this evidence appears to support the field results of this study which indicate that even very small differences in the degree of stagnation of ground water are important in reducing the unfavorable influence of flooding on the growth of forest trees over the life of the stand.

A third factor associated with site quality of fir and spruce was the composition of the forest stand. Where spruce and fir were associated with hardwoods such as aspen, yellow birch, red maple and black ash, the site quality was highest. Such may not be so much a reflection of the favorable influence of the hardwoods upon the spruce and fir, although Heiberg (1939) believes soil improvement by hardwoods

may be a factor, but rather a reflection that site quality is already sufficiently high as to permit the successful growth of the more demanding hardwoods. Where spruce and fir were associated with white cedar, the site quality was somewhat lower, and where tamarack was present the site quality was very low. The above results agree well with those found by Bowman (1944).

The site index of white cedar, based on total height at maturity (Gevorkiantz and Duerr, 1939), was determined for each plot. Despite the fact that the white cedar was highly defective, the increment cores obtained indicated ages well in excess of 100 years, except on plot U-2 where the single codominant cedar was only 48 years old.

The site quality for white cedar was much lower than that for spruce and fir wherever they occured together. These species were most often associated on sites of medium quality for each. Within the range of sites where cedar and spruce-fir occured together, a positive relationship existed between the site index of white cedar to site index of spruce and fir, indicating that white cedar responds to swamp characteristics in a manner similar to that of spruce and fir (Figure 49). The absence of white cedar on the very poorest spruce sites, however, and its scarcity on the best spruce-fir sites indicates that the ecological amplitude of cedar is narrower than that of spruce and fir.

Annual radial growth and water levels.- The site index of species in swamps is an expression of the cumulative effects of all factors affecting the growth of dominant and codominant trees during the life of the stand. On all sites, however, growth in any given year may be better or poorer than for any other given year.

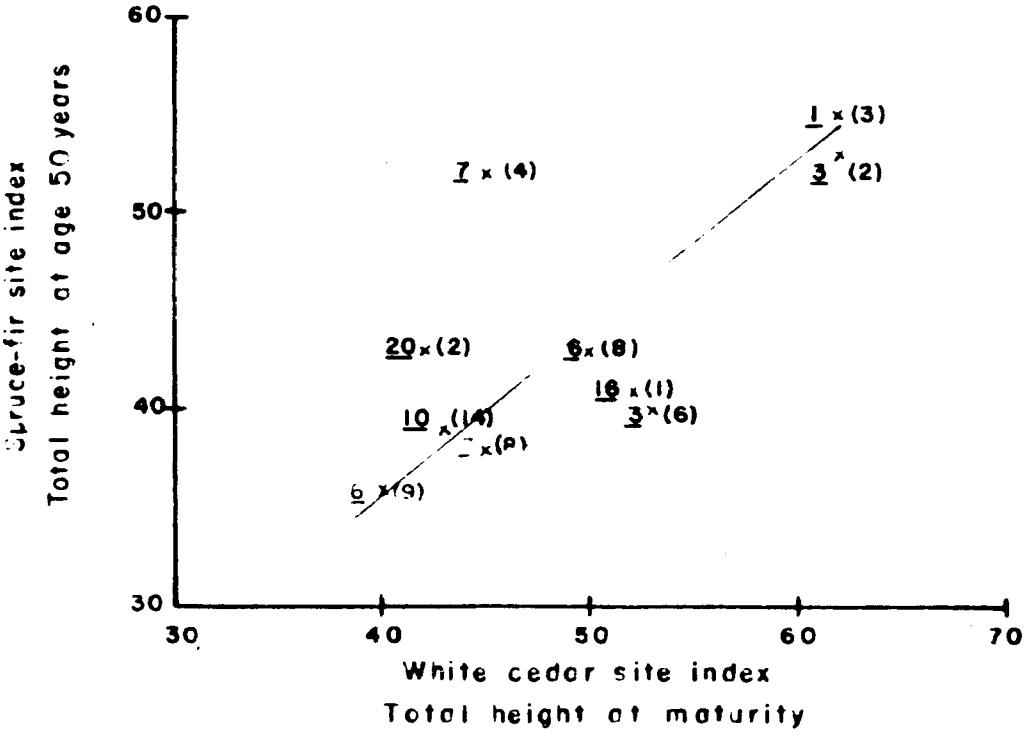


FIGURE 49. Relationship between site index of spruce-fir and white cedar where they are associates on the same swamp plots. 6 = number of spruce and fir, and (9) = number of white cedar trees in each sample.

It has been shown that the site index for spruce and fir and white cedar is related to the position of the ground water in the several swamp sites. It therefore appears that the position of the water level may act as a limiting factor in tree growth in years of extremes in water levels, either high or low. For this reason, a method of estimating the water level in each swamp type on the basis of precipitation records has been devised in order to test this hypothesis in relation to annual water levels in a given swamp.

Water levels in a well on plot CC-1 (Swamp type II-A) were recorded continuously by a Leupold and Stevens Model "F" water level recorder during the summers of 1956 and 1957. During the same period, a weather station was maintained in a forest opening nearby. It has been possible to establish the relationship between water levels in this well and precipitation, taken from the records at this station in the following manner.

First, a rating curve of drop in water level over days since the last rain over 0.25 inch was established by plotting actual water levels from the hydrograph during the growing seasons of 1956 and 1957 (Figure 50).

Second, a regression showing rise in water levels following rainfalls up to 1.59 inches in 24 hours was calculated (Figure 51).

From these two charts it was possible to estimate the depth of the ground water from weather records at any time during the summer by cumulatively summing the fall in water level for each day without rain and the rise in level with each rain with the following modifications.

1. Precipitation less than 0.02 inches in 24 hours was ignored.
2. Precipitation of 0.02 to 0.10 inches in 24 hours maintained

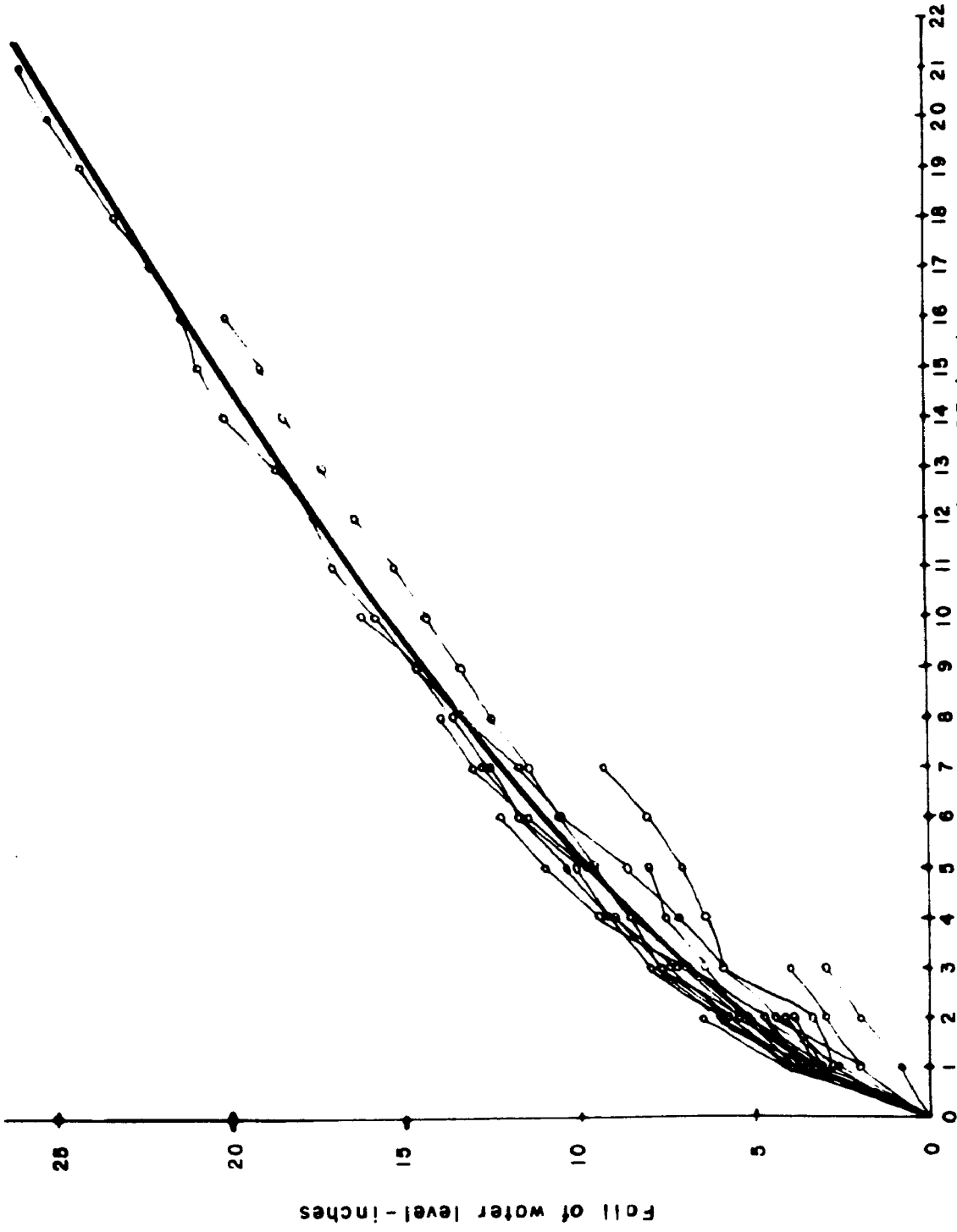


FIGURE 50. Rating curve of fall of water level at plot CC-1 by days since last rain exceeding 0.25 inch.

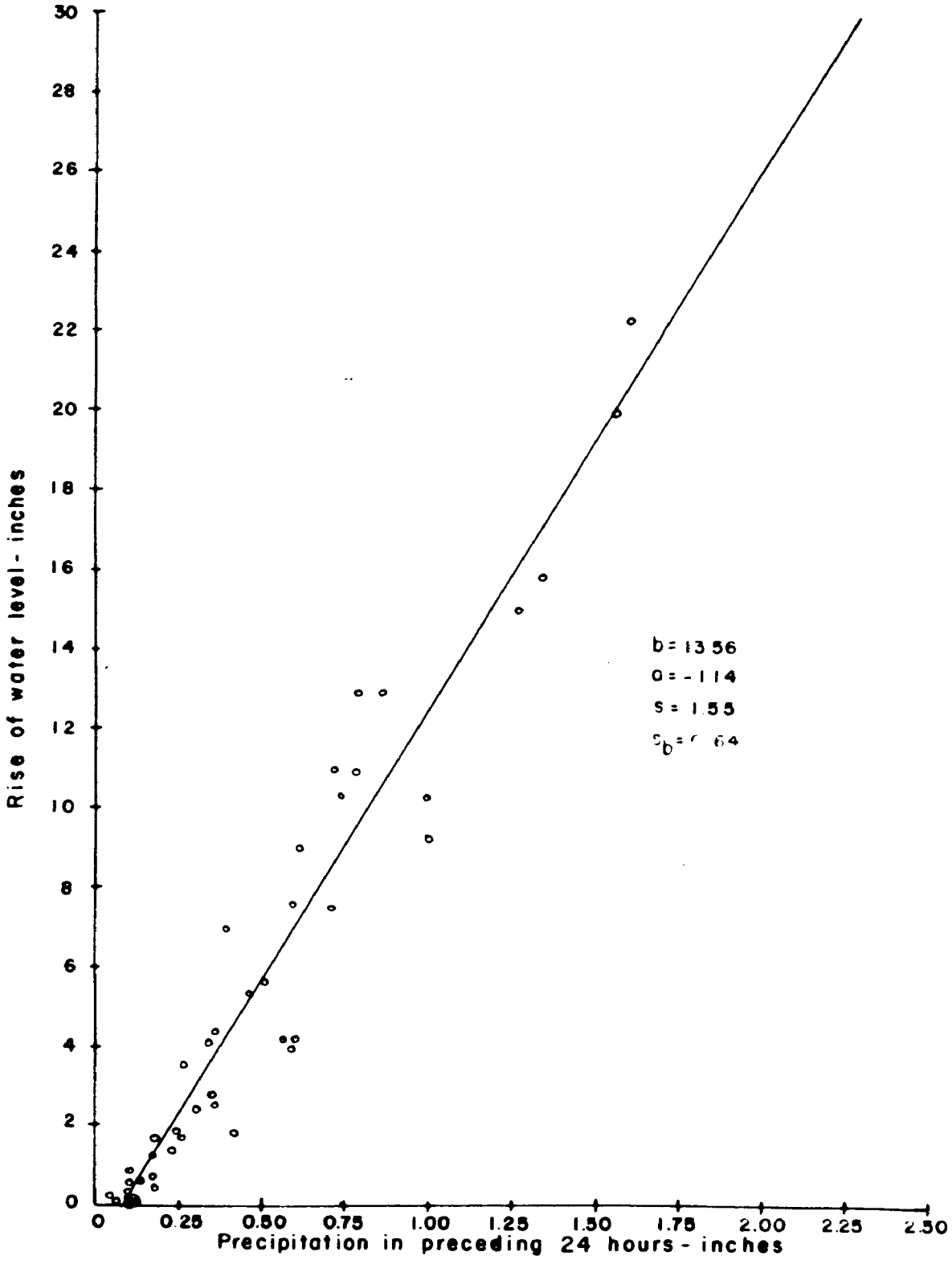


FIGURE 51. Rise of water level at plot CC-1 in relation to amount of precipitation received in the preceding 24 hours.

water levels unchanged on the day it fell, and thereafter the fall in water level continued as if the precipitation had never fallen.

3. Following a day with 0.11 to 0.24 inches of precipitation, the fall in water level equalled that in (2) above, plus any rise caused by the precipitation.

4. In no case did the water level rise higher than a depth of 8 inches below the soil surface. All rainfall in excess of that necessary to bring the ground water to that level was ignored. The drop in the ground water began at 8 inches depth on the first day following cessation of such precipitation.

5. All estimated water levels were arbitrarily begun at 8 inches depth on May 1 of each year. Ground water levels are at or near their maximum at this time before heavy vegetational demands begin.

The estimated water level based on weather records from the station in the forest opening, however, had no value other than that of indicating the existing relationship between water levels and precipitation records. In order to estimate water levels for years other than 1956 and 1957, it was necessary to utilize the weather records from Stambaugh, Michigan, 25 miles south-south-east of the well at CC-1. A comparison of daily precipitation at CC-1 and Stambaugh indicated that only a fair relationship existed between the two stations, the calculated regression showing that precipitation at Stambaugh exceeded that at CC-1 by 0.06 inches per inch, with a standard error of 0.70 inches (Figure 52). Since most of the variation occured on days with

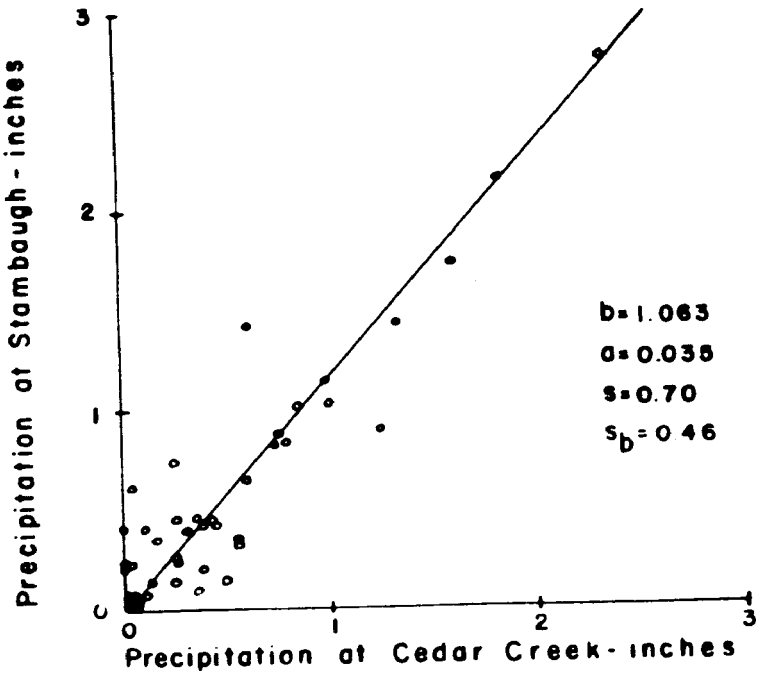


FIGURE 52 Relationship between daily precipitation at Cedar Creek swamp and Stambaugh, Michigan during the summers of 1956 and 1957.

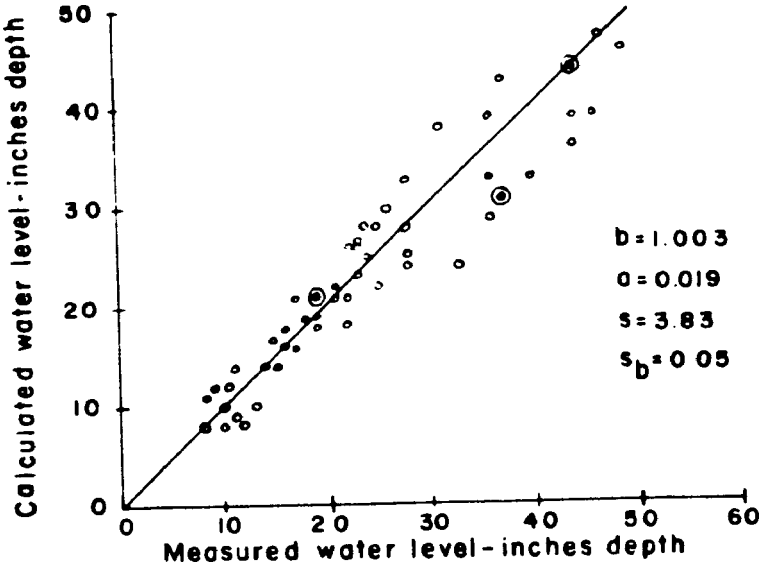


FIGURE 53. Relationship between calculated and measured water levels, plot CC-1, summers of 1956 and 1957. ◎ = two observations.

rainfall less than 0.50 inch, which affect water levels least, the rainfall as given in the records of the U. S. Weather Bureau for Stambaugh were used in spite of the large standard error.

Water levels of well CC-1 were then estimated on the basis of the Stambaugh records for the growing seasons of 1956 and 1957, a very wet and a very dry year, respectively, in order to compare them with the actual water levels obtained by the water level recorder. The results were somewhat better than expected. A calculated regression of estimated water levels upon actual water levels, taken biweekly for the two seasons showed the mean estimated water level to have a slope of 1.003 upon actual water levels, with a standard error of slope of only 0.05 inches. The standard error of the regression was 3.83 inches. The estimated water level was therefore within 3.83 inches of the actual water level 2 times out of 3, and within 7.66 inches 19 times out of 20 (Figure 53).

This relatively good relationship between estimated and actual water levels, in spite of the variation in the individual relationships between precipitation and water level rise, drop of water level during rainless periods and precipitation at Stambaugh and CC-1 is due to many compensating factors, important among which are:

1. Local convection storms occur during the summer, resulting in a poor relation between Stambaugh and CC-1 precipitation on any given day, but over short periods of time they tend to compensate for each other. However, the weather station at Stambaugh seems to catch more precipitation than the one at CC-1 during all storms.

2. Unusually high rises in water level resulting from a given amount of precipitation are usually accompanied by an unusually rapid

fall in level. This is especially true when water levels are initially high preceding rainfall. When water levels are initially low, both the amount of rise and the rate of fall are usually reduced.

An additional factor which serves to reduce the error in calculated water levels occurs when heavy rains raise the water level to its maximum height. Any time the precipitation is sufficient to raise the estimated water level above its maximum any accumulated error is reduced (when estimated levels are higher than actual levels) or entirely eliminated (when estimated levels are lower than actual levels). Thus it has been possible to estimate water levels at well CC-1, with a type II-A water level, on the basis of weather records at Stambaugh, Michigan. A close examination of figure 5 reveals that the fluctuations of each water level type were related to those of type II-A, which fluctuated directly with precipitation. Stable water level types I-A and I-B, as well as type II-B-1 prior to the development of a large precipitation deficit, exhibited fluctuations in a ratio of 1:7 with type II-A (Figure 5A). During the early part of the growing season, water levels in type II-B-2 approximated those of type II-A until the water level in type II-A fell below 25 inches from the soil surface. Water levels below 25 inches indicate that a considerable precipitation deficit has developed. The inflow from the subsurface reservoirs which maintained the springtime high water levels in types II-B-1 and II-B-2 largely ceased at about the same time.

Thereafter the relationship of water level fluctuations in these types to those of type II-A changed. Type II-B-1 fluctuated with precipitation in a ratio of approximately 3:5 with type II-A and type II-B-2 continued to fall until a base level was reached and a stable,

FIGURE 54. Relationship between water levels at plot CC-1 and in swamps of various water level types studied.

but much lower water level was maintained throughout the rest of the summer. After the underground reservoir has been depleted in early summer, it is unlikely that the high water levels of these types would be restored during the same summer, as the large amount of water used by vegetation during the growing season almost precludes the possibility of the accumulation of a large moisture storage surplus.

Ground water levels at plot CC-1 were estimated for each growing season for the period 1930 to 1957, inclusively, based on weather records taken at Stambaugh, Michigan.

An attempt was made to relate estimated annual water levels to radial growth of dominant and codominant coniferous trees in the various swamps studied. Increment cores were extracted from all sound balsam firs, white and black spruces, tamaracks, hemlocks, and white cedars in the above crown classes. The width of each annual ring of the air dry cores was measured to the nearest 0.01 mm on the Swedish automatic registering tree ring measuring machine (Ecklund, 1949).

The mean ring width of all the conifers in each swamp of similar water level type was plotted over a numerical index consisting of the total number of day-inches that the calculated water level at CC-1 remained below a depth of 25 inches during the period June 1 to September 1 for each season from 1930 through 1957. (For example, five day-inches could represent a water level one inch below the 25 inch level for five days or five inches below for one day.) The 25 inch depth was selected to eliminate the change in water level relationship between CC-1 and type II-B-1 and II-B-2 swamps. The index does not represent a given depth of water, but is only an index which helps integrate the affects of both time and space.

A regression line was fitted to the data, and the correlation coefficient was calculated for each regression (Figures 55, 56, 57, 58

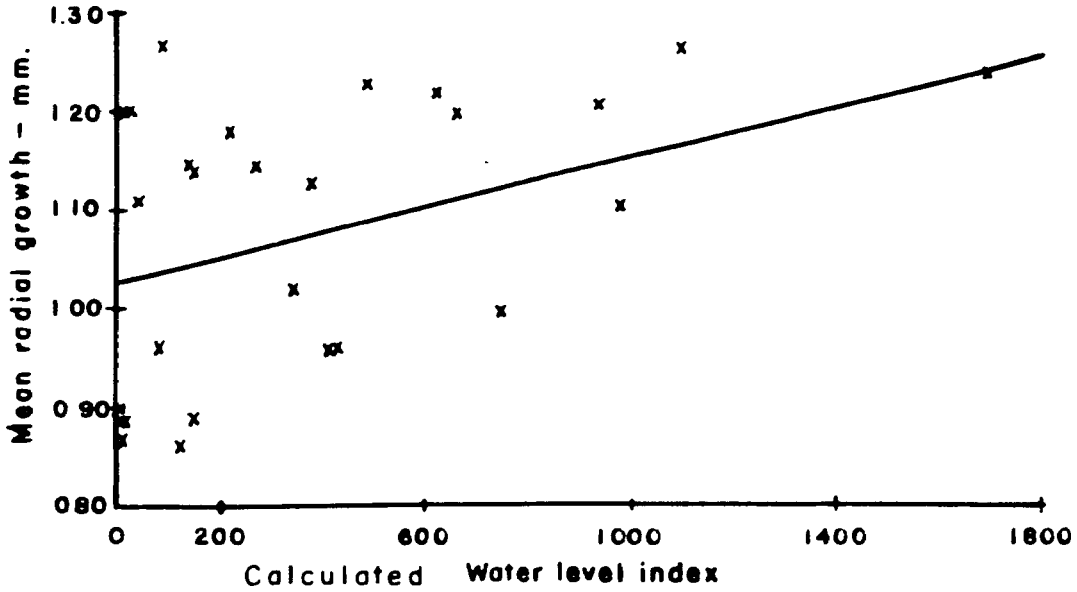


FIGURE 55. Relationship between annual radial growth of conifers in type I-A swamps and water level indices, 1930-1957. Based on 34 balsam firs, 28 black spruces, 11 white cedars, 2 tamaracks and 1 white spruce. r=+0.389, significant at the 95% level.

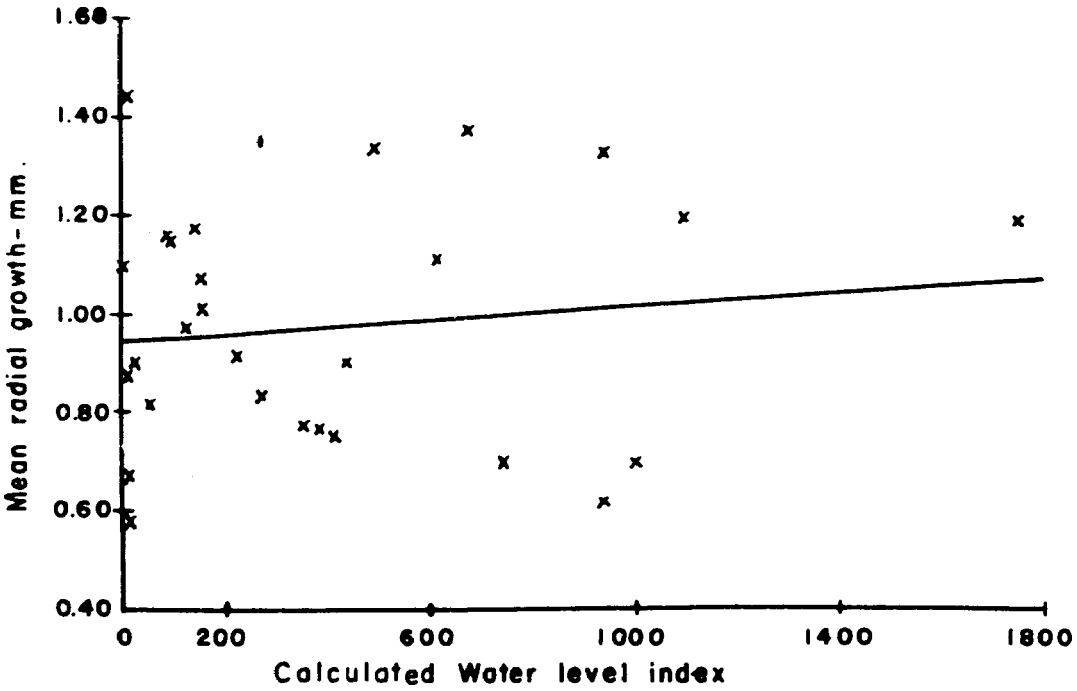


FIGURE 56. Relationship between annual radial growth of conifers in type II-A swamps and water level indices, 1930-1957. Based on 7 balsam firs, 2 white spruces and 1 black spruce. r=+0.125, not significant.

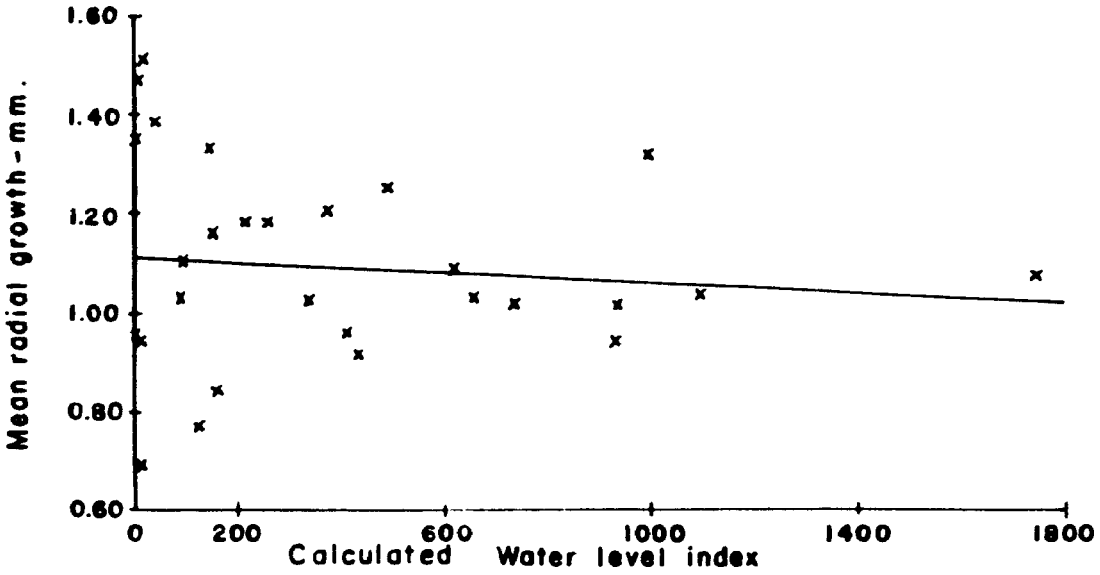


FIGURE 57. Relationship between annual radial growth of conifers in type 11-B-1 swamps and water level indices, 1930-1957. Based on 10 black spruces and 4 white cedars. r=-0.124, not significant.

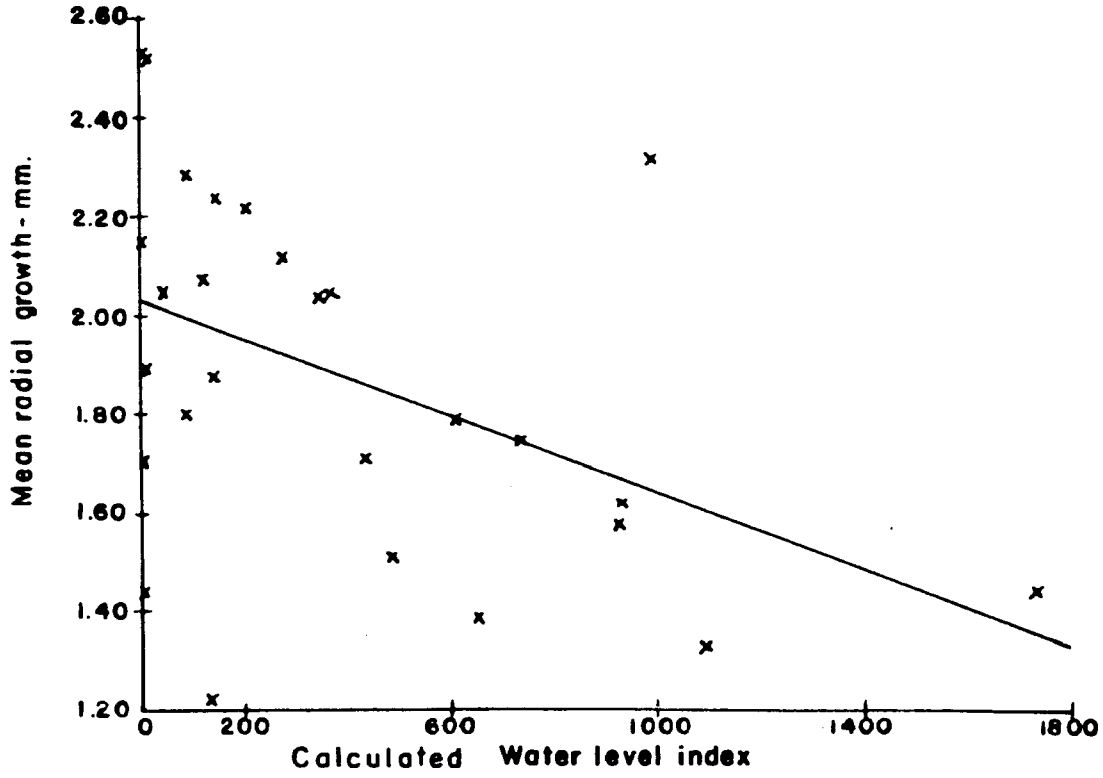


FIGURE 58. Relationship between annual radial growth of conifers in type 1-B swamps and water level indices, 1930-1957. Based on 5 balsam firs, 5 white spruces and 2 black spruces. r=-0.324, not significant.

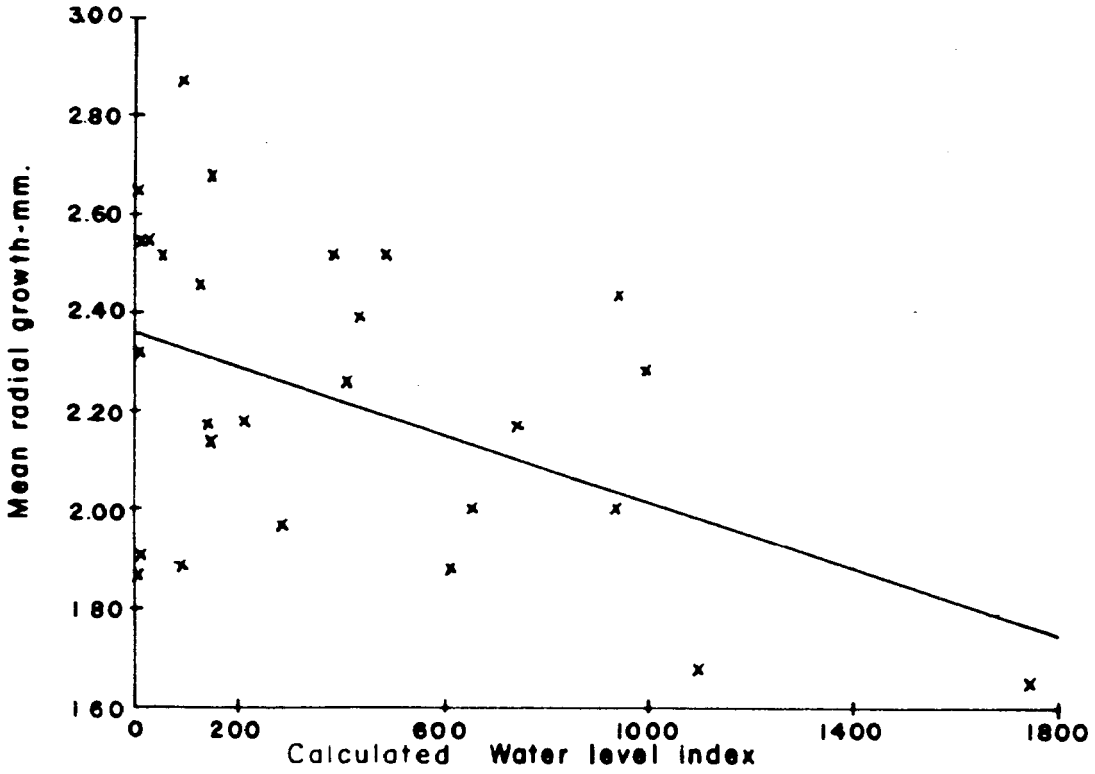


FIGURE 59. Relationship between annual radial growth of conifers in type II-B-2 swamps and water level indices, 1930-1957. Based on 3 balsam firs, 9 white spruces and 1 hemlock. $r = -0.433$, significant at the 95% level.

and 59). A significant relationship between annual radial growth and the water level index existed for only two of the five swamp types, but the significant relations were opposite in direction and represented the extremes of water level conditions found in the swamps studied.

The relation was positive in type I-A swamps, the best growth occuring with the highest water level index (representing lowest water levels), and negative in type II-B-2 swamps, where growth decreased as the index increased. Even though the remaining regressions were not significant, when the five water level types are considered as a series, a distinct progression appears in the trend of the relation of radial growth to water level index. The reversal from increased growth during dry years in swamps with high, stable water levels to decreased growth during dry years in swamps where the water level falls deep below the root zone proceeds regularly from wetter to drier swamp sites.

These results contradict work conducted by Lyon (1949), who found that secondary growth trends of white pines in bog and uplands were similar after the first 30 years of their life. He did, however, suggest a negative relation existed during the early years. It is possible that the road that he mentions as being near the bog was constructed when the pines were about 30 years old and changed water conditions sufficiently to cause a change in the growth pattern.

Effects of ground water modified by micro-relief

Swamp forests are often characterized by a hummocky surface, created on the generally flat surface of the swamp by frost action and uprooted trees. Three micro-sites result: hummocks, depressions and undisturbed flats. Since the effects of ground water upon swamp forests

are strongly related to the depth of the water table, the micro-relief features may influence the establishment and growth of individual trees. The data in table 17 indicate that hummocks are the most favorable micro-sites, flats are moderately favorable, and that depressions are distinctly unfavorable sites for successful growth and establishment of forest trees.

The trees growing on hummocks, flats and in depressions were separated into crown classes by water level types. In types I-A, II-A, and II-B-1, where the ground water is shallow and the soil is waterlogged almost to the surface during most of the year, all crown classes were found most frequently on hummocks, less frequently on flats, and only a few intermediate and suppressed trees grew in the depressions. The basal area of the trees was even more revealing of the significance of micro-sites. Almost 73 percent of the basal area was found on hummocks, 27 percent on flats, and less than 1 percent in the depressions.

Where the ground water was sufficiently deep to avoid waterlogging of the soil surface, as in type I-B and II-B-2, conditions for establishment were similar on either hummocks or flats. No trees were found in the depressions, however, probably due to temporary ponding of water and the fact that the depressions are subject to filling by drifting litter which may smother the young seedlings.

Indirect influences of ground water

Wind. Wind damage presents a serious problem in swamp forests. A survey of windthrown, broken and badly sprung trees on the sample plots studied showed that 28 percent of the trees on plots with a

TABLE 17

RELATION OF TREE CROWN DEVELOPMENT TO POSITION OF THE TREE WITH RESPECT TO MICRO-RELIEF FEATURES

Water level type	Number of trees per acre by position class*															
	Dominant			Codom.			Intermed.			Suppressed			Total			
	H	F	D	H	F	D	H	F	D	H	F	D	H	F	D	All
I-A	70	21	0	80	40	0	81	60	2	40	30	1	274	151	3	428
II-A	60	15	0	45	10	0	45	20	0	30	10	20	180	55	20	255
II-B-1	80	0	0	95	5	0	115	5	0	30	5	0	320	15	0	335
I-B	70	30	0	50	80	0	100	99	0	30	50	0	250	259	0	509
II-B-2	10	4	0	13	10	0	23	70	0	17	27	0	63	151	0	214
Weighted Average	59	24	0	68	31	0	78	56	1	33	25	3	238	136	4	378

*H-hummock, F-flat, and D-depression.

periodically or permanently high water table have been affected by wind damage. In swamps with a lower water table, only 18 percent of the trees were damaged during the same period. The high amount of damage in swamps with very high water tables is undoubtedly related to the shallow roots previously discussed, and occurs in spite of the fact that the stands have not been opened by cutting. Most of the windthrown trees were conifers.

Fire. On 13 of the 16 plots, the presence of charcoal in the soil, fire scars on dead and living trees and the presence of fire species such as trembling aspen indicated past fires. In the three swamps where no evidence of fire was found, the water level was high and stable.

A heavy accumulation of organic material on the ground characterizes most swamps, especially where the high spring and early summer water level has restricted the depth of rooting so that windthrown trees are added to the other accumulations of inflammable materials. The worst swamp type from this standpoint is type II-B-1, where a high water level exists during spring and early summer of dry years and throughout wet years, thus causing a heavy accumulation of organic material. Then the water level falls sufficiently to allow the organic material to dry considerably in periods of drouth, creating a frequent and severe fire hazard.

On the other hand, the fire hazard is less in swamp types with a high stable water table, and in swamps with lower spring levels. In the former, the organic material remains moist almost to the surface except in extreme drouth, and in the latter large accumulations of organic material are less likely to build up in hazardous amounts.

Insects.- Insects such as the larch sawfly, which pupate in the litter or moss beneath tamarack trees may be considerably influenced by the position of the water table and the weather during the cocoon spinning period, depending upon the water level type. Where the water level is high and stable as in type I-A, cocooning takes place near the soil surface and heavy mortality by small rodents may prevail. On the other hand, where the water level falls in a dry summer, the larvae may penetrate so deeply into the soil before finding suitable conditions for cocooning that they may be drowned by the high water levels the following spring. Populations of the sawfly may thus vary with weather and water levels in swamp forests containing tamarack. (Graham and Satterlund, 1959).

Populations of other noxious insects may be related indirectly to water levels as they affect windthrow. The eastern spruce bark beetle became epidemic in the study area following the severe windstorm of 1941, building up centers of infestation in windthrown and root sprung spruce in swamps where the rooting depth was restricted by a high water table. Only prompt salvage of wind damaged and infested spruce averted a heavy loss.

Disease.- Ground water undoubtedly influences the swamp forest in other ways which have not been subjected to investigation. The high incidence of heart rot in white cedar in these swamps may be related to some characteristic of the ground water, possibly its low base ion content. Root rots, common in several species, may find entrance into the tree following mortality of the roots from flooding.

Although white pine was formerly present in many swamps as scattered large trees, early cutting has removed them. Reproduction

is largely lacking, due to the absence of seed trees and the presence of white pine blister rust. The favorable conditions for currents and gooseberries, alternate hosts of blister rust, in most of the swamp types investigated portends the elimination of white pine from present swamp stands.

All of the foregoing illustrate actions by ground water upon the swamp forest and some results of these actions. The reactions of the swamp forest upon ground water are also important and are considered next.

CHAPTER IV

REACTIONS OF SWAMP FORESTS UPON GROUND WATER

In the hydrologic cycle, plants react upon water directly in interception and transpiration, while they may indirectly influence the infiltration of water into the soil, the rate and amount of percolation through the soil down to the ground water and direct evaporation from the soil surface.

Interception

Measurements of interception in a swamp forest were made at only one plot; CC-1. The nearby weather station in a forest opening served as a standard of comparison. Four 3 inch rain gages were placed on plot CC-1 and measurements taken after every period of rainfall as discussed in Chapter II. The measurements have meaning only for the plot on which they were taken, because the density and species composition of the other study plots vary widely from CC-1. Nevertheless, they have value as they indicate the considerable influence of interception upon the amount of water reaching the forest floor, especially during light showers.

The present forest stand measured is a mixed hardwood-conifer swamp containing 123 square feet of basal area per acre composed of 53 per cent white cedar, 26 per cent yellow birch, 14 per cent balsam fir and 7 per cent black spruce. Also present near the plot are scattered

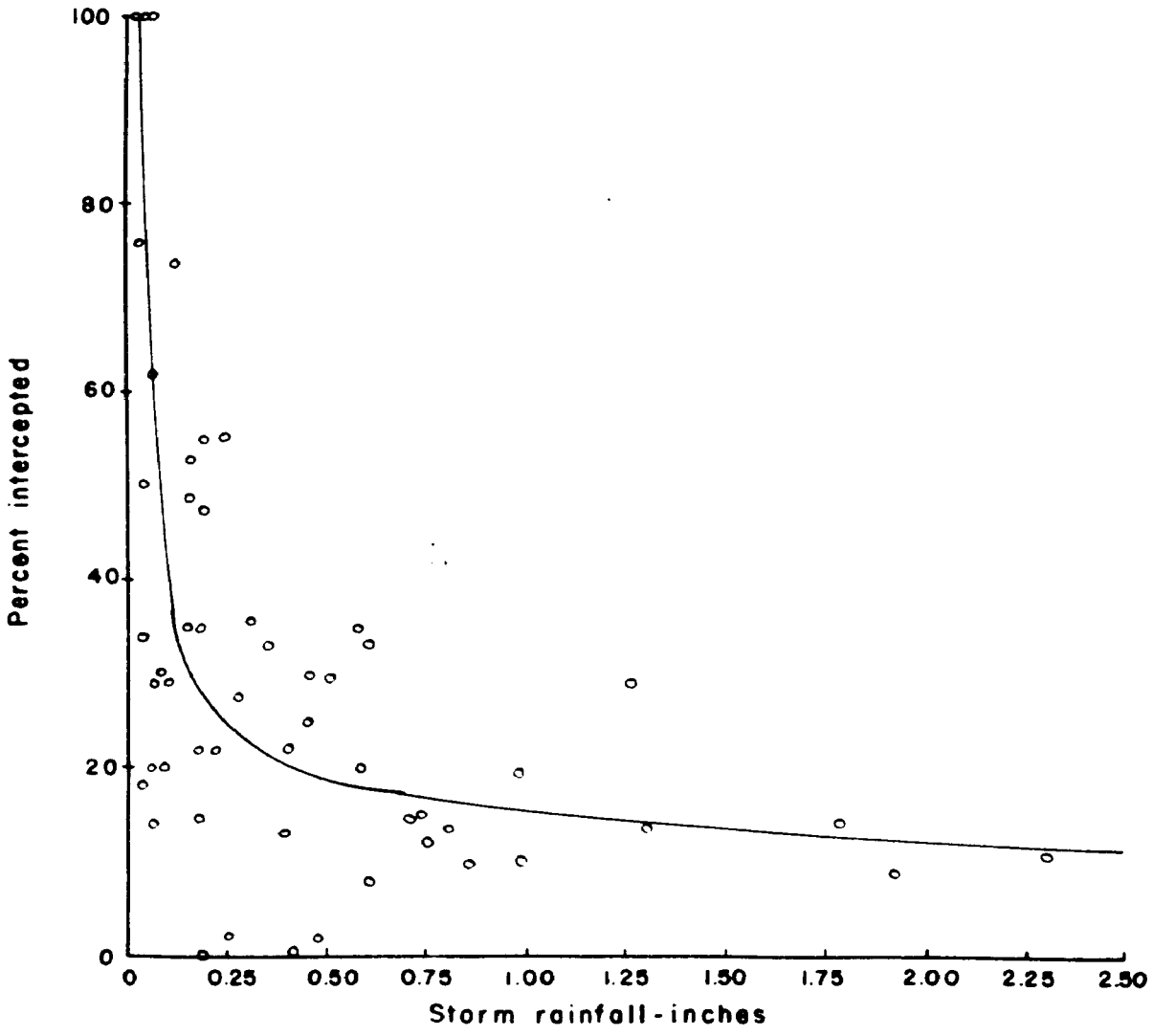


FIGURE 60. Interception of rainfall by the forest at plot CC-1 as related to storm size, summers of 1956 and 1957. Stemflow not measured.

hemlocks, white spruces, white pines and red maples. The crown canopy is 60 percent closed, with the relatively broad crowns of yellow birch comprising almost one-half of the total. Windthrow and subsequent salvage operations removed 80 square feet of basal area of spruce and fir from the area following a severe windstorm in 1949.

Interception of precipitation in this stand varied from storm to storm. Since no record of wind speed and direction or precipitation intensity is available it is not possible to interpret storm characteristics which might have caused the differences observed. The relationship between interception and amount of precipitation for 59 storms ranging from 0.01 to 2.32 inches in size is shown in figure 60.

In the 59 storms measured, actual precipitation was 22.26 inches. Of this amount 18.43 inches reached the ground. Interception therefore accounted for 17 percent of the total precipitation. The amount of stemflow was not measured, but since stemflow was observed only during the heaviest storms, except on the smooth barked balsam fir, the amount is considered negligible. Unmeasured interception by lower vegetation is likely to be sufficient to offset the stemflow which occured.

Interception of precipitation by the forest represents the initial manner in which forests react on the ground water; by preventing a portion of the recharge that might otherwise occur. It may be argued that interception does not represent an independent loss of precipitation from an area, inasmuch as the energy used in evaporation of this water might be otherwise available for transpiration. Nevertheless, it must be considered a loss in this paper as the amount of net rainfall reaching the ground provided the basis upon which evapo-transpiration from the upper soil layers was computed.

Evapo-transpiration

During the summer of 1956, a hydrograph of ground water levels was obtained for the period July 5 to September 5 (Figure 3). That season was wet and cool. The maximum temperature of the summer was 84°F. It occurred on July 26 and August 7. The minimum temperature was 33°F., and occurred on August 20. A temperature almost as low, 34°F., was recorded on July 17. Rainfall for the period was 7.56 inches, with high antecedent soil moisture levels. The maximum height of the water table was 8 inches below the soil surface, which is the maximum possible at well CC-1. The minimum fell only to a depth of 30 inches. Ample moisture was available for plant growth at all times.

In contrast, during 1957 the water level in well CC-1 was recorded throughout the entire growing season from May 10 to October 1. The weather in 1957 was warm with extended dry periods. A maximum temperature of 91°F., was recorded on July 18 and August 2. Low temperatures of 39°F. were reached on July 16 and 24, and on August 4 the temperature fell to 34°F. The last frost occurred on June 7 in the spring and the first light frost of fall occurred on September 4. Rainfall for the period was 14.70 inches, a somewhat misleading figure, as only 8.79 inches fell during the period May 10 to August 22. The maximum height of the water table reached 8 inches and the minimum level fell to a depth of 48 inches. Small herbs and tree seedlings were observed in a wilted condition on dry exposed hummocks on several occasions, and some mortality of tree seedlings resulted.

The estimated use from the ground water during the cool moist season of 1956 was 6.76 inches between July 5 and September 1. This

amount is, of course, considerably less than the total evapo-transpiration for the period.

In 1957, under drouth conditions, ground water losses between July 5 and September 5 were only 3.30 inches, and during the entire period of measurement from May 10 to October 1, 1957, only 9.86 inches. A graphic comparison of the direct contribution by ground water to evapo-transpiration during the two seasons as related to the depth of the ground water is shown in figure 61.

It is apparent that ground water is readily available to tree roots, and thus for evapo-transpiration, only when it lies less than 30 inches beneath the soil surface. Most of the absorbing roots were in the 0-12 inch soil stratum, although some penetrated to a depth of 22 inches. The effective height of the capillary fringe in this sandy soil apparently does not exceed 18 or 20 inches when the water level was falling, and was even less when water levels were rising.

An examination of figure 62 reveals clearly that the availability of the water was greatest when the level was between 16 and 24 inches. Less water was extracted by the vegetation when the water rose above or fell below these levels. With deeper water levels, this phenomenon is easily explained by the inability of the soil to transmit water upward at a rate as rapidly as the vegetation could absorb it. As the water level fell, the number of capillaries capable of transmitting water upward to the roots decreased. The rate of water movement in the fewer capillaries performing this function also decreased (Lewis, 1937; Moore, 1939).

With water levels higher than 16 inches there are probably several reasons for the decreased absorption of ground water by tree roots.

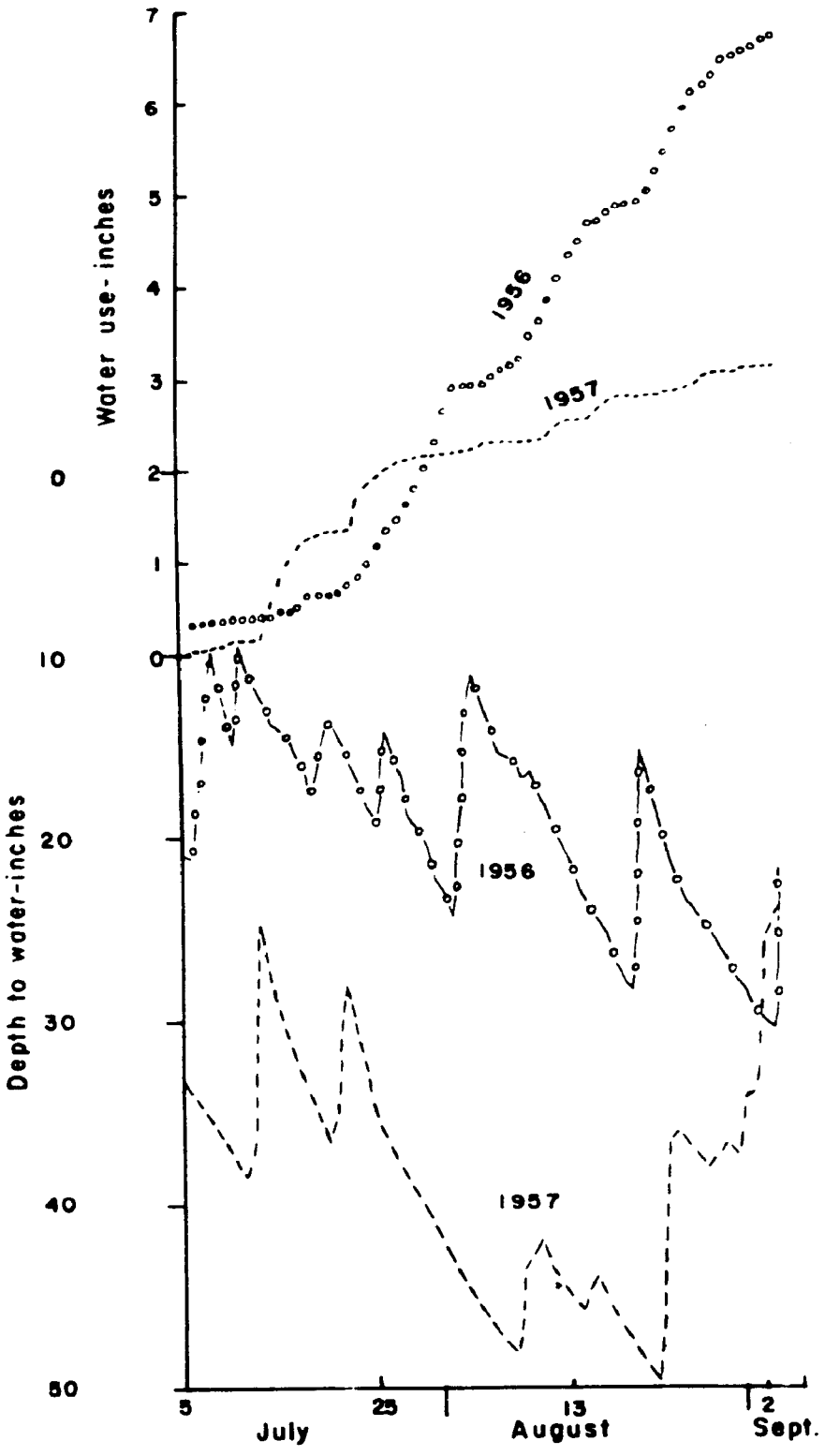


FIGURE 61. Ground water levels and use at plot CC-1 in part of 1956 and 1957.

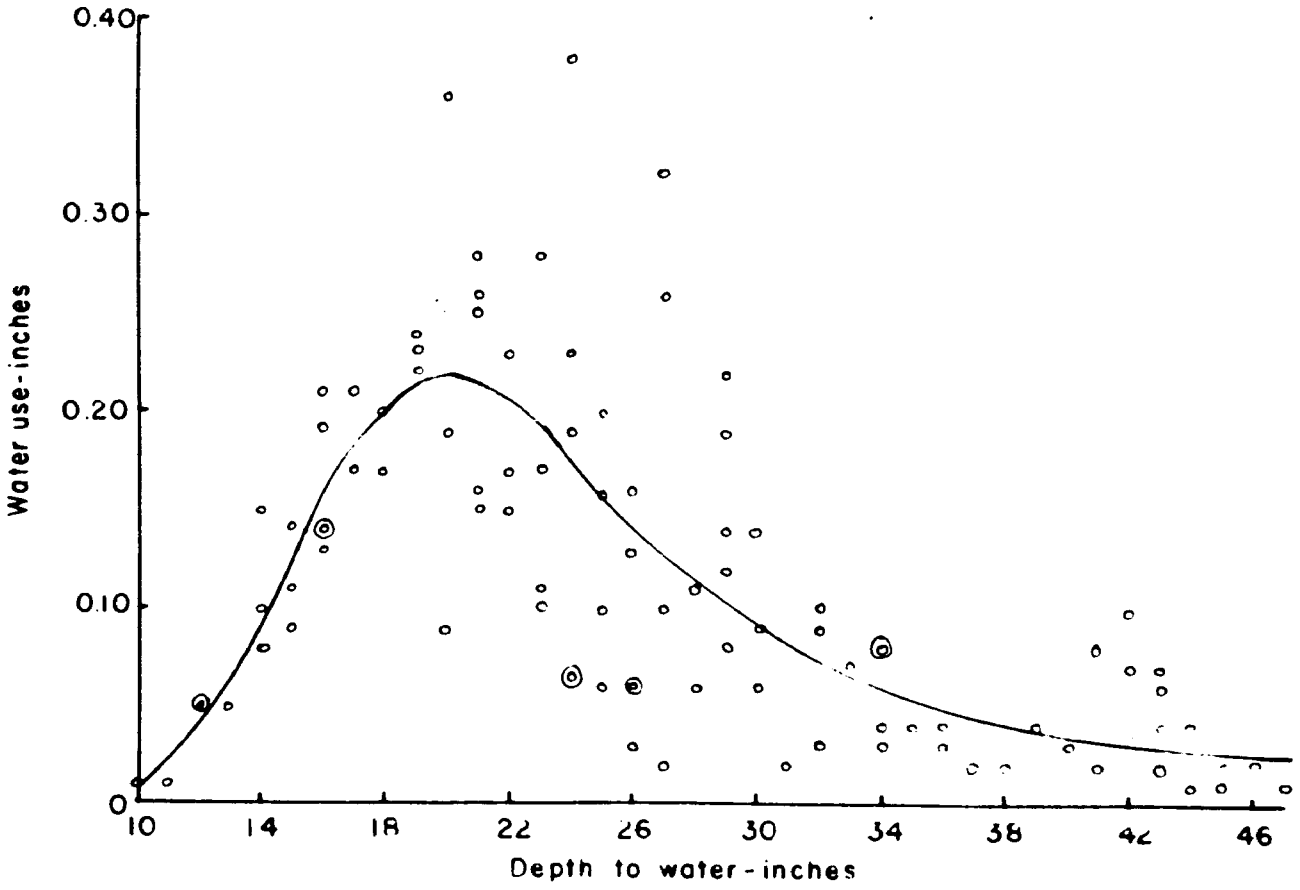


FIGURE 62. Daily ground water use at plot CC-1 as related to water levels, summers of 1956 and 1957. ⊙ = 2 observations.

Some of the roots were flooded at high water levels, with the result that they absorbed less moisture, possibly due to the inhibition of respiration (Henderson, 1934; Childers and White, 1942; Caughey, 1945; Parker, 1950). This phenomenon goes hand in hand with reduced transpiration. Root injury and clogging of conductive tissue by the decomposition products of dead cells may further impede absorption by flooded tree roots (Kramer, 1951).

It is important to note that such high water levels were usually transient, prevailing only for a few days after periods of high rainfall. At high ground water levels the transpiration stress on the vegetation is often sharply reduced, partly because the cloudy, humid weather that often prevails is inimical to a high transpiration demand, and partly because the evaporation of intercepted water from the surface of the vegetation utilizes energy that might otherwise be available for transpiration. Thus, the draft upon the ground water by vegetation is reduced when the root zone is flooded.

At this point, some misconceptions regarding the estimation of water use from water level fluctuations should be clarified. Evapotranspiration is generally assumed to be the cause of these fluctuations, as indeed it is (White, 1932). But, actual ground water removal takes place by absorption into the vegetative roots, not by transpiration from the leaves. If absorption of moisture took place at exactly the same rate and synchronized with evapo-transpiration, this distinction would not be necessary. Such, however, may not always be the case. Work by Kramer (1937) indicates that the rate of absorption of water by roots may lag behind the rate of transpiration in conifer, hardwood, succulent and herbaceous plants when transpiration takes place at a

high rate, even though the plant has a plentiful supply of water, thus creating an internal water deficit in the plant.

At night, when the transpiration rate may be negligible, absorption of water continues, and this deficit is reduced, even though the rate of absorption of ground water may be only 10 to 20 percent of the daytime rate. Thus, when one assumes that the slope of the hydrograph represents the true rate of ground water recharge, he may be somewhat in error. This error is greater under drouth conditions when there is little water available in the upper soil layers. Then, a continuous internal water deficit could develop in a tree. The rate of absorption of water under such conditions might show little daily variation because the supply of ground water to the plant may be continuous night and day, at a rate limited only by the capacity of the soil to transmit the water upward.

When roots are flooded, and absorption is similarly reduced, a similar continuous absorption rate may occur, thus giving a somewhat misleading picture of evapo-transpiration losses as determined from the water level fluctuations.

Such discrepancies must be variable, the amount depending upon the internal moisture deficit in the vegetation and depth of the ground water. When water levels are low, and most of the moisture is absorbed from the soil above the capillary fringe the total error should be small. During high water following precipitation, internal water deficits are likely to be reduced. Again, the amount of error would be low. The greatest error would likely occur with ground water levels immediately below the roots during periods of high transpiration stress. Even though the error at any one time might be slight, over a full

growing season the amount of water use calculated by measures of ground water fluctuations would invariably be low, as the error is accumulative in nature. The figures given in this dissertation do not contain any estimate of the quantity of error which is inherent in the method used.

Water use from the ground water represents only a part of the total water use by swamp forests. Whenever the capillary fringe lies below the soil surface, vegetation obtains a part of its water requirements from the water held in the soil above the fringe. Although the absorption of water from the capillary fringe may be indicated by diurnal fluctuations of the ground water, that absorbed from the soil above the fringe cannot. For this reason fiberglas soil moisture units were installed in order to estimate this additional water loss, as outlined in Chapter II.

The fiberglas units were not completely satisfactory, because the level of precision in measuring soil moisture was considerably lower than had been expected. A part of this inaccuracy may have been due to the fact that the units were calibrated in the laboratory instead of in the field. Laboratory calibration has led to imprecise results by other investigators (Remson, 1956; Horton, 1955). In addition, however, several inexplicable discrepancies were observed. For example, an increase in moisture content of 0.09 inch of water in a 21 inch soil layer was indicated during a two day rainless period when the water level was falling. Only by the use of moisture units, however, could the hundreds of measurements necessary in this study be collected. Although the error involved cannot be precisely estimated, the amounts of water involved were probably small (Horton 1955) and the errors

should tend to be compensating over a long period.

Another difficulty in the use of fiberglas soil moisture units was due to the fact that the plastic covering of the wire leads proved exceptionally attractive to porcupines. These animals chewed through both covering and wire lead, necessitating frequent splicing of the lead. In several cases, the resistance readings taken after splicing deviated from that to be expected. These were excluded from analysis. After a day or two of dry weather, the readings appeared again to agree with the other units in the stack, and after waterproofing the splice the data were again included.

The computed moisture losses from the soil layer above the water table during the summer of 1957 are given in table 18. During the period from June 7 to October 1, a greater quantity of water was removed from the soil lying above the ground water than was supplied by the ground water itself. This is not surprising since the ground water fell below a level where it was readily accessible to tree roots throughout most of the summer. During such periods the swamp vegetation was restricted to the use of the available water in the soil in the same manner as on any upland site. Whenever the water level fell to a low level as in swamp types II-A, II-B-1 and II-B-2, the net result was a moisture deficit as severe as on many nearby upland sites.

In 1956, moisture units were not available to measure soil moisture losses above the ground water. Therefore, it has been necessary to estimate these losses from data taken during 1957. During 1957, there were 22 days when water level, vegetation and climatic conditions were similar (Table 19). The mean daily moisture loss from the soil layer above the water table during these periods was 0.061

TABLE 18

MOISTURE USE FROM THE SOIL LAYER ABOVE THE WATER TABLE.
PLOT CC-1, SUMMER OF 1957

Date	Depth to water ins. (1)	Net ppt. since last reading inches (2)	Inches moisture deficit below field capacity in upper soil inches (3)	Moisture change since last reading inches Col (2) ∠ (3)-(3) preceding plus	minus	Cumulative Days of record	Cumulative Water losses
6/7	20.7	-	0.92	-	-	0	-
6/8	22.6	0.00	0.85	0.07		1	-0.07
6/10	25.5	0.00	0.97		0.12	3	0.05
6/11	25.7	0.04	0.47	0.26		4	-0.21
6/12	22.8	0.16	0.78		0.37	5	0.16
6/18	11.9	1.56	0.13		0.91	11	1.07
6/21	17.4	0.02	0.48		0.37	14	1.44
6/22	16.7	0.17	0.25	0.06		15	1.38
6/27	21.0	0.04	0.47		0.26	20	1.54
6/28	22.3	T	0.63		0.16	21	1.70
6/29	23.4	T	0.56	0.07		22	1.63
7/2	27.9	T	0.73		0.17	25	1.80
7/5	31.1	0.17	0.81		0.15	28	1.95
7/10	36.2	0.16	0.89		0.24	33	2.19
7/11	37.0	0.00	0.84	0.05		34	2.14
7/12	35.0	0.18	1.39		0.73	35	2.87
7/13	21.8	0.68	0.72	0.01		36	2.86
7/16	29.8	0.00	0.85		0.13	39	2.99
7/18	32.9	0.00	1.22		0.37	41	3.36
7/19	34.5	0.00	1.25		0.03	42	3.39
7/20	33.7	0.22	1.17		0.14	43	3.53

Table 18 - Continued

Date	Depth to water ins. (1)	Net ppt. since last reading inches (2)	Inches moisture deficit below field capacity in upper soil inches (3)	Moisture change since last reading inches Col (2) + (3)-(3) preceding plus	minus	Cumulative Days of record	Water losses
7/22	26.0	0.41	0.90		0.14	45	3.67
7/23	29.4	0.00	1.13		0.23	46	3.90
7/25	33.5	0.00	1.04	0.09		48	3.81
7/26	34.6	0.00	1.53		0.49	49	4.30
7/30	38.9	T	2.22		0.69	53	4.99
8/2	41.7	T	2.70		0.48	56	5.47
8/5	42.6	0.05	2.90		0.25	59	5.72
8/7	45.8	0.00	3.18		0.28	61	6.00
8/8	42.7	0.56	2.48	0.14		62	5.86
8/9	42.1	0.00	2.80		0.32	63	6.18
8/10	39.7	0.28	2.56		0.04	64	6.22
8/12	41.6	0.06	2.79		0.29	66	6.51
8/15	42.3	0.41	2.96		0.68	69	7.19
8/16	42.0	0.00	2.93	0.03		70	7.16
8/22	47.1	0.02	3.64		0.77	76	7.93
8/24	33.3	1.14	2.56		0.06	78	7.99
8/29	33.6	0.14	2.60		0.18	83	8.17
8/30	33.8	0.00	2.58	0.02		84	8.15
9/2	23.3	0.80	1.12	0.66		87	7.49
9/5	22.7	0.20	0.69	0.23		90	7.26
9/6	24.2	0.00	1.06		0.37	91	7.63

Table 18 - Continued

Date	Depth to water ins. (1)	Net ppt. since last reading inches (2)	Inches moisture deficit below field capacity in upper soil inches (3)	Moisture change since last reading inches Col (2) + (3) - (3) preceding plus	minus	Cumulative Days of record	Cumulative Water losses
9/8	27.4	0.00	1.62		0.56	93	8.19
9/9	28.7	0.00	1.75		0.13	94	8.32
9/11	30.7	T	1.90		0.15	96	8.47
9/13	27.7	0.30	1.57	0.03		99	8.44
9/17	21.4	0.66	1.18		0.27	103	8.71
9/18	23.4	T	1.32		0.14	104	8.85
9/20	24.6	0.08	1.38		0.14	106	8.99
9/24	10.2	1.67	0.49		0.78	110	9.76
9/26	14.6	0.05	0.56		0.12	112	9.88
9/27	15.8	0.00	0.64		0.08	113	9.96
10/1	18.9	0.00	0.67		0.03	117	9.99

TABLE 19

A COMPARISON OF FACTORS AFFECTING WATER USE IN 1956 WITH THOSE OF JUNE 18-JULY 5; JULY 13-16, AND 22-23, 1957 AT PLOT CC-1

Factor	1956	1957
Vegetative development	Fully leaved	Fully leaved
Vegetation quantity		Unchanged from 1956
Temperature °F.		
Maximum	84	87
Minimum	33	39
Mean daily	62.3	62.5
Mean daily precipitation-inches	0.12	0.13
Water level depth-inches		
Maximum	30.1	30.8
Minimum	8.0	9.1
Mean daily	19.8	21.8

inches per day. Although the daily loss undoubtedly varied widely from this amount, by adding 0.06 inches per day to the losses from the ground water in 1956, it is possible to estimate the total moisture loss from plot CC-1 during 1956.

A comparison of the total estimated water use, from both the soil and the ground water for the period July 5 to September 5, 1956 and 1957 is made in figure 63. Evapo-transpiration was consistently greater during the warm, dry summer of 1957 until the decreased availability of soil moisture became a limiting factor. Then the rate of water absorption fell below that of 1956 with its cooler, wetter weather and an ample supply of available water. Had an ample supply of soil moisture been available throughout 1957, total evapo-transpiration would probably have exceeded that of 1956.

The total moisture losses computed in this manner do not represent the total evaporative water losses, for the interception loss must also be considered. In 1956 this loss was 1.09 inches, and in 1957 during the same period the loss was 1.08 inches. The total loss measured for the two periods, July 5 to September 5, 1956 and 1957 is 11.34 and 10.50 inches respectively.

The potential evapo-transpiration of this area for the same periods were 9.30 and 9.87 inches, respectively. (Thornthwaite and Mather, 1955). Thus the total measured evaporative water use for the two periods exceeded the potential use, using the formula of Thornthwaite and Mather, by an average of only 13 percent, and can be considered to be in reasonable agreement with potential evapo-transpiration.

The evaporative water loss so far discussed occured only during a part of the growing season wherein weather conditions, vegetative

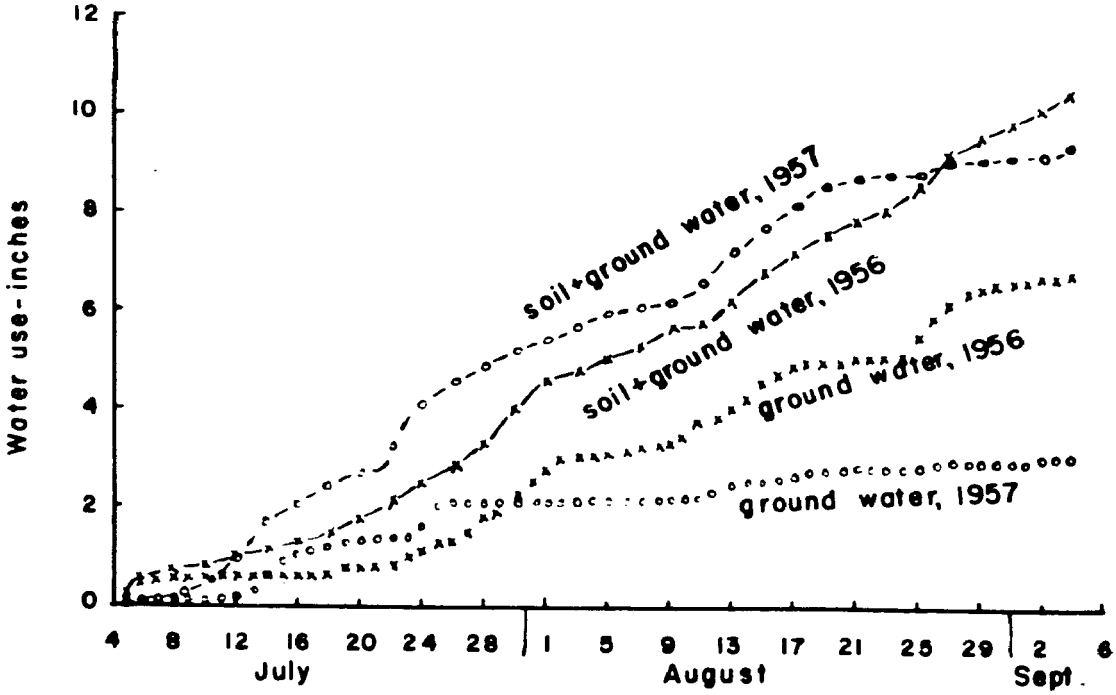


FIGURE 63. Cumulative water use by source at plot CC-1, summers of 1956 and 1957.

development and length of day are rather uniform. It does not represent the complete picture.

In 1957, water use by the forest at plot CC-1 was determined for the period from May 10, when the buds of the hardwoods were just beginning to burst, until October 1, when most of the hardwoods had shed many of their leaves. Soil moisture measurements above the water table could not be made until June 6, 1957. Prior to that date only water level fluctuations were measured. In the cool, wet soils of the swamp, the incompletely leafed trees probably used little more water than was indicated by the fluctuations in the water table. At that time maximum depth to ground water was only 26 inches. Therefore, the water use shown by this method is deemed sufficiently accurate to show the trend in water use.

The seasonal trend in water use is shown in figure 64. During the late spring period while the trees were developing their leaves, water use remained very low. On several warm, sunny days in May wilting was observed in the newly opened leaves of yellow birch and red maple seedlings and saplings, probably as the result of low soil temperatures. Low soil temperatures may have restricted the ability of the roots to absorb sufficient water to maintain the leaves in a turgid condition under the high transpiration stress that was developed. Kramer (1942) has observed such an inhibiting effect on absorption.

The last frost of spring occured on June 7, 1957, and by June 11, all hardwood trees were in full leaf. Rapid shoot and leaf growth was also evident on the conifers at this time. Water use increased rapidly following this period and remained high until the middle of August, at which time seedlings of red maple, hard maple and yellow birch were

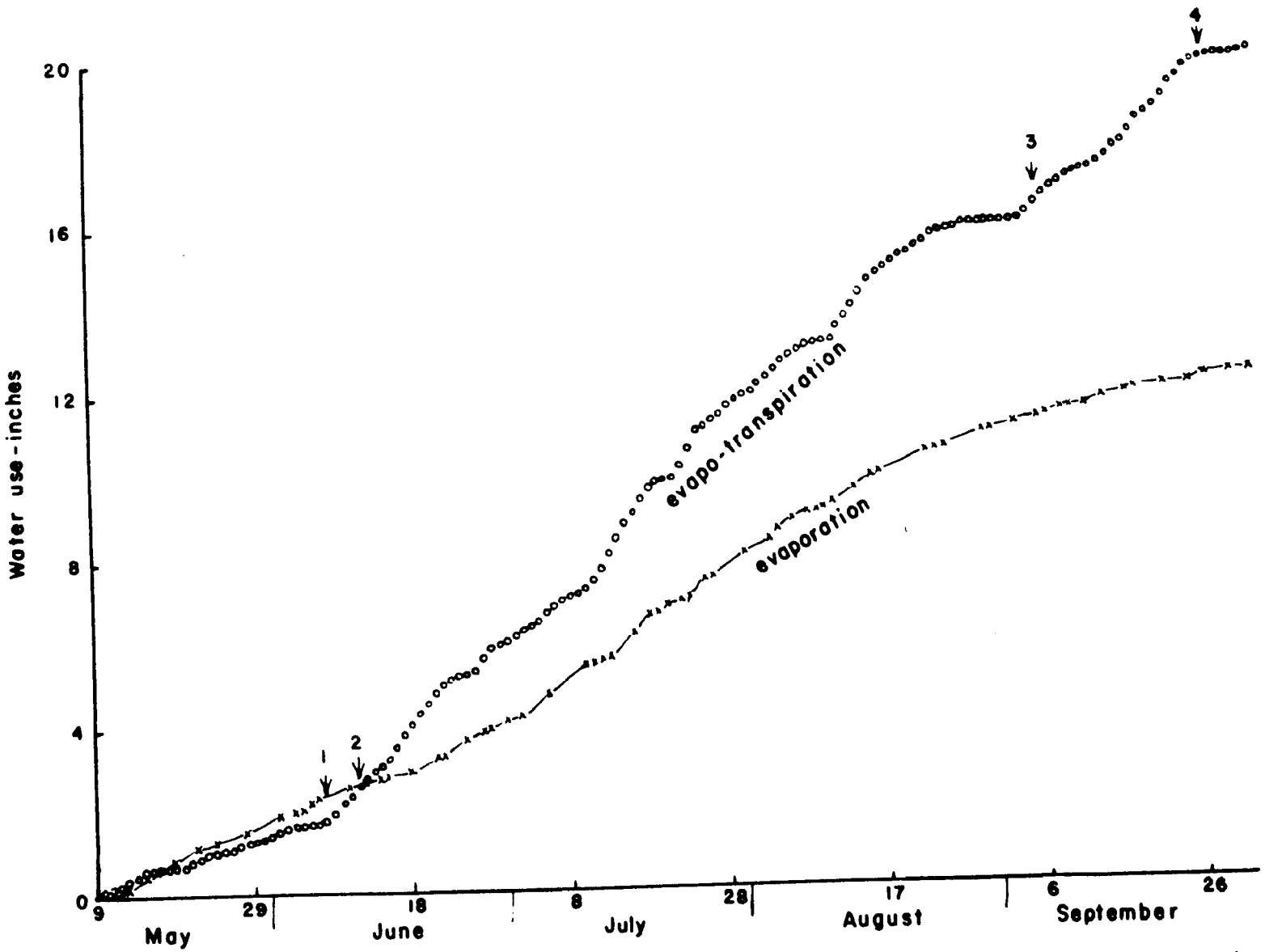


FIGURE 64. Cumulative evapo-transpiration in Cedar Creek swamp and evaporation from a nearby standard U.S. Weather Bureau pan during the growing season of 1957. 1 = last spring frost, 2 = all hardwoods in full leaf, 3 = light frost, leaf coloration began, 4 = hard frost, heavy leaf fall began.

observed to be wilting, indicating that soil moisture levels in the upper parts of hummocks were very low, and that the lack of moisture was limiting water use. Heavy rains in late August replenished the moisture supply, and heavy water use began anew.

A light frost occurred the night of September 5, 1957, and the leaves of yellow birch, black cherry, trembling aspen and red maple began to turn color. At the same time, white cedar leaves began to turn brown over about one-third of the leaf surfaces. Water use remained fairly high, however, until the heavy frost of September 25, 1957. Thereafter, water losses dropped sharply.

It is apparent that the rate of water use in a swamp forest, where an ample supply of water is available, closely follows the trend of vegetational development. This is not to imply a simple causal relationship, however, for it is more than likely that vegetative growth and development is responsive to the same seasonal progression of temperature and length of day that influences evapo-transpiration. This is borne out by the trend of the curve of cumulative evaporation from water in a standard U. S. Weather Bureau pan, which may be also seen in figure 64. During the period of leafing out in the spring, and again after the first hard frost in the fall, the rate of evaporation from an open pan closely approximates the rate of evapo-transpiration measured in the swamp forest.

Evaporation from the soil.- To this point, evapo-transpiration has been considered as a single process. In order to determine the approximate role played by transpiration and evaporation separately, a trenched and an untrenched subplot were established on plot CC-1 and soil moisture measurements taken as indicated in Chapter II.

The natural litter was undisturbed on both plots. The results of these measurements are shown in table 20. In the soil layer above the water table, evaporation alone removed only 15 percent as much water as was removed by evaporation and transpiration together. When the additional moisture contributed to the transpiration stream by the ground water is considered, evaporation from the soil was only 8.5 percent of total evapo-transpiration.

TABLE 20

WATER LOSS IN CEDAR CREEK SWAMP FROM TRENCHED, UNTRENCHED PLOTS PLOTS AND A STANDARD U. S. WEATHER BUREAU EVAPORATION PAN DURING SELECTED PERIODS IN 1957

	Water Loss in Inches				
	Untrenched Plot			Trenched Plot	Open pan
Date	Soil	Groundwater	Total	Soil	
6/7-10	0.04	0.34	0.38	0.02	0.30
7/13-19	0.53	0.94	1.47	0.11	0.79
7/22-30	1.32	0.28	1.60	0.14	0.87
8/5-7	0.28	0.01	0.29	0.00	0.01
8/29-30	-0.02	0.09	0.07	0.05	0.44
Total	2.15	1.66	3.81	0.32	2.61

The evaporation from a standard U. S. Weather Bureau pan located nearby in a small forest opening may also be used as a standard for comparison. In this comparison, evaporation from the forest soil was 12 percent of that in the pan and total evapo-transpiration from the swamp forest was 146 percent. These figures represent the mean of several water level and soil moisture conditions.

The effect of forest cover upon the moisture content of the soil

underlaid by a water table is also shown in figure 65, which represents the moisture deficit from field capacity at weekly intervals in the trenched and untrenched subplots at plot CC-1. The differences shown do not represent relative rates of water loss, but instead indicate the integrated net result of variable rates of evaporation, evapotranspiration, water level fluctuations and precipitation throughout the summer season.

During periods of high water levels and high soil moisture conditions with frequent light rains, as in June, 1957, there was little difference in the amount of water stored in the soil between the trenched and untrenched plots, even though it is apparent that the actual moisture use was considerably greater in the untrenched plot. In both, ample recharge by precipitation prevented any large moisture deficit. Probably the major difference between the two plots was that more water percolated down to the ground water in the trenched than in the untrenched plot.

As the season progressed, however, soil moisture levels in both plots decreased. The ground water level fell and the trees in the untrenched plot drew more and more upon the upper soil for their moisture requirements. Summer rains did not penetrate the drier soil in the untrenched plot as deeply as in the more moist trenched plot, and were often quickly absorbed, thereby being less effective in reducing the moisture deficit. Therefore the difference in the amount of stored water in the two plots increased.

Precipitation in late August and September was in excess of water use by vegetation and as the soil moisture deficits in both plots were reduced the differences between the two plots became less.

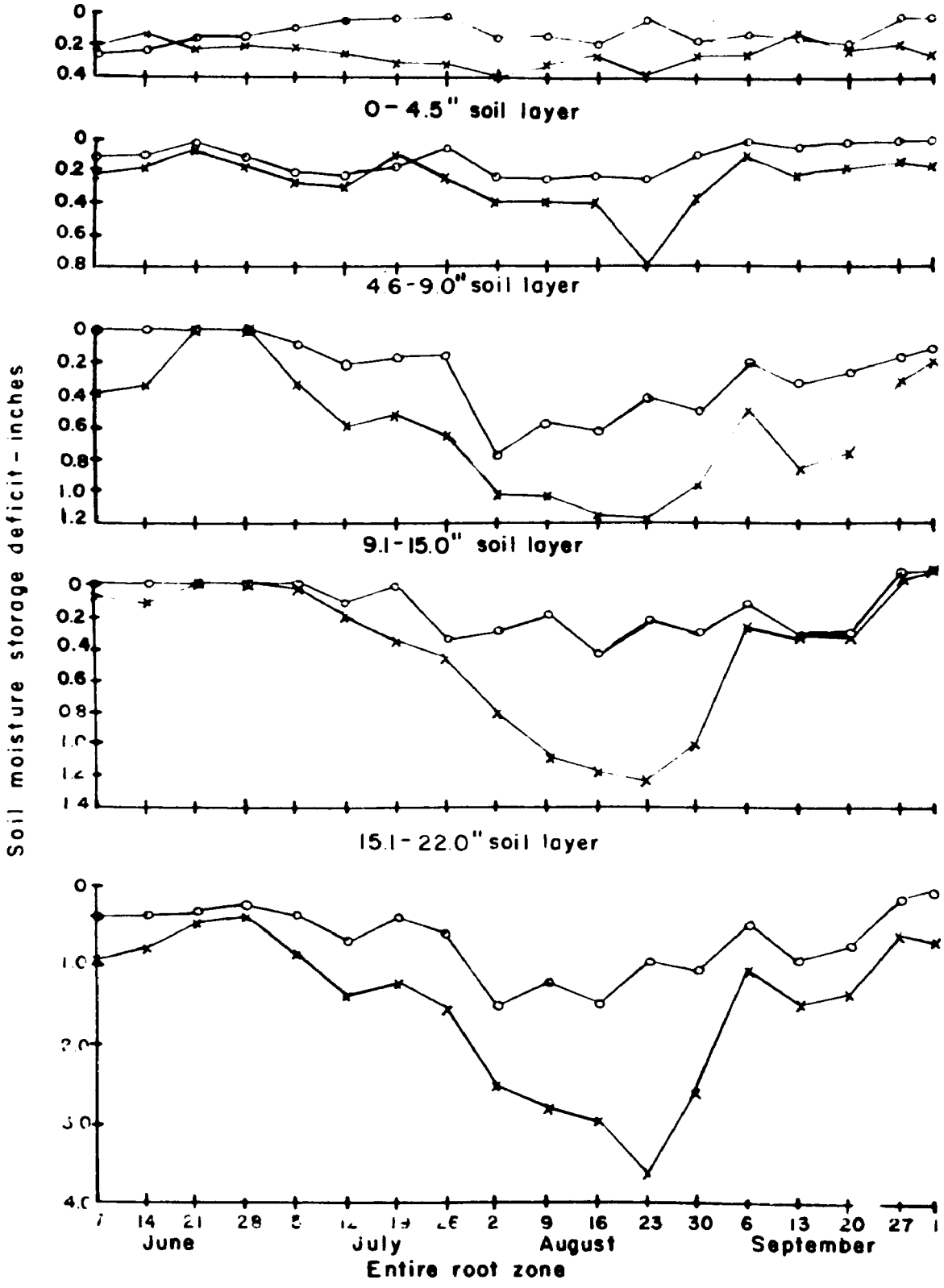


FIGURE 65. Soil moisture storage deficits in trenched (o—o) and untrenched (x—x) subplots, plot CC-1, summer of 1957.

A noticeable difference in the trend of moisture content in the upper and lower soil levels exists, indicating that the driest soil layer in either subplot was not always at the surface. This phenomenon is due to the occurrence of light summer rains which penetrated only a slight distance into the soil. Therefore the trend in moisture content fluctuations is not synchronized between the different soil depths, even in the same plot.

Evapo-transpiration by swamp types.- The removal of moisture from the soil and ground water has been discussed on the basis of measurements possible only on one intensively instrumented plot. Although the weather in the study area was similar at all plots, water levels and forest cover were not. A consideration of water use under other swamp conditions is in order.

According to Thornthwaite and Mather (1955), potential evapotranspiration in any fully vegetated area with an unlimited water supply is the same under uniform weather conditions. Thus any variation in water use between the various swamps studied would depend on the availability of water and the degree to which the stand fully occupied the site.

During 1956, and similar wet years an ample supply of water is available in all swamp types, and water use would likely be rather uniform. In a dry year such as 1957, available water may become restricted in all swamp types except I-A, characterized by shallow, stable water levels. Therefore, it would be expected that water use during dry years would be greatest in this type.

The degree to which water becomes limiting may be expected to vary with the storage capacity of the root zone as well as with water

levels. Thus, on the basis of known root depths, soils and water levels, water use during drouth periods may be expected to decrease in the following order by water level types: I-A, I-B, II-A, II-B-1, II-B-2. This order is partially substantiated by soil moisture and precipitation measurements taken during the summer of 1957.

Evapo-transpiration at well CC-1 (type II-A) during the period June 7 to October 1, 1957 was 17.8 inches. On the type II-B-2 plots, the calculated average use was only 14.5 inches. The latter figure was based only on changes in soil moisture above the water table. The ground water contribution was considered negligible as the water level fell to a depth of 5 feet in June, and remained low throughout the summer. Interception losses by the relatively dense canopies of the II-B-2 plots certainly exceeded those at CC-1, so evapo-transpiration was certainly less than 14.5 inches. The 3.3 inches difference in evapo-transpiration, however, does indicate that substantially more water is used in the wetter swamps than on the swamp borders during drouth periods.

Water storage in swamp forests

On upland sites, the amount of storage space in which precipitation may be retained is inversely proportional to the amount of moisture removed from the soil in the evapo-transpiration processes of the forest. It is partly due to this creation of water storage space that forest cover is often considered an important factor in flood control.

Swamp forests, however, perform such a function only to a limited degree, depending chiefly upon the ground water level in each

particular swamp. In swamps where the ground water level is shallow and essentially stable, soils remain moist throughout the growing season despite the high water use by the forest, and the retention storage capacity is increased only to a slight degree even during long dry periods. Where water levels are lower, the amount of available storage capacity is increased, and may equal that created on upland sites (cf. figures 42, 43, 44, 45 and 46).

Upland forests also are considered important flood control factors due to the favorable influence they exert upon the soil through the addition of litter and by root activity which improves the ability of a soil to absorb water falling thereon and temporarily detain a part of it in the larger soil interstices created as a result. The depth of the soil may also be slightly increased as a result of this accumulation of organic material.

Swamp forests also perform this function. In fact, litter accumulations are often much greater in swamps, resulting in the formation of thick organic layers due to the slow rate of decay in wet areas. These thick organic layers may impede storm run off for only a short time, but this action is sufficient to eliminate sharp peaks of streamflow and provide more stable conditions for release of water into streams that arise in the interior of swamps, as brought out in the discussion of water level types in swamps. The value of swamps in reducing peak flows, however, would decrease as the length of the storm increased, being greatest in short, intense storms and almost negligible during long, steady storms.

During drouth periods, however, swamp forests may reduce streamflow substantially by using ground water which might otherwise

reach the streams, as do the phreatophytes in western United States (Robinson, 1958). This effect is doubly serious, for it occurs when streamflow is normally low, and to the greatest degree in swamps where streamflow is sustained directly by ground water supplies near the soil surface.

CHAPTER V

SUMMARY AND CONCLUSIONS

The results of this study indicate that variations in site quality and species composition of swamp forests are clearly associated with differences in the height of the water table and its pattern of fluctuation in response to precipitation and intervening dry periods. The redox potential and seepage rate of the ground water appeared to be factors of minor importance. The specific conductance of the ground water differed little between the swamps studied, and was clearly unrelated to site quality or species composition.

In 1956, a wet summer, water levels remained stable on 14 of the 16 plots studied. Observations in the dry summer of 1957, however, revealed that water levels fell to a low level on 7 of the 16 plots as the drouth intensified. Ground water levels and their pattern of fluctuation provided a simple and useful basis for classifying swamps into types.

Swamps exhibiting persistently high water levels were generally characterized by organic soils and forests of low to moderate productivity dominated by white cedar, black spruce and balsam fir. In an old burn area, trembling aspen dominated two plots, but was rapidly being replaced by spruce and fir. The overstories on all plots in this type were open, frequently due to windthrow. Advance reproduction, consisting mostly of balsam fir, with a small quantity of black spruce and a scattering of white cedar and hardwoods was developing in the openings. Two-thirds of all trees, and an even larger proportion of

dominant and codominant trees were found growing on hummocks on these wet sites.

The roots of white cedar, balsam fir, black and white spruce, tamarack, black ash and trembling aspen penetrated as much as 4 inches below the water table. Root density decreased gradually with depth.

The site indices of spruce and fir in swamps with high stable water levels ranged from 26 to 48 feet at age 50 years. The poorer sites were associated with poorly decomposed peat soils with low redox potentials and the better sites were associated with well decomposed muck and mineral soils with higher redox potentials. White cedar site indices were similarly low, and the cedars were much older than the spruce and fir with which they shared dominance. The secondary growth of dominant and codominant conifers showed a statistically significant relation to estimated water levels, being greater in dry years than in wet years.

In some swamps, high stable water tables were maintained in wet years, but following periods of precipitation deficiency, the water level fell. On the two plots studied in this type, organic soils were less well developed. At one, the hummocks were poorly decomposed sedge and woody peat, while the depressions were characterized by a thin muck overlying a sandy loam subsoil. On the other, the hummocks were sandy and the depressions supported sphagnum mosses. All of the dominant and 95 per cent of the codominant trees in this type grew on the hummocks. Hardwoods, consisting of yellow birch and red maple were more plentiful, occupying almost one-half of the crown canopy, although fewer in number than the conifers. Reproduction counts indicated

that conifers were maintaining their position as a major component of the stands.

The root penetration of white cedar, balsam fir, black spruce, yellow birch and red maple extended slightly below high water levels, but all roots were well above the water table in time of drouth.

The site index of spruce and fir averaged 41 feet at age 50 years, or slightly higher than in swamps with a persistent high water table. Secondary growth, however, showed no relation to estimated water levels, suggesting that a reduced supply of water during dry years may have been as effective in restricting growth as excess water was in wet years.

The productivity of the two swamp types mentioned above was the lowest found in this study and presents a problem if such areas are to contribute an increased supply of pulpwood for the well developed paper industry in the area. The results of this study suggest two possibilities for increasing pulpwood yields. The first of these would be to increase the proportion of spruce and fir in these stands by cutting white cedar, since cedar takes approximately twice as long as spruce and fir to develop to a given size. The presence of advance reproduction of black spruce and especially balsam fir, indicates that a cedar cutting program is likely to be successful in this respect.

A second means of increasing production is suggested by the occurrence of a majority of the best developed trees on hummocks, increased secondary growth of conifers during dry years where water levels are essentially stable, and the restricted root penetration by all species where water levels are high throughout wet years, but fall below the root zone during periods of drouth. This method is drainage.

Well planned drainage offers fruitful possibilities-not only for increasing the growth of desirable conifers, but losses from windthrow which contribute to poor stocking on these sites might be reduced if water levels were lowered sufficiently to facilitate deeper root penetration.

On two plots where water levels rose near the soil surface only for brief periods following precipitation during the growing season, a gley horizon was formed in the mineral soils several inches below the uppermost water levels. The forest cover was dominated by conifers, but contained a small amount of yellow birch and red maple. As on other plots characterized by high water levels during at least part of the growing season, a preponderance of the trees grew upon hummocks. Advance reproduction was abundant, with red maple and yellow birch dominating the larger seedling size classes. Balsam fir appeared to be the only conifer successfully reproducing.

Examination of soil pits revealed that roots of yellow birch, red maple, white cedar, balsam fir and black spruce penetrated well below high water levels, and a few roots penetrated the gley horizon. The excavation of individual root systems on this type was especially revealing. The three most successfully reproducing species; balsam fir, red maple and yellow birch, all had roots that penetrated deeply below high water levels. Hemlock, white cedar, and black and white spruce roots penetrated below high water levels to a lesser extent, while the living roots of hard maple were restricted to a shallow depth which was above even the high water levels.

These observations are suggestive of a reason for the commonly observed dominance of yellow birch and red maple, among the hardwoods,

and the limited occurrence of hard maple on poorly drained sites. Despite the fact that both yellow birch and red maple are less tolerant of shade than hard maple, their well developed root systems may be the factor that enables them to occupy the equivalent position preempted by hard maple on well drained sites. Thus, the large numbers of small hard maple seedlings that are commonly observed on wet sites may be misleading as an indication of the future composition of the developing stand.

Several other implications of importance to the management of swamp forests arise from observations on the plots with a rapidly fluctuating water level. The successional trends appear to be strongly in the direction of red maple and yellow birch. On these sites, however, the site index for spruce and fir of 48 feet at age 50 years indicates that the productive potential for pulpwood species is above the average for swamp sites. Red maple is a low quality tree, and although some high quality yellow birch grows on these sites, growth is slow and merchantable heights are short. The problem resolves itself into deciding whether to manage for spruce and fir or hardwoods. If spruce and fir are the desired species, it will be necessary to develop some method of keeping the hardwoods under control.

A question also arises in respect to possible undesirable side effects of drainage measures in the wetter swamps. While drainage may be expected to result in increased growth of swamp conifers, it may also result in creating conditions which favor the development of undesirable hardwoods. The answer to this question depends in large degree whether or not the high persistent water table or some other factor or factor complex, such as limited nutrient supplies and/or

poor aeration, is responsible for the limited development of hardwoods on wet sites. Further investigation is necessary.

Drainage is not likely to be an important consideration in the remaining swamp types where water levels do not rise above a depth of 18 inches below the soil surface. These swamp margin sites were not only the most productive of all sites studied for spruce and fir, with site indices ranging from 49 to 55 feet at 50 years of age, but the secondary growth of conifers showed a statistically significant reduction when estimated water levels fell deeply in dry years.

No important restriction in root development was apparent in the mineral soils on these sites. Gleization was weak and sometimes absent. The forest stands were well stocked, with crown coverages ranging from 66 to 88 per cent closure, and windthrow appeared to be a minor problem. The most important factor from the standpoint of management was the extremely strong development of hardwoods, including hard maple. Only a scattering of conifers, mostly balsam fir, were successfully reproducing. It is possible, in view of the relatively complete crown closure, that openings in these stands might result in better coniferous reproduction. Many of the conifers in the upper crown canopy probably became established following fires which opened the original stand, as fire scars older than most of the spruces and firs are present on living trees on all four plots having moderately deep high water levels.

It is clear that ground water exerts important influences upon swamp forests. It is certain, although perhaps not so obvious, that swamp forests also react importantly upon ground water conditions.

The swamp forest at one plot intercepted approximately 17 per cent of the precipitation from 59 storms during the summers of 1956 and

1957, neglecting that which may have been diverted to stemflow. Swamp forests also transpire large quantities of ground water. During the dry summer of 1957, evapo-transpiration was greatest where water levels were shallow and stable, and the water supply was unlimited throughout the summer. On the plots where the water table fell well below the root zone, evapo-transpiration was limited to the supply of moisture held in the root zone. Replenishment of the moisture was largely dependent directly upon precipitation. In both cases, evapo-transpiration probably consumed most of the summer rainfall, and in addition, evapo-transpiration on plots where water was always available in unlimited quantity probably exceeded precipitation during the period from May 10 to August 22, 1957.

Measurements of soil moisture with fiberglas units in three plots where the water level fell well below the root zone provided a basis for estimating evapo-transpiration. The results were compared with estimated evapo-transpiration derived from a combination of soil moisture measurements and analysis of well hydrographs on a plot with a strongly fluctuating water table. They revealed that evapo-transpiration in swamps with a continuous supply of abundant water probably exceeded that on the drier swamp margin by 3.3 inches of water during the period June 7 to October 1, 1957. Estimated water losses in the wetter swamp were essentially the same as calculated potential evapo-transpiration as defined by Thornthwaite and Mather (1955). Limited observations indicated that direct evaporation from the soil surface was approximately 8 per cent of total evapo-transpiration.

Two direct influences are attributable to the use of ground water by swamp forests. In swamps with a high stable water level, a

considerable amount of water that might otherwise reach the streams is lost through evapo-transpiration. In swamps where the water level falls during periods of precipitation deficiency, vegetational use contributes to the falling water table, and in addition, by extracting soil moisture from above the water table, creates a storage space which will retain precipitation, and delay recharge of the ground water supply.

The moisture storage capacity created in swamp soils by evapo-transpiration of the forest varies by water level types. Where water levels were shallow and stable, storage capacities were negligible, averaging less than 1 inch of water during the driest week of 1957. Where water levels were deeper, and the vegetation withdrew moisture mainly from the soil above the capillary fringe, storage capacities created were proportional to soil moisture extraction between storm periods.

The net influence of swamp forests upon streamflow is therefore variable. Where water levels are shallow and stable, streamflows during dry periods are depleted in proportion to evapo-transpiration use. During wet seasons, little storage capacity is available to hold precipitation and that falling on such areas contributes quickly to streamflow. Where water levels are deeper, less depletion of low flows may be expected and soil storage capacities sufficient to retain considerable amounts of precipitation are created.

Drainage efforts to increase forest production may be either favorable or unfavorable to the water resource, depending on conditions in a given swamp. Low streamflows may be increased by dropping the ground level below tree roots, which would decrease the transpiration draft, at least until root growth adjusted to the lowered water level

(Robinson, 1958). On the other hand, low streamflows might be further decreased if the ditches permit a rapid depletion of the underground reservoirs which feed the swamps.

Timber cutting in swamp forests should seldom have a deleterious effect on the water resource and could increase the low flows in summer. Spring flood levels would not likely be changed, for although forest vegetation may create considerable storage space for precipitation on upland soils, this effect is limited in swamps, especially during wet periods when a large moisture storage capacity is most necessary. Ground water levels could be expected to rise following cutting, but this effect would be negligible when water levels are near their maximum height anyway. A rise in ground water levels during dry periods would be desirable, as streamflow would be sustained at a higher level, thus providing an improved habitat for aquatic life.

The water resource could easily be damaged, however, if streambank trees were removed or trees felled and slash piled directly into the streams. Water temperatures would rise and the current would be slowed. Many streams in the area studied are only marginal trout waters and such changes might destroy them as trout habitat.

Suggestions for future research

It is inevitable that any investigation which is limited in scope will lead to more problems than can be answered with the facilities and time at the disposal of the investigator. One can only hope to delineate and frame those problems in such a way that future investigations will be more fruitful.

The strong relationship between ground water and swamp forests

emphasizes the need for a simple manner of classifying water level characteristics. The techniques used in this study are time consuming and cannot be used in wet years when most swamps have a high, stable water level. Qualitative observations suggest that a classification based on the location of swamps with respect to topography in combination with the soil conditions and cover types may be possible. The data contained herein tend to substantiate these observations, but are too limited to be conclusive.

Once swamps can be classified so that problem types may be delineated, the need for research is greatest with respect to the problem of the increasing dominance of undesirable hardwoods in mixed conifer-hardwood swamps. The evidence presented in this work suggests that the core of the problem lies with red maple and yellow birch.

Research designed to meet the hardwood problem may be profitably directed along several avenues. Investigations to determine the relative rates of conversion of swamp forests from conifers to hardwoods under several conditions of soils, water levels and cutting may well prove fruitful. The work of Zasada (1952), as well as this study indicates that the rate of conversion may vary considerably in relation to water levels and soil types.

Any cutting in swamp forests which removes the valuable coniferous component and leaves the hardwoods can only be expected to result in an increase in the dominance of the hardwoods in the next stand. Studies to determine the feasibility of hardwood removal during cutting may help to overcome the problem. Supporting studies on utilization of poor quality swamp hardwoods would certainly enhance the opportuni-

ties for removing these species. The growth and yield of swamp conifers may increase sufficiently to make hardwood removal profitable, but too little is known of the response of swamp conifers to release to tell.

No investigation would be complete if it did not yield basic information as to why certain species compete successfully in swamps, while others do not. The germination and establishment of swamp species should be investigated on various soil and water conditions. Root development may be the key factor in the success of a species in a swamp environment. The availability of nutrients in poorly aerated conditions may limit the success of certain species. An evaluation of the nutrient availability and requirements of swamp trees would be desirable. The full productive potential of swamps will not be realized until foresters learn more about the factors which determine this potential.

Research to determine methods of increasing the productivity of swamp forests may also prove fruitful. Until recently, drainage of forested swamps has not been practiced to any great extent, probably because of the rather poor results obtained from early drainage studies in the Lake States (Zon and Averell, 1929; LeBarron and Neetzel, 1942). Yet, successful drainage is widely practiced in other parts of the world and is gaining increased attention in the southern United States. The relation between site index of spruce and fir to water levels shown in this study suggests that perhaps drainage has not been given a fair chance to prove itself in the Lake States. This situation is likely due to the fact that the drainage operations in the studies earlier mentioned were not planned in the proper manner and at the right place. It is not then unusual that the results were poor; anything else would

have been purely accidental.

In order for drainage of forested swamps to be successful in this country, research into the type of swamps which will respond to drainage, as well as the methodology of drainage itself, is necessary. The unrealized productive potential of forested swamps due to excess water is worthy of much more consideration than it has received to the present.

Swamp forests are not limited to the production of wood. The values of such forests for winter food and cover for wildlife may be greater than for any other use, especially on sites where the productive capacity is low or where species composition is more favorable to wildlife than timber production. A classification of swamp forests in respect to present or potential use, based upon their value for timber production, wildlife production and their influence upon the water resource would be highly desirable.

Wherever wildlife and water values are high, future research should be conducted in such a manner so as to include the consideration of these values, which may result in a modification of techniques and recommendations serving to increase timber production alone.

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APPENDIX A

LIST OF SCIENTIFIC NAMES OF PLANTS AND ANIMALS MENTIONED IN THE TEXT

Trees

alder, tag	Alnus rugosa (Du Roi) Spreng.
ash, black	Fraxinus nigra Marsh.
ash, mountain	Sorbus americana Marsh.
aspen, trembling	Populus tremuloides Michx.
basswood	Tilia americana L.
birch, yellow	Betula alleghaniensis Britton
birch, white	Betula papyrifera Marsh.
cedar, white	Thuja occidentalis L.
cherry, black	Prunus serotina Ehrh.
elm, American	Ulmus americana L.
fir, balsam	Abies balsamea (L.) Mill.
hemlock	Tsuga canadensis (L.) Carr.
maple, hard	Acer saccharum Marsh.
maple, red	Acer rubrum L.
pine, white	Pinus strobus L.
spruce, black	Picea mariana (Mill) B.S.P.
spruce, white	Picea glauca (Moench) Voss
tamarack	Larix laricina (DuRoi) K. Koch

Shrubs	
currant) gooseberry)	Ribes spp.
Mosses	
sphagnum	Sphagnum spp.
Insects	
eastern spruce bark beetle	Dendroctonus piceaperda Hopk.
larch sawfly	Pristophora erichsonii Htg.
spruce budworm	Choristoneura fumiferana Clem.
Vertebrate animals	
deer	Odocoileus virginianus borealis Miller
porcupine	Erethizon dorsatum dorsatum Linnaeus
snowshoe hare	Lepus americanus Erxleben

APPENDIX B

COMPOSITION OF ORGANIC SOILS AND MECHANICAL ANALYSIS OF MINERAL SOILS ON EACH PLOT

Plot: E-1

Organic layer: Deep sphagnum moss peat, poorly decomposed. Containing fragments of well-preserved woody material. Some sedges, spruce needles and leaves of leatherleaf. pH 5.3

Mineral Soil: Not reached.

Plot: U-2

Organic layer: Matrix-many roots, old needle fragments, sedges, bud scales, sphagnum mosses. Body-fine fragments of wood, sedges, mosses, incompletely decomposed mixed with amorphous organic material, dark brown to black in color. pH 5.5

Mineral Soil: Stony sandy loam - 80% of volume in small stones. 6.9% clay, 18.7% silt, 74.4% sand. pH 6.2

Plot: C-1

Organic layer: Depth to 4 feet over "blue organic clay". Woody peat, matrix of rotten wood, stems of sedges, body of black amorphous material. Moderately consolidated. Many sand grains included throughout. pH 7.1

Mineral Soil: Not reached.

Plot: C-2

Organic layer: As C-1, except amorphous material is more of a dark brown, color no sand grains evident. Contained 2 bivalve mollusk shells approx. 1 mm dia. No "blue organic clay" reached. pH 7.3

Mineral Soil: Not reached.

Plot C-3:

Organic layer: Patches of sphagnum peat, undecomposed, poorly consolidated, in a woody peat. Matrix of small, rotten pieces of wood, body dark brown to black amorphous organic material. Fine sand grains visible throughout. Moderately consolidated. pH 7.3

Mineral Soil: Not reached.

Plot C-4:

Organic layer: As C-3, somewhat darker in color. pH 7.0

Mineral Soil: Not reached.

Plot C-5:

Organic layer: Matted, laminated leaf litter over stones, incorporated into sandy loam.

Mineral Soil: Very stony. A_1 at 4" depth: sandy loam - 10.6% clay, 10.9% silt, 78.5% sand. Grey sandy loam at 7" depth: 7.0% clay, 19.3% silt, 73.7% sand. Brown sand at 12" depth: 4.0% clay, 10.0% silt, 86.0% sand. pH 6.5

Plot P-2:

Organic layer: Well decomposed small wood fragments, body is black amorphous material. Many shallow, extensive sphagnum patches. Organic soil to 7" depth, contains many fine sand grains. pH 6.8

Mineral Soil: Grey sand to 14" depth: 2.5% clay, 10.3% silt, 87.2% sand. Brown sand below 14" depth: 0.2% clay, 0.3% silt, 99.5% sand.

Plot P-3:

Organic layer: Matrix-very small, well decomposed wood fragments. Body-black amorphous material. Some charcoal fragments. Considerable very fine sand. Tightly consolidated at 36" above mineral soil. pH 6.9

Mineral Soil: 36" ± - yellowish mottled loamy sand - 3.7% clay, 14.6% silt, 81.3% sand. pH 6.2

Plot E-4:

Organic layer: On hummocks, mull humus; in depressions, sphagnum mosses.

Mineral Soils: Yellow, rusty-6" depth: sandy loam - 8.4% clay, 20.4% silt, 81.2% sand, pH 6.8
Grey-black gleyish at 12" depth: sandy loam - 8.0% clay, 20.8% silt, 81.2% sand. Black at 16" depth (contains charcoal): sandy loam - 9.9% clay, 27.5% silt, 62.6% sand. Grey pink at 24" depth: sandy loam - 12.5% clay, 28.0% silt, 59.3% sand.

Plot E-5:

Organic layer: Mull humus.

Mineral Soil: A2 at 6": sandy loam - 8% clay, 25.4% silt, 65.9% sand, pH 5.3
B at 10": loamy sand - 4.8% clay, 15.7% silt, 79.5% sand, pH 6.1
G at 20": sandy loam - 9.9% clay, 19.8% silt, 70.3% sand.
C at 30": sandy loam - 8.5% clay, 23.5% silt, 68.0% sand.

Plot CC-1:

Organic layer: Mull humus.

Mineral soil: A2 at 6": sandy loam - 6.4% clay, 25.6% silt, 68.0% sand, pH 5.9.
B at 12": sandy loam - 5.5% clay, 31.6% silt, 62.9% sand, pH 6.0
G at 15": sandy loam - 9.6% clay, 37.6% silt, 52.8% sand.
C at 24": loamy sand - 6.5% clay, 16.2% silt, 77.3% sand.

Plot CC-2:

Organic layer: Mull humus.

Mineral soil: A2 at 6": loamy sand - 4.8% clay, 16.3% silt, 78.9% sand, pH 5.9
B at 15": loamy sand - 4.5% clay, 11.0% silt, 84.5% sand, pH 5.9
Hardpan at 36": sandy loam - 12.7% clay, 23.0% silt, 64.3% sand.
C at 5'6": sandy loam - 10.5% clay, 19.6% silt, 69.9% sand.

Plot P-1:

Organic layer: Mull humus.

Mineral Soil: A_2 at 9" depth: sandy loam - 7.5% clay, 21.9% silt, 70.6% sand. pH 6.1
B at 12" depth: sand - 3.4% clay, 8.3% silt, 88.3% sand.
G at 24" depth: sandy loam - 5.8% clay, 20.5% silt, 73.7% sand.
C at 36" depth: gravelly sand - 1.6% clay, 1.5% silt, 96.9% sand.

Plot P-4:

Organic layer: Mull humus.

Mineral Soil: A_2 6" depth - loamy sand containing charcoal - 4.4% clay, 15.3% silt, 80.3% sand, pH 6.2
B at 14" depth - sand - 1.6% clay, 4.5% silt, 93.9% sand.
C at 26" depth: sand - 1.5% clay, 3.0% silt, 95.5% sand.

Plot U-2

Organic layer: Mull humus.

Mineral Soil: A_2 at 6" depth: silt loam - 13.9% clay, 56.0% silt, 30.1% sand, pH 5.8
B at 12" depth: sandy loam - 10.3% clay, 33.3% silt, 56.4% sand, pH 6.2
B at 18" depth: gravelly sandy loam - 5.2% clay, 29.4% silt, 65.4% sand.
C at 36" depth: gravelly loamy sand - 3.6% clay, 25.1% silt, 71.3% sand.