AN ANALYSIS OF THE HYDROLOGIC BUDGET IN GLACIAL SANDS UNDER PINE AND HARDWOOD FORESTS

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

Dean Howard Urie

1965

This is to certify that the

thesis entitled

AN ANALYSIS OF THE HYDROLOGIC BUDGET IN GLACIAL SANDS
UNDER PINE AND HARDWOOD FORESTS

presented by

Dean Howard Urie

has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Forestry

Major professor

Date December 17, 1964

A039

ABSTRACT

AN ANALYSIS OF THE HYDROLOGIC BUDGET
IN GLACIAL SANDS UNDER PINE AND HARDWOOD FORESTS

by Dean Howard Urie

A method of analysis was developed for determining the water yield as net ground-water recharge and the evapotranspiration from areas of homogeneous vegetation. The technique used is an unconfined lysimeter approach which is applicable where there is no surface runoff and the water yield is reflected in changes in storage in water-table aquifers. The tests of the method were made on the Udell Experimental Forest of the Lake States Forest Experiment Station (U.S. Forest Service) located in the northwestern part of Michigan's Southern Peninsula.

The evaluation of changes in ground-water storage required separating the water-table fluctuations into recharge, seepage flow recession and evapotranspiration components. The seepage flow recession rate was predicted from the conformation of the water table in the vicinity of each local study area. Positive and negative deviations from the predicted recession rate due to seepage were attributed to recharge or evaporation losses, respectively. The individual components were then weighted by the specific yield of the aquifer layer in which the fluctuation occurred. The products of this operation were accumulated to obtain the volumes of gross recharge, seepage flow, and evapotranspiration from local ground-water storage.

The studies were conducted in medium textured outwash plain sand soils. Two categories of water-table levels were sampled, 15-18 feet and 0-8 feet. In the shallower areas, a portion of the root zone was saturated during the early part of the growing season. Comparisons

were made of the evaporation and water yield for a two-year period beneath: (1) a 34-year-old jack pine (Pinus banksiana Lamb.) stand, (2) a 20-year-old red pine (P. resinosa Ait.) plantation with an oak (Quercus sp. L.) overstory and (3) mixed hardwoods of pole and sawtimber size. The hardwoods were composed of upland oaks on a well-drained (15-18 foot water table) area and lowland species consisting mainly of red maple (Acer rubrum L.), white birch (Betula papyrifera Marsh.) and American elm (Ulmus americana L.) on a poorly-drained soil.

Net water yields were greatest under the deciduous forests where the average for the two years was 15.3 inches. In the pine plantations, the average water yield for the same period was only 12.4 inches. These differences in net ground-water recharge were caused by the greater evapotranspiration losses in the conifers, 20.7 inches versus 17.1 inches in the hardwoods. The annual patterns of recharge and evapotranspiration showed these differences to occur while the hardwoods were dormant. The water content of the snowpack was least under the densest conifer stands and greatest under hardwoods. These snowpack differences were reflected in the inputs of ground-water recharge following snow melt.

The depth of the water table was inversely related to the ground-water losses due to evaporation. Analysis of diurnal well level fluctuations showed that evaporation losses ceased in poorly-drained soils when ground-water was below 4.5 feet under hardwoods and below 5.5 feet under jack pine. Evaporation losses under red pine were still evident, though slight, when the water table was 8 feet below the mean land surface. These differences in water-table depth effects were partially explained by corresponding differences in the rooting depths of the three species.

AN ANALYSIS OF THE HYDROLOGIC BUDGET IN GLACIAL SANDS UNDER PINE AND HARDWOOD FORESTS

By

Dean Howard Urie

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Forestry

1965

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance and encouragement of the members of the Guidance Committee: Drs. A. E. Erickson, W. J. Hinze, S. O. Serata, and D. P. White. To Sidney Weitzman and John Arend of the Lake States Forest Experiment Station, and especially to W. D. Striffler, formerly of this station and now with the Central States Experiment Station, thanks are due for their patient help over the past few years.

Special thanks are due to all the past and present co-workers at the Cadillac Field Office who have helped with field measurements and participated in seemingly unending discussions of the merits of alternative approaches to the problems of analysis.

VITA

Dean Howard Urie

Candidate for the Degree of
Doctor of Philosophy

Final Examination: December 17, 1964

Guidance Committee: J. L. Arend, A. E. Erickson, W. J. Hinze, S. O. Serata
and D. P. White (Major Professor)

Dissertation: An Analysis of the Hydrologic Budget in Glacial Sands
Under Pine and Hardwood Forests

Outline of Studies:
Major subjects: Forestry, Watershed Management
Minor subjects: Soil Science, Geology

Biographical Items:
Born February 12, 1929, Craftsbury, Vermont

Undergraduate Studies:
University of Vermont, 1947-1949
University of Michigan, 1949-1951
B.S. Forestry, 1951

Graduate Studies:
Oregon State University, 1956-1958
M.S. Agriculture (Soils), 1959

Michigan State University, 1961-1964
Ph.D. Forestry, 1965

Experience:
Forestry Research Technician, Department of Forestry, University of Vermont (Burlington, Vermont), 1954-1956; Graduate Research Assistant, Soils Department, Oregon State University (Corvallis, Oregon), 1956-1958; Research Forester (Hydrologist), Lake States Forest Experiment Station (Cadillac, Michigan), 1958 to date.

Member:
Society of American Foresters
Soil Science Society of America
National Waterwell Association (Technical Division)
Sigma Xi
Xi Sigma Pi
Michigan Association of Conservation Ecologists
Michigan Academy of Science, Arts, and Letters

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

CHAPTER I

INTRODUCTION

One of the more complete, yet concise, descriptions of the hydrologic cycle has been given by McGuinness (1963) who wrote of "that endless circulation of water from the primary reservoir, the ocean, to the atmosphere, the land, and back to the ocean over <u>or</u> <u>beneath</u> the land surface." As ground-water is a part of this cycle, it must be in motion, however slow.

The relative importance of this subsurface routing of water from the land toward the sea is dependent on the infiltration capacity of the soil surface. Where these rates are high, a large portion of rainfall moves into and through the ground-water aquifers. In those areas of the Lake States Region of the United States which are covered with coarse textured glacial drift, the portion of streamflow which is derived from such aquifers is the major part of the total flow. Here the ground-water route forms the connecting link between the land and the surface water features.

The portion of total precipitation which flows by surface or underground routes from a land area is dependent on the amount of water evaporated from that land and from the vegetation which is growing upon it. This evaporation loss may occur when rain or snow is intercepted by the surface parts of the vegetation or it may cycle through the soil to the roots of the plants and be transpired. The nature of the vegetation, its surface area, its depth of rooting and its physiological characteristics influence the amount of this evapotranspiration recycling within the greater cycle. In forest land management, considerable study has been given to the effects of various vegetative conditions on the division of total precipitation into the evaporation and runoff categories. Traditionally these studies have relied on stream-flow measurements to obtain the runoff quantity. In such high infiltration areas as are found in much of the northern part of Michigan's Southern Peninsula, the direct relationship between small areas of surface and the flow of the widely spaced streams is so masked by the mosaic of vegetative conditions that the influence of a single cover type is obscure. In order to reduce the size of the surface area to be studied to that represented by a definable cover type, it is necessary to evaluate the water yield at a more immediate point. The ground-water flow which represents this water yield occurs at that immediate point and, despite the many difficulties involved in its determination, provides the only practical in situ method by which the water balance for such an area can be resolved.

The deep mantle of coarse textured glacial drift which covers the Southern Peninsula of Michigan represents a giant mound of saturated unconsolidated sediments. Subsurface drainage from this mound seeps into the streams along most of their course. Many of the large and small lakes which dot the landscape are but surface emergences of the ground-water body. Thus, the ground-water resource is the source of streams, the continuation of lakes; the water supply of the region in both its used and potentially useful forms.

Precipitation in the northern part of Michigan's Southern Peninsula ranges from 28 to 32 inches per year. This rainfall maintains the saturated layer at its normal level about which fluctuations occur with seasonal and longer term variations in rainfall. Surface and subsurface flow constantly drain water from the saturated zone toward the local base level of the Great Lakes. That portion of the total precipitation which represents true ground-water recharge must replace this drain to maintain the normal level. When vegetative demands for water alter the evaporation vector of the hydrologic equation, the remaining recharge portion must also be altered.

Such variables of vegetative cover as density, dormant season interception, depth of rooting, periodicity of moisture utilization and physiological adaptation to poorly drained soils may have measureable effects on the amount of evaporation from the land surface. These same factors are likely to be altered by the land management practices of forestry. Planting conifers with deep root systems, dense winter crowns and long transpiration periods in place of grasses or deciduous forests, is likely to affect the water balance.

Information from studies in the Lake States and elsewhere in the northeastern part of the United States has documented the smaller amounts of snow accumulation in dense conifer stands (Weitzman and Bay, 1958; Dils and Arend, 1956; Striffler, 1959; Hart, 1963). Soil moisture levels have also been shown to remain at low levels under conifers for longer periods than under hardwood forests (Urie, 1959). Water in the snowpack is a major part of the total annual ground-water recharge (McGuinness, 1941). When soil moisture deficits exist it is impossible for precipitation to recharge the ground-water supply. These two facts point to an expected alteration of the ground-water balance following the establishment of conifer plantations. This is indirect evidence. Actual measurements of volume of ground-water recharge and the attendant effects on the hydrologic balance are needed.

This study has sought to evaluate the hydrologic budget under coniferous and deciduous forest cover in a relatively uniform sand aquifer situation where surface runoff is practically nonexistent. Under this situation the ground-water balance is the hydrologic balance. These forest types and watershed conditions are prevalent throughout central and northern Michigan and Wisconsin. Accordingly, the results of this study should have regional application.

CHAPTER II

OBJECTIVES OF THE STUDY

The present study represents the first comprehensive investigation of the effects of forest cover and reforestation on hydrology under northern Lower Michigan conditions. This study is a part of the research program in forest watershed management problems which is being conducted by the Lake States Forest Experiment Station.

The sample watershed area selected for intensive study is located in southern Manistee County about ten miles east of the Lake Michigan shoreline in the northwestern part of Michigan's Southern Peninsula (Figure 1). This area, the Udell Experimental Forest, is representative of much of the publicly owned forest lands in Michigan and adjoining states. It is comprised of 3800 acres of federal lands on the Huron-Manistee National Forest which were set aside in 1960 for research in forest-ground-water relations. The overall project is designed to compare the water economy of the various forest conditions as they now exist and to determine what changes are produced by the forest management practices currently in use in the region.

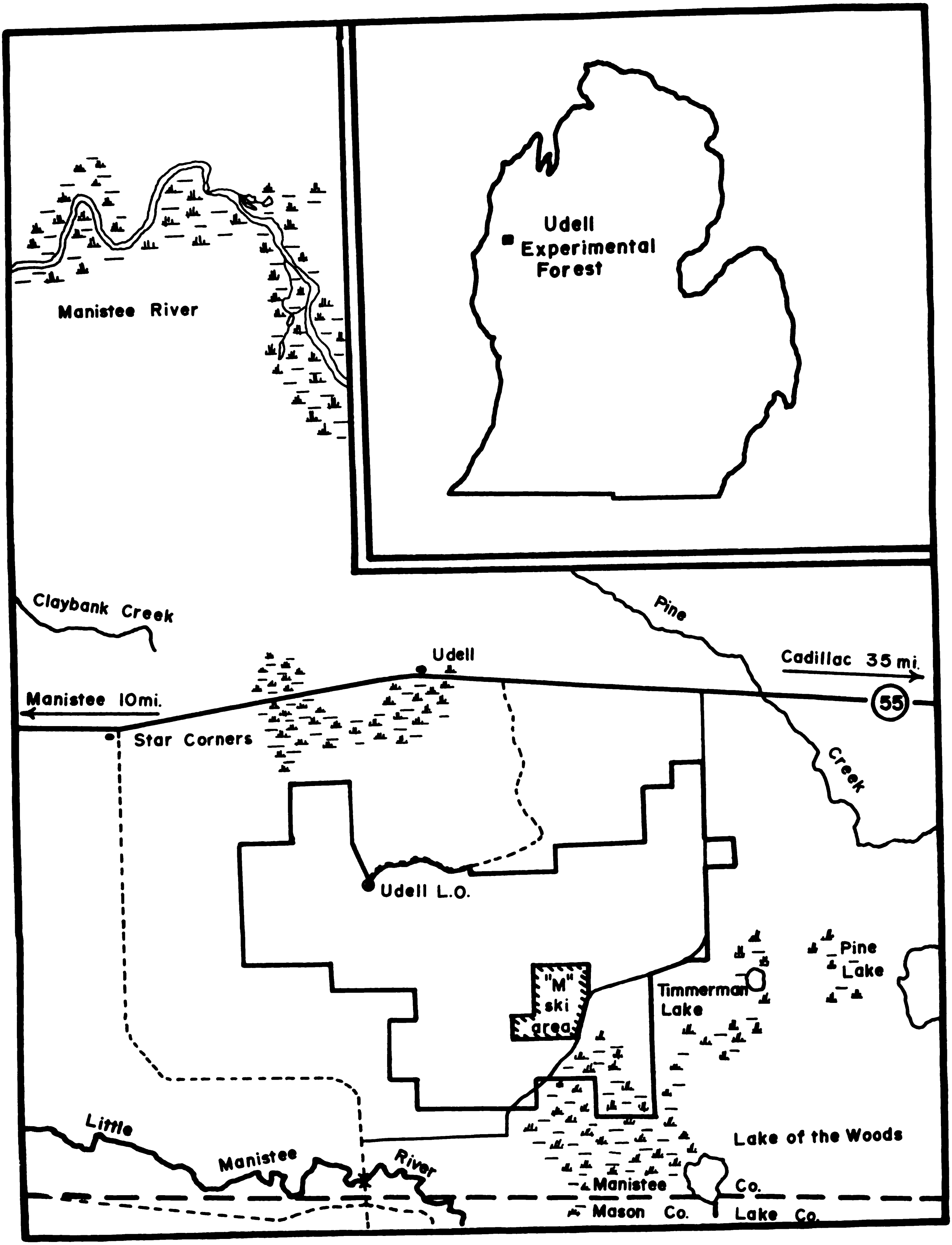
The specific objectives of the study reported here were:

1. To develop methods for deriving the hydrologic budget for local sectors within a broad ground-water basin, using well data.

2. To use these methods for deriving the ground-water recharge, seepage flow losses, and evapotranspiration losses from the history of water-table fluctuations beneath three common forest cover types.

3. To determine the effect of ground-water depth on the hydrologic budget under these three cover types.

Figure 1. The location of the Udell Experimental Forest in Michigan's Southern Peninsula between the Manistee and Little Manistee Rivers.


Udell
Experimental
Forest
Manistee River
Claybank Creek
Pine
Creek
Udell
Cadillac 35 mi.
55
Manistee 10mi.
Star Corners
Udell L.O.
"M"
ski
area
Timmerman
Lake
Pine
Lake
Lake of the Woods
Little
Manistee
River
Manistee
Co.
Mason
Co.
Lake
Co.

CHAPTER III

REVIEW OF LITERATURE

The estimation of the evaporation portion of the hydrologic budget of ground-water basin has been attempted in two general ways. Where a well defined basin is drained by a stream, the water yield of the basin is computed from the discharge of this stream. Evapotranspiration is then computed from the difference between total precipitation and runoff over a period which begins and ends with equal water storage.

Where a surface stream is not available to provide a measure of the water leaving the basin, an alternative approach is necessary in which the changes in ground-water storage are determined directly from well measurements.

Estimation of Ground-Water Budgets Using Surface Runoff Measurements

Ground-water levels measured in wells over the entire basin in Pomperaug, Connecticut were related to the level of runoff during periods when the stream-flow was assumed to be coming from seepage flow (Meinzer and Stearns, 1929). This relationship changed during the growing season when evaporation losses from vegetation reduced the portion of the seepage flow which left the basin. The authors found only a minimal measure of ground-water losses to evapotranspiration when they subtracted the ground-water runoff in the summer from that of the winter months, using periods when water-table levels were similar. Rasmussen and Andreasen (1959) utilized the same type of instrumentation in

Maryland. They solved the equation:

$$P = R + ET + \Delta SW + \Delta SM + \Delta GW$$

where P is precipitation, R is runoff, ET is evapotranspiration, ΔSW is the change in surface water storage, ΔSM is the change in soil moisture and ΔGW is the change in ground-water storage. Weekly solutions of this equation for ET were plotted against calender weeks. A smoothed curve through these plots was used to solve for a convergent storage coefficient for the aquifer materials. These convergent solutions for the gravity yield of the sediments permitted a solution which was in agreement with the theoretical curve of seasonal ET.

Olmsted and Hely (1962) applied an average gravity yield determined from the volume of aquifer dewatered by measured amounts of dormant season stream-flow to obtain measures of ground-water discharge from summer well recession. The evapotranspiration loss in a western Pennsylvania drainage basin was found to be about one-fourth of the total ground-water discharge.

In Illinois, Schicht and Walton (1961) separated the gross ET derived from P-R determinations into soil and ground-water losses. They constructed rating curves relating ground-water runoff to mean ground-water stage for both dormant and growing seasons. The difference between the two curves was attributed to ET from ground-water supplies. They then computed the expected loss for the annual pattern of ground-water stages to obtain a ground-water ET value.

Estimation of Ground-Water Budgets Where Surface Runoff Data is Not Applicable

White (1932) used the diurnal fluctuations of the water table to obtain a measure of ET in a closed basin in Utah. By computing a recharge rate for the 24-hour period and adding on the net daily reduction in storage, he computed daily and seasonal ET rates for various types of vegetative cover.

Ferris (1959) has suggested a similar approach to that of White for the evaluation of evaporation effects on Michigan ground-water levels. Where the rate of water-table change without ET is predictable, he showed that a measure of the evaporation loss can be derived from the accumulated deviation of the actual water level from this predicted curve.

Holstener-Jorgensen (1961) compared the seasonal drawdown of ground-water levels in Danish clay soils. In an area where surface runoff was negligible during the growing season, the amount of precipitation required to restore water-table levels to their spring stage was considered equal to the total ET for the period between equal high water-table stages. By this method, the author was able to demonstrate differences in moisture use between forest types and to show seasonal patterns of moisture use.

The direct evaluation of evapotranspiration drawdown from the accelerated rate of water-table drawdown during daylight hours assumes that the area of uniform water-table depth and uniform vegetation with even moisture use is sufficiently large so that the rate of drawdown is similar over the area of the aquifer which contributes to ground-water flow beneath the study well.

Troxell (1936) has shown a graphical method for solving the problem of changing ground-water inflow due to increased head differences during periods of rapid ET drawdown under shallow water-table vegetation. This requires an estimation of the changing head due to the inflow-outflow balance in the absence of ET losses. The net ET loss is then calculated from the accumulated difference between the predicted head change and the total head change occurring when evapotranspiration is included. This is, in effect, a separation of the subsurface flow balance which occurs due to the actual history of head change and the net loss in head due to ET. In the situation where no inflow increase occurs, the two vectors of total head change during a measurement period are multiplied by the drainable porosity or specific yield to obtain a volumetric measure of the two categories of ground-water loss.

In essence the two methods differ in that, where stream-flow data is used an entire drainage basin is evaluated as a unit. Where stream-flow data is lacking, or impossible to relate to a sufficiently localized area, the changes in ground-water storage which occur in a localized segment of the aquifer are analyzed. As was indicated earlier, the geologic condition in the deep drift areas of Michigan necessitate the use of the latter method.

CHAPTER IV

DESCRIPTION OF GENERAL STUDY AREA

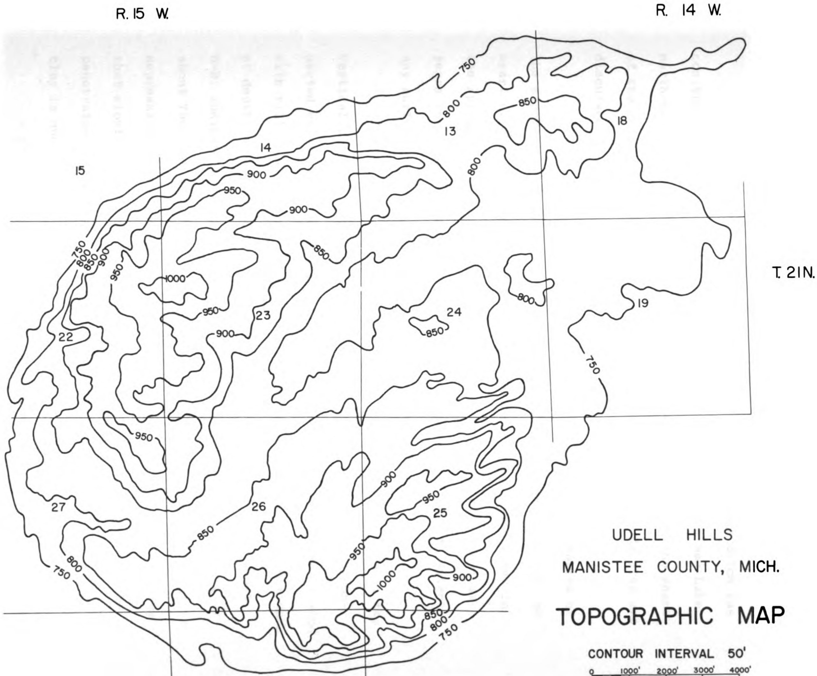
The Udell Experimental Forest includes 3800 acres of National Forest land in the southeastern part of Manistee County, Michigan. The Forest includes parts of two townships, Township 21 North, Range 14 West, and Township 21 North, Range 15 West (Figure 2). The experimental area includes large portions of an isolated moraine. This upland feature is approximately two miles in diameter and is characterized by a broken ring of sandy ridges along the northwest and western portion as well as along the southeastern edge.

Elevations range from 700 feet above sea level at the lowest points on the western outwash plains to 1030 feet at the highest ridge-tops. Most of the hillsides have gentle slopes between five and 15 percent. A few short slopes exceed 25 percent.

The upland portion is situated on a broad outwash plain which slopes gently westward, except as dissected by the major west flowing rivers. The Manistee River, with a water surface at about 600 feet elevation, flows about three miles north of the Udell Forest. The Little Manistee River borders the south edge of the morainal feature at a distance of only one-half mile. Pine Creek, tributary to the Manistee River, flows within one-fourth mile of the northeast corner of the research area. The only other perennial stream, Claybank Creek, arises from an extensive swamp area along the north border of the Udell Hills.

A concentration of surface flow in the extensive swamp area in the southeastern portion of the experimental area produces a discharge

Figure 2. Topographic Map, Udell Hills, Manistee County, Michigan.



UDELL HILLS

MANISTEE COUNTY, MICH.

TOPOGRAPHIC MAP

CONTOUR INTERVAL 50'

0 1000' 2000' 3000' 4000'

FIGURE 2

of two-three cubic feet per second during periods of high ground-water levels. This runoff flows westward for three-fourths of a mile along the ditch associated with a raised woods road.

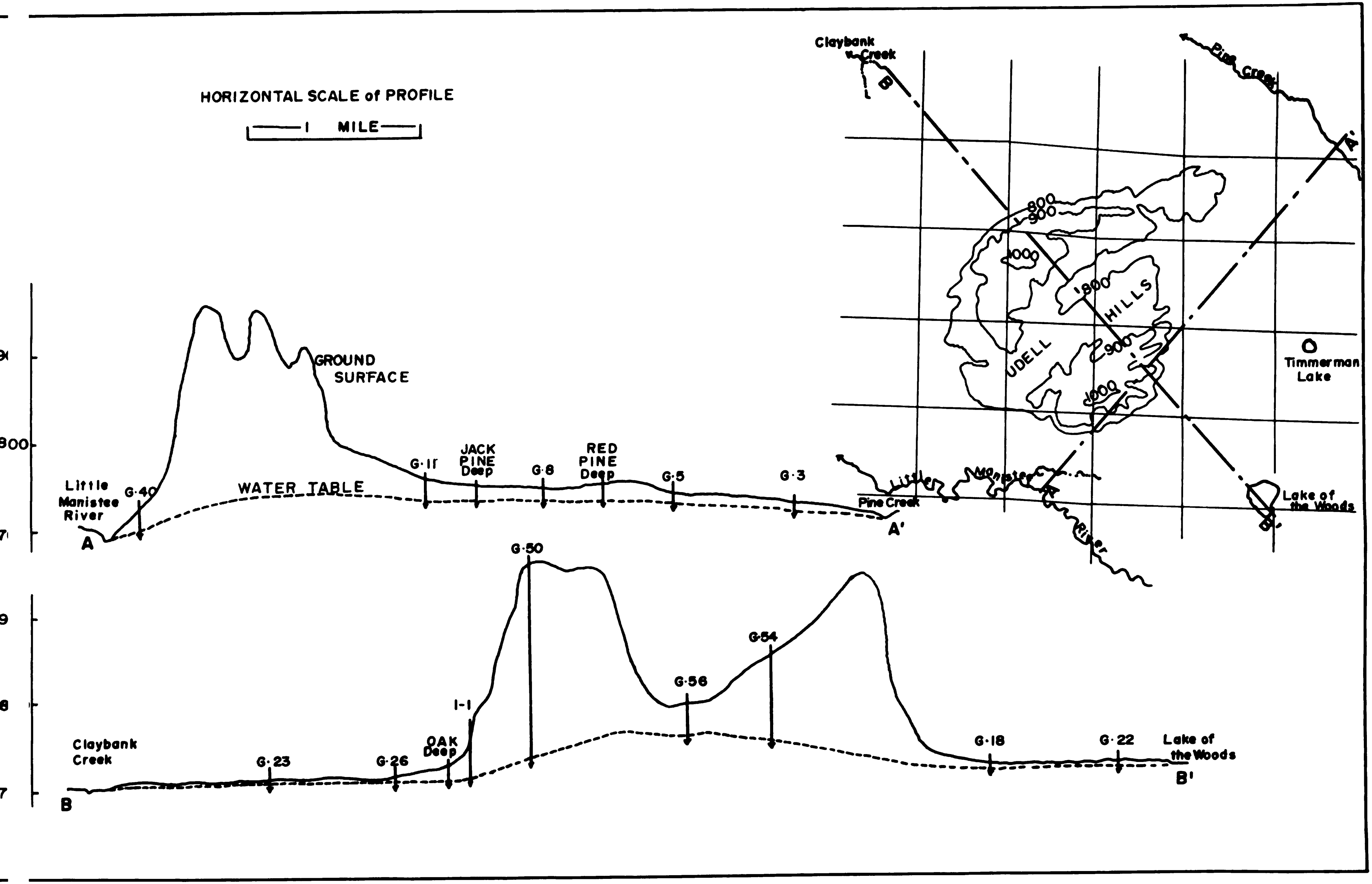
During early periods of agricultural use, a drainage ditch was constructed to conduct high water from the vicinity of Timmerman Lake north-northeast to Pine Creek. The effects of this ditch on the shape of the ground-water surface along the east border of the study area are discussed below.

All of these surface flows are at, or along, the boundaries of the experimental area. The only surface waters which occur within the heart of the study area are small bogs which contain surface water in the spring. Observations over the entire study area during the four years in which instruments have been installed, have failed to detect any surface runoff from the highly permeable soils.

The depth of the sand mantle in the ridge areas is shown in two vertical profiles (Figure 3). The depths shown by well logs are connected by straight lines. The moraine is shown to be predominantly sand with till clay and sandy clay underlying the western and northern ridges at depths of 200 feet or more. Four wells, located west of transect B-B; indicate a higher clay lens in the center of the western ridge at about 790 feet above sea level. The presence of numerous small bogs in depressions in the center bowl between the surrounding ridges suggests that slowly permeable layers are present near the surface. Well G-56 penetrates such a layer at a depth of ten feet. This layer of sandy clay is underlain by permeable sands from 17 feet downward.

A partially penetrating well at the Manistee Ski Area, located near the base of the eastern face of the moraine, showed clay layers

Figure 3. Profile of water-table elevations in relation to land surface and surface water features, Udell Experimental Forest and vicinity.



HORIZONTAL SCALE of PROFILE
1 MILE
GROUND SURFACE
WATER TABLE
Little Manistee River
A
A'
G·40
G·11
JACK PINE Deep
G·8
RED PINE Deep
G·5
G·3
800
Claybank Creek
B
B'
G·23
G·26
OAK Deep
I-1
G·50
G·56
G·54
G·18
G·22
Lake of the Woods
Pine Creek
Little Manistee River
Timmerman Lake
UDELL HILLS
800
900
1000

which extend between elevations of 710 feet to 620 feet. These clays are underlain by permeable sand aquifers. A partially penetrating well at the east one-fourth corner of Section 18, T21N, R15W, shows permeable sands to a depth of 52 feet. Below this depth, alternating thin zones of reddish till materials interrupted the sand to a depth of 120 feet. Indirect evidence from seismic and resistivity surveys [1/] suggests that, under the outwash plain on the east side of the uplands, the saturated sand aquifer is at least 100 feet thick with no continuous slowly permeable layers above this depth.

Soils and Vegetation

Most of the soils of the Udell Experimental Forest, on both morainal and outwash areas, are formed from medium sand parent materials. The major portion of these soils is within the limits of the Grayling sand series. The soils range from regosols, with minimal profile development, to incipient podzols having a light brown colored B with no visible structure. In interior valleys, a higher content of silt in the surface horizon results in visible improvement of the site quality even though the textural change is insufficient to alter the soil type classification.

Imperfectly drained soils cover approximately ten percent of the land area. These soils, in which the water table is within the developed solum during a part of the year, are a complex of Saugatuck and AuGres

---

[1/] Hinze, W. J., et. al. 1964. A geophysical investigation of hydrogeologic characteristics of the Udell Hills area, Manistee County, Michigan. Unpublished file report. Dept. of Geology, Michigan State University, East Lansing, Michigan.

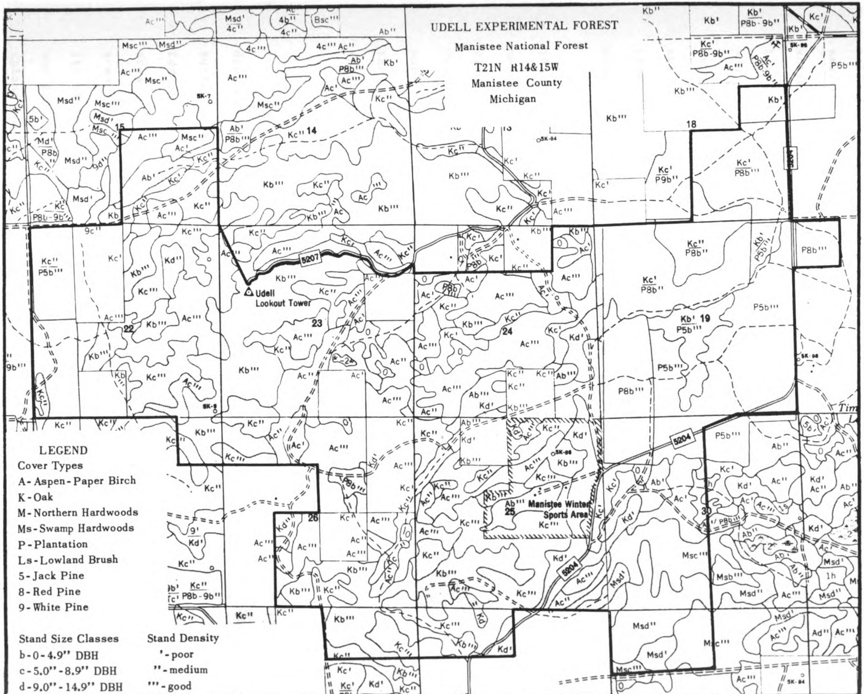
loamy sands. The Saugatuck profile is characterized by a well-developed ortstein layer in the lower B horizon. The AuGres soils, which are irregularly intermixed, have strong cementation in the B horizon but have no continuous cemented layer. These imperfectly drained soils are located along boundary strips near swamp areas of Rifle peat of varying thickness over mineral soil. Soils of the Maumee series occur where the organic matter layers are only 6 to 12 inches deep over gray mottled sands.

The water table in these poorly-drained soils varies from the surface to 24 inches below the surface during the growing season. Following the cessation of moisture use by vegetation, the water table returns quickly to near the surface where it remains at a relatively high level until spring.

Distribution of Vegetation Types

Native vegetation follows the pattern of the soil differences (Figure 4). On the Grayling sands of the uplands and well-drained outwash plains, the northern pin oak type (Society of American Foresters, 1954) is the major forest cover. In this type northern pin oak (*Quercus ellipsoidallis* E. J. Hill), white oak (*Q. alba* L.), northern red oak (*Q. borealis* Michx. f.), and black oak (*Q. velutina* Lam.) are the principal species. Bigtooth aspen (*Populus grandidentata* Michx.) and quaking aspen (*P. tremuloides* Michx.), which form a small component of these stands on the exposed ridges and flat slopes, become the dominant species in the sheltered valleys and on the lower slopes. Red maple (*Acer rubrum* L.) and paper birch (*Betula papyrifera* Marsh.) are prevalent where the water table is high enough for ground-water to suppliment the

Figure 4. Forest cover types, Udell Experimental Forest and vicinity.


UDELL EXPERIMENTAL FOREST
Manistee National Forest
T21N R14&15W
Manistee County
Michigan
Udell Lookout Tower
Manistee Winter Sports Area
LEGEND
Cover Types
A-Aspen-Paper Birch
K-Oak
M-Northern Hardwoods
Ms-Swamp Hardwoods
P-Plantation
Ls-Lowland Brush
5-Jack Pine
8-Red Pine
9-White Pine
Stand Size Classes
b-0-4.9" DBH
c-5.0"-8.9" DBH
d-9.0"-14.9" DBH
Stand Density
'-poor
"-medium
'''-good

soil moisture supply. In the forested swamps American elm (*Ulmus americana* L.), black ash (*Fraxinus nigra* Marsh.), red maple, northern white cedar (*Thuja occidentalis* L.) and eastern hemlock (*Tsuga canadensis* L.) are the major species. Eastern white pine (*Pinus strobus* L.) and red pine (*P. resinosa* Ait.) were formerly important constituents as is evidenced by the frequency of stumps on uncleared lands. These species now occur only as occasional stems or in isolated small groves. Jack pine (*P. banksiana* Lamb.) in natural stands is locally prevalent, especially on the outwash plains.

Pine plantations of jack, red and white pine, established since 1934, cover approximately 1100 acres or nearly one-third of the experimental area. The oldest plantations were installed on cleared lands. Plantings since 1940 have had varying degrees of hardwood overstory. Timber stand improvement operations in 1955 and 1956 resulted in a partial release of the underplanted pine. Approximately 200 acres of the red pine plantation still has a considerable degree of hardwood overstory.

Drainage Basins and Water-Table Slopes

The Udell Experimental Forest is situated on the ground-water divide between the Manistee and Little Manistee Rivers. Drainage to the surface flow outlets of the Pine Creek and Claybank Creek produces a conformation of the water-table surface which divides the north side of the area into two sub-basins. Water-table contours on the south side of the area are less affected by surface drainage than by the relative permeability of the saturated layer (Figure 5). Profiles of surface elevations and ground-water levels show a generally high water-table level in the upland portion with evidence of perched water tables in the interior basin.

Figure 5. Topography of the water table and approximate ground-water basin boundaries, Udell Experimental Forest and vicinity, July 26, 1963.

CHAPTER V

DESCRIPTION OF LOCAL STUDY AREAS

Six study areas were selected on outwash plain sites for intensive measurements of the ground-water balance under three representative forest cover conditions (Figure 6). The study areas selected were typical of many pine plantations, pine plantations with a hardwood overstory and mixed hardwood forests characteristic of the site conditions represented. Under each forest type, an area was selected where groundwater was within the rooting zone during at least a portion of the growing season. As closely as possible, the same forest cover conditions were replicated in deeper water-table areas where the saturated zone was well below depths at which its water would be available for transpiration.

Stand conditions on the six study areas are summarized in Table 1. A 100-percent tally of all trees over 2.5 inches in diameter was obtained on 3 one-acre plots in each location. Crown density measurements were made at 25 systematically selected points in each area using a spherical densiometer (Lemmon, 1956).

The jack pine plantations, which were established in 1934 at a spacing of six by six feet, have most trees and the densest basal area stocking per acre. Crown closure is uniform in comparison to that of the red pine plantations with an oak overstory, as is shown by the lower variance of the individual density observations. This uniformity is even greater by comparison during the dormant season when the overstory oak provide effectively no crown cover.

Figure 6. Plot and instrument locations, hydrologic budget study, Udell Experimental Forest.

PLOT AND INSTRUMENT LOCATIONS

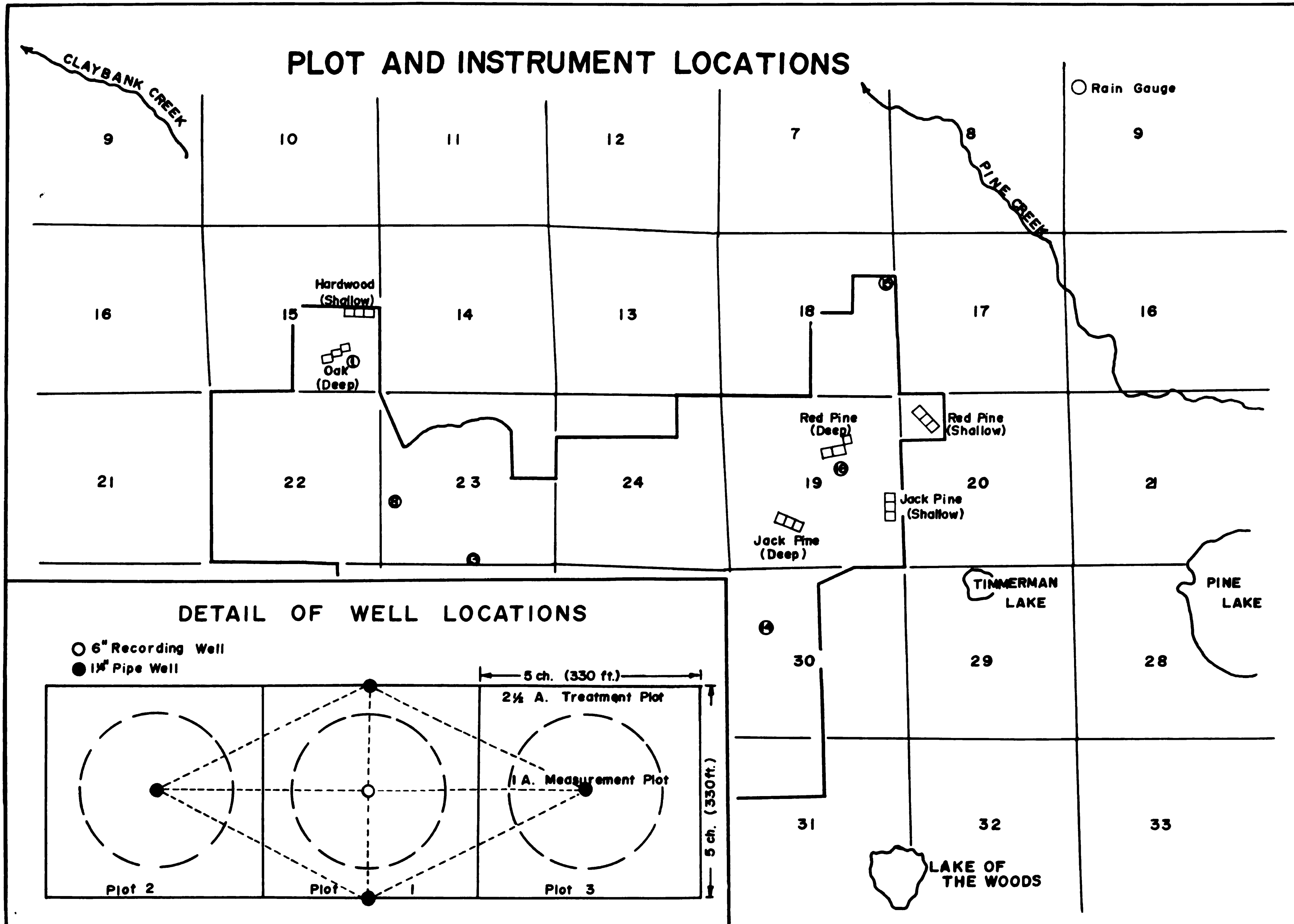


TABLE 1

STAND CONDITIONS ON SELECTED STUDY AREAS

Study Area	Trees Per Acre [2/]	Basal Area (Ft^2/A)	Mean Diameter (in)	Crown Density Summer (%)	Crown Density Winter (%)	Variance of Density (%) [1/]
Jack Pine(S) [3/]	766 (729) [5/]	94.7 (88.5)	4.59 (4.60)	81.8	±80	8.1
Jack Pine(D) [4/]	809 (688)	103.4 (85.3)	4.56 (4.66)	84.6	±83	5.4
Red Pine (S)	708 (580)	86.5 (59.7)	4.49 (4.25)	80.6	±70	14.2
Red Pine (D)	578 (458)	74.8 (40.5)	4.39 (3.98)	70.0	±60	18.4
No. Hdwds(S)	322	72.7	5.88	83.8	±10	12.6
Oak (D)	461	78.6	5.11	81.3	±10	6.8

1/ Variance of 25 systematically located crown density measurements.

2/ Trees 2.5 inches at DBH and larger.

3/ Shallow water-table area.

4/ Deep water-table area.

5/ Figures in parentheses refer to pine only.

The lowland hardwood area has the fewest number of trees, the largest average diameter and a high variability in crown density during the growing season.

CHAPTER VI

STUDY METHODS

Delineation of Basin Boundaries

The initial investigations of the ground-water situation in the outwash plain portions of the Udell Experimental Forest were directed toward defining the boundaries of the ground-water basins. Under a separate study, 56 wells were installed at one-half mile intervals along a rectangular grid system. A leveling survey related datum elevations at each well site to established U.S. Geological Survey bench marks. From water-table measurements taken over this grid, it has been possible to locate the perimeter of ground-water basins and to define the approximate surface topography of the saturated layer throughout the year and over the period of the present study (Figure 5).

Instrumentation of Local Study Areas

Three study plots were located in each of the three forest cover type water-table depth conditions. Each five-chain (330 foot) square plot was located in an area of uniform topography and characteristic forest stand conditions. In most instances, it was possible to also place these plots adjacent to one another (Figure 6). The jack pine areas were chosen near the water-table divide between the Manistee and the Little Manistee Rivers. The red pine areas with the oak overstory were nearer to the Pine Creek seepage line. Both the hardwood study areas were located on the northwest lower slope of the uplands section.

The six study areas were assigned abbreviated cover-depth labels which will be utilized throughout this report. These labels were: Jack Pine (deep) and (shallow), Red Pine (deep) and (shallow), Oak (deep) and Hardwood (shallow). The general term "Hardwood" was used in this instance because of the mixture of such species as red maple, paper birch, American elm, bigtooth aspen, and northern red oak on the imperfectly drained soils of this local study area.

A one-acre circular plot was delineated around each of the three plot centers. This central plot was used for measurements of stand characteristics. A partially penetrating well was installed at the center of each plot. The key well for each local study area was located in the central plot. This was a six-inch diameter well equipped with a water level recorder (Figure 7). All other wells were constructed with 1 1/4 inch galvanized steel pipe attached to a sand drive well point.

Datum elevations for each well, of both types, were established and checked against the datum of the one-half mile grid well network. Water levels in all non-recording wells on the local study areas were measured at weekly intervals. The key recording wells were also measured manually at this same frequency. The water level shown on the recorder chart was corrected to the beginning and ending levels determined by direct tape measurements for each weekly period. All water-table depths were recorded to the nearest 0.01 foot.

A rain gage network has been in operation on the Udell Experimental Forest since November, 1959. The gages which were used for the present study are shown in Figure 6. Local precipitation amounts were measured at Station 1 for the Oak (deep) and Hardwood (shallow) areas, from Stations 14 and 16 for the two Jack Pine areas, and from Stations 15

Figure 7. Six-inch diameter well equipped with water level recorder, Oak (deep) study area, Udell Experimental Forest.

and 16 for the two Red Pine areas. A total of 12 raingauges were operated throughout the two-year study period on the entire experimental forest.

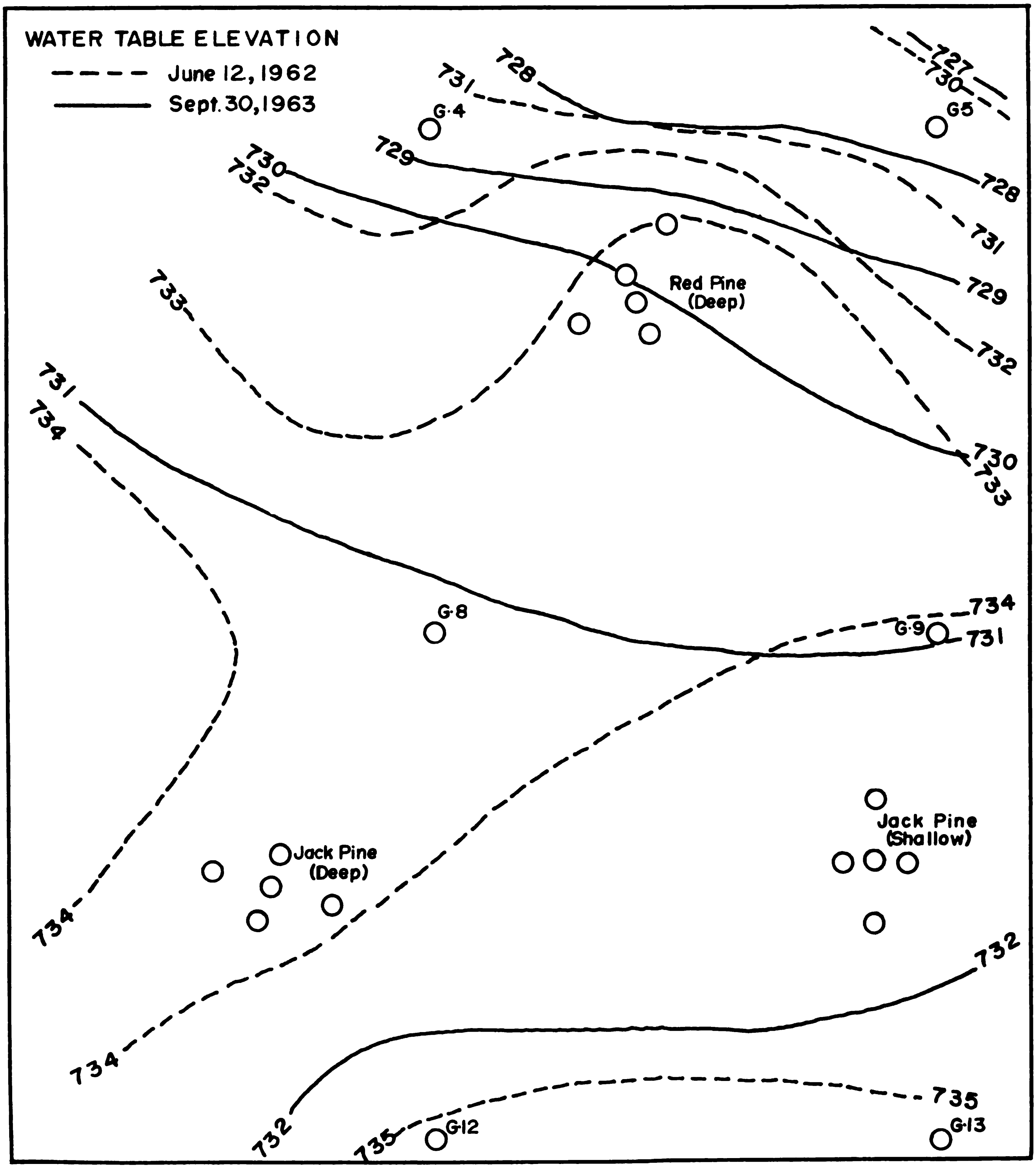
Snow measurements were taken with a Mt. Rose snow sampling tube along five-point snow courses under timber stand and slope conditions representative of each raingauge station. Supplementary snow sampling was carried out on the local study areas.

Data from the two-year period beginning October 1, 1961, and ending September 30, 1963, were used in the present study.

Derivation of Predicted Water-Table Recession Rates

The changes in contour spacing of the ground-water surface are shown in Figure 8 for the maximum and minimum stages occurring during the two-year study period. The June 12, 1962, conditions represent the water-table surface at a time when the majority of the grid wells were at their highest levels. At this time of year the gradient of the water table steepens rapidly with increasing distance from the water-table divide. The lowest stages were reached at the end of the two-year study period. The maximum gradient of 19 feet per mile occurs near the Pine Creek seepage line. Near the crest of the basin the gradient approaches zero. The shape of the water-table profile remains relatively unchanged, the low stage profile representing a uniform lowering of the ground-water level of the entire slope. Minor changes in the gradient in the immediate vicinity of individual wells were found to be related to the rate of ground-water subsidence during non-recharge periods. Even though these gradient changes were small, the differences between the approximate tangent to the water-table surface up the flow line from a well and the tangent below the well was related to the average daily recession rate.

Figure 8. One-foot water-table level contours in the vicinity of three local study areas, June 12, 1962, and September 30, 1963.



WATER TABLE ELEVATION
June 12, 1962
Sept. 30, 1963
727
728
730
731
728
G·4
G5
729
730
732
728
731
Red Pine
(Deep)
733
729
732
731
734
730
733
G·8
734
G·9
731
Jack Pine
(Shallow)
Jack Pine
(Deep)
734
732
734
735
732
735
G·12
G·13

The change in storage in the vertical sub-section of the aquifer represented by a well is equal to the difference between the rate of ground-water inflow and outflow during periods of negligible recharge or evaporation loss. The flow through a vertical section of the aquifer may be expressed:

$$Q = PAI \qquad \text{(VI-1)}$$

Where P is the average or effective permeability, A is the cross-sectional area of a unit width, and I is the water-table slope.

At a given point along a flow line, the change in storage is equal to:

$$\Delta S = PuAuIu\text{-}PdAdId \qquad \text{(VI-2)}$$

Where the subscripts u and d represent conditions up-slope and down-slope from the well.

Over an arbitrarily short interval along a flow line the thickness of the aquifer and its permeability may be assumed to be constant as long as the thickness is not significantly affected by the raising and lowering of the water table. Equation (VI-2) then becomes:

$$\Delta S = PA\ (Iu\text{-}Id) \qquad \text{(VI-3)}$$

The change in storage is directly proportional to the change in piezometric head as long as the specific yield of the aquifer materials which are drained remains constant.

$$\Delta H = \frac{PA\ (Iu\text{-}Id)}{Sy} \qquad \text{(VI-4)}$$

and

$$\Delta H = C\ (Iu\text{-}Id) \qquad \text{(VI-5)}$$

From equation (VI-5) the relationship between the rate of well recession due to gravity flow should be linearly related to the difference between the water-table slopes above and below the well. This relationship was studied for the six recording wells used for determining ground-water budgets. Only periods of negligible recharge and low evapotranspiration drain were considered.

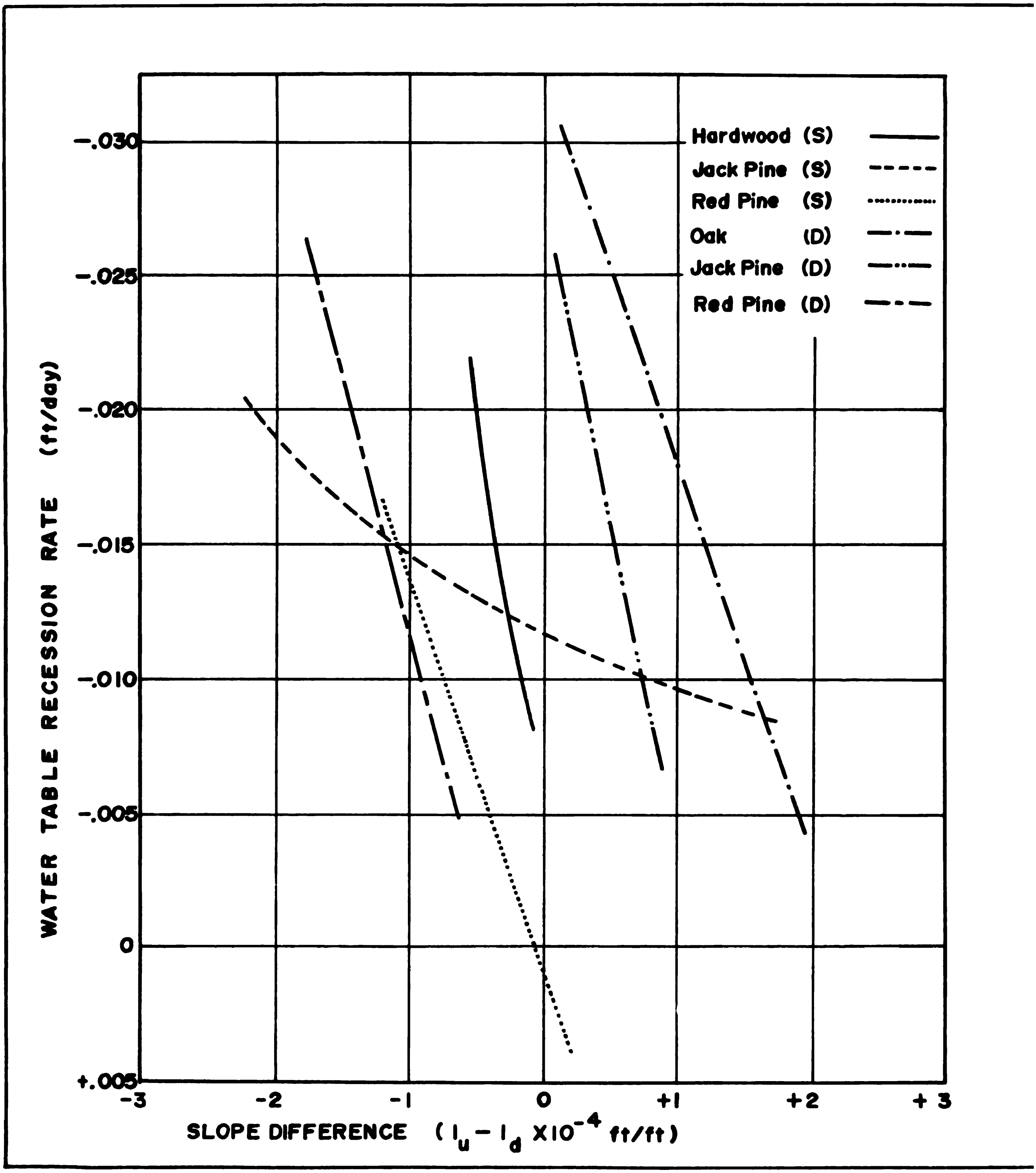
Local ground-water level contours were plotted from weekly and monthly well measurements in the vicinity of each of the six study areas. From these contours, the slope above and below the central recording well was computed from the respective distances to the nearest contour line along the flow line passing through the well. The average daily recession in the well level was then plotted against this computed difference in water-table gradient (Figure 9).

Four of the areas showed slope relationships in which the gradient steepened along the flow line. In the Jack Pine (deep) area the location of the plots near the water-table divide resulted in very small slopes which could only be roughly defined by the contouring method. There appeared to be a consistant concavity to the slope in this area which suggests variability in the transmissibility. The rate of water-table decline was linearly related to the difference in slopes, however.

In the Oak (deep) plots, the up-slope gradient was also consistantly larger than the slope below the well. The up-slope area, which is known to be underlain with till clays at the foot of the adjoining moraine, probably has a lower permeability than the outwash sediments below the well.

The rates of water-table recession in the Jack Pine (shallow) and Hardwood (shallow) wells could be related linearly to the slope

Figure 9. Daily water-table recession rates due to seepage flow in relation to the difference in water-table slope above and below the study well.



Hardwood (S)
Jack Pine (S)
Red Pine (S)
Oak (D)
Jack Pine (D)
Red Pine (D)
WATER TABLE RECESSION RATE (ft/day)
-.030
-.025
-.020
-.015
-.010
-.005
0
+.005
-3
-2
-1
0
+1
+2
+3
SLOPE DIFFERENCE (I_u - I_d X10^-4 ft/ft)

difference only after adjusting for the specific yield of the layer in which the recession occurred. In the other four areas, the variations in specific yield were too small to affect the relationship of volume of seepage to the change in well level.

Separation of Components of Water-Table Fluctuations

The principal analytic technique utilized for the evaluation of the ground-water budgets was the separation of the various components of fluctuation in the water-table movements. The method used by White (1932) for fluctuations within a closed basin was modified to consider the recession rate due to seepage outflow (Figure 9). In general, the equation for the change in water-table elevation for a given time period can be written:

$$\Delta H = \Delta HRg - \Delta HRog - \Delta HETg \qquad \text{(VII-1)}$$

where ΔHRg = change in head due to recharge from precipitation
$\Delta HRog$ = change in head due to net seepage flow
$\Delta HETg$ = change in head due to evapotranspiration drain

The rate of water-table change due to seepage flow was determined from the relationship between recession rates during non-recharge periods and the differential ground-water gradients along the flow line in which the observation well is located. These recession rates were found to be relatively constant in the deeper water-table areas. In the Hardwood (shallow) and the Jack Pine (shallow) areas, the recession rates were influenced by the changes in the specific yield of the aquifer when the water-table fluctuations occurred within the developed solum. Seepage flow recession rates in these conditions were estimated from the rate of water-table recession during the late night hours (12 midnight to

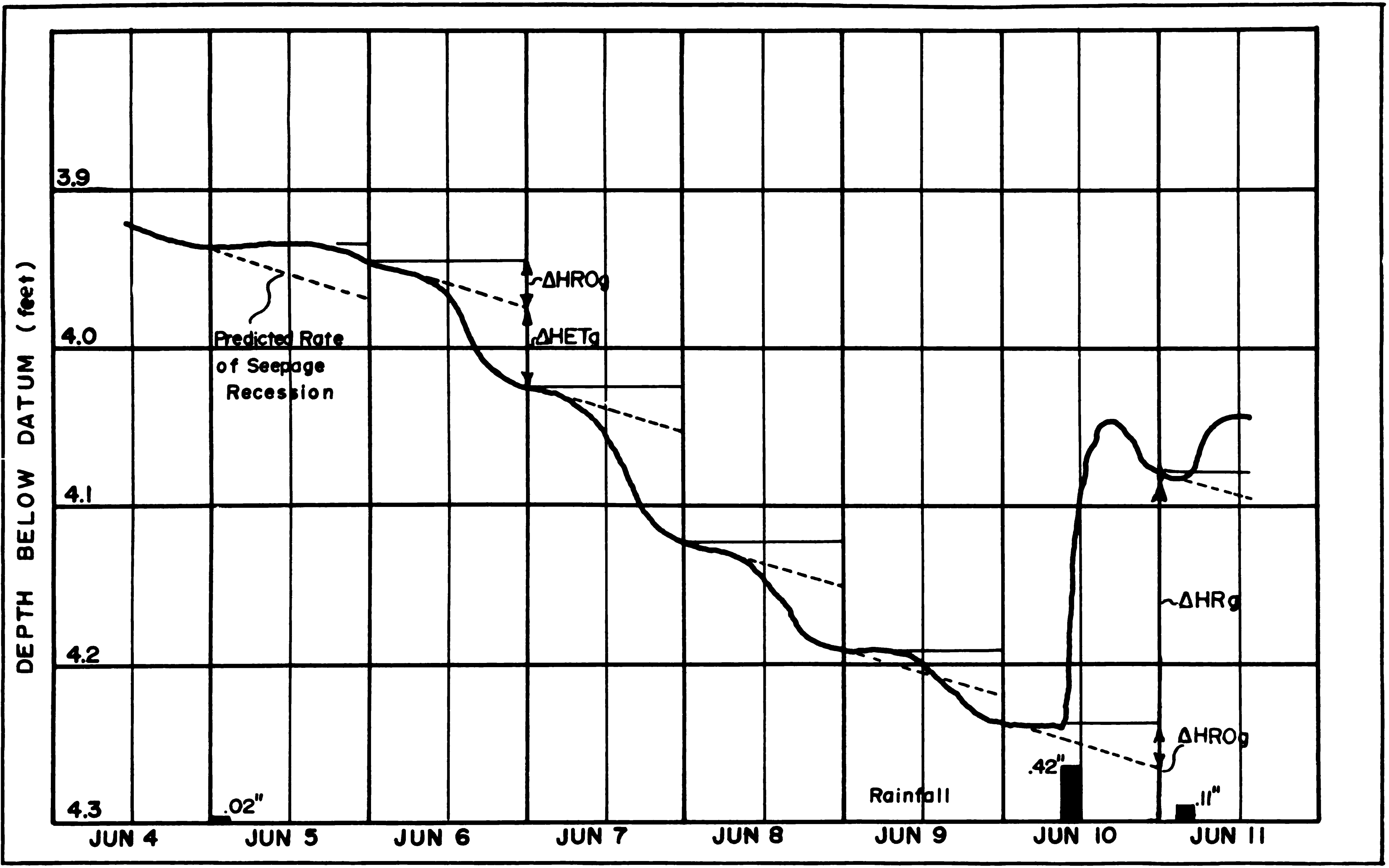
6 A.M.), (Figure 10).

The total water-table change during a 24-hour period was determined from the recording well data. The rate of seepage flow recession was subtracted from this total. When the difference between these amounts was positive, a net daily head change due to recharge was indicated. When the difference was negative, that is, when the total daily recession exceeded the expected seepage loss, an evapotranspiration loss was posted. Conversion of these three values; ΔH due to seepage flow, ΔH due to recharge, and ΔH due to evapotranspiration; to volumetric units required the application of appropriate specific yield values.

Determination of Specific Yield for Aquifer Layers

Theoretically, the term specific yield, when applied to unconfined aquifer conditions, refers to the ratio of the total volume of aquifer to the volume of water which will drain by gravity from the aquifer (Todd, 1959). This ratio is usually expressed as a percentage, but for the purposes of this study where the ratio was used directly in decimal form, the data were so expressed. Over short time periods, the passage of the maximum capillary rise miniscus through a layer of uniform sand has been shown by Smith (1961) to remove about 90 percent of the total drainable water from sands with effective grain sizes of 0.25 to 0.30 millimeters diameter such as are found in the Udell aquifers. Early experiments by King (1898) demonstrated that even after 2-1/2 years complete equilibrium was not yet established in five foot vertical columns of sand. Smith's theoretical analysis of King's results, as well as tests of non-uniform sands conducted by Hazen (1892), showed that initial drainage gives a

Figure 10. Separation of the components of water-table level fluctuations, Hardwood (shallow) study area.



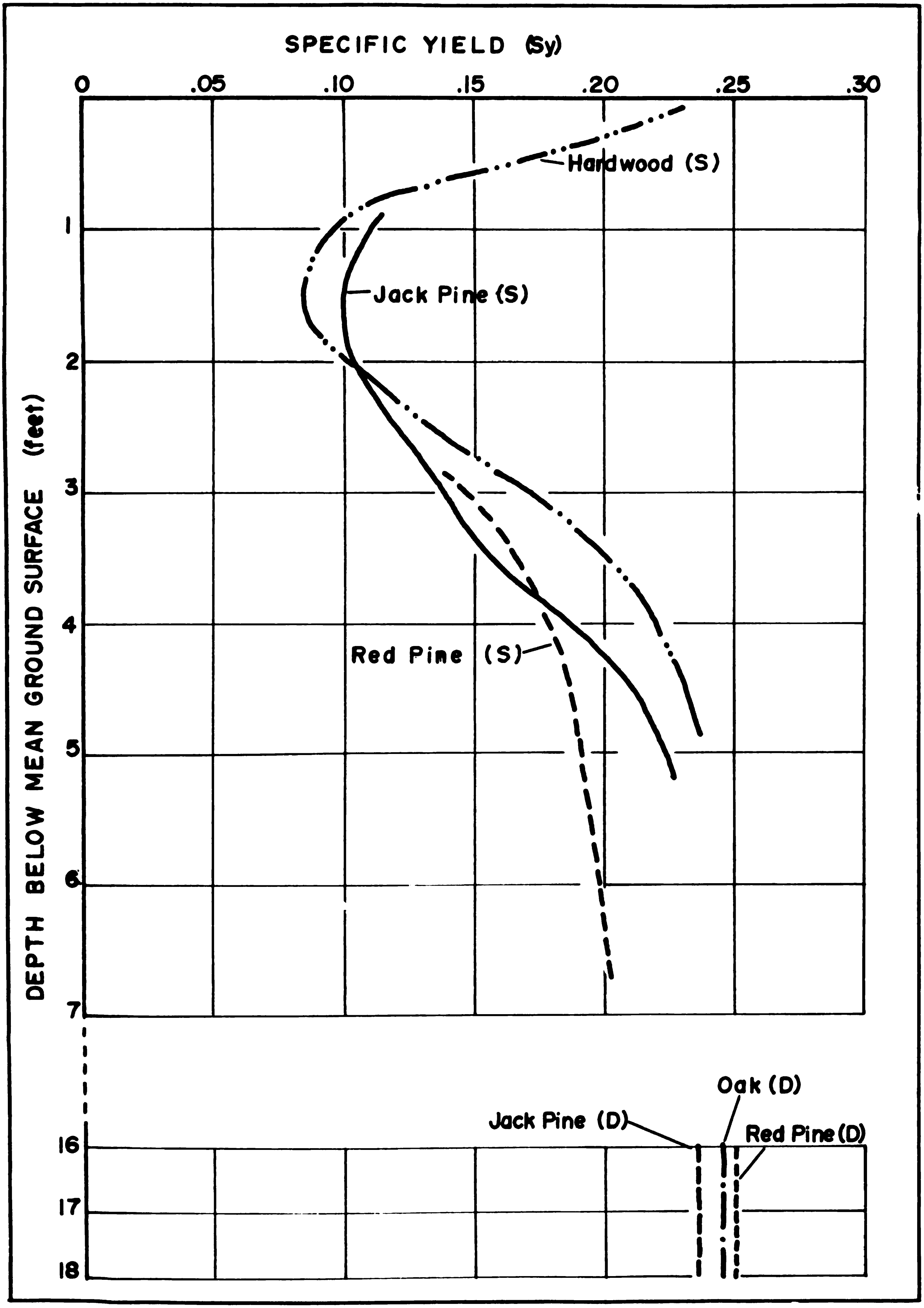
DEPTH BELOW DATUM (feet)
3.9
4.0
4.1
4.2
4.3
JUN 4
JUN 5
JUN 6
JUN 7
JUN 8
JUN 9
JUN 10
JUN 11
Predicted Rate of Seepage Recession
ΔHROg
ΔHETg
ΔHRg
ΔHROg
Rainfall
.02"
.42"
.11"

good approximation of the specific yield. This fact becomes particularly important when the daily fluctuations of the water table are to be evaluated. Childs (1960) characterized the concept of a specific yield as a rough approximation necessary for progress.

Specific yield values in the shallow water-table plots were estimated by measurement of the rise in well levels above the expected recession during periods of recharge. Recharge events were selected during periods when soil moisture deficits were negligible, mostly during the dormant season. Gross precipitation measured in the open was adjusted for interception losses by use of published curves of net interception versus storm intensity (Kittridge, 1949). A scatter diagram of the ratio of throughfall to water-table rise was plotted against the depth within the aquifer. The Hardwood and Jack Pine (shallow) areas showed definite zonation which corresponded to the degree of soil profile development (Figure 11).

Specific yield values in the Red Pine (shallow) area and in all deep water-table plots were less variable and no consistent pattern could be found in the subsoil layers. Specific yield values for these deeper strata were derived by draining 24-inch columns of undisturbed sediments removed from the aquifer layer just above the lowest water-table stage. These columns were drained for 48 hours with the top of the column protected against evaporation loss. The difference in moisture content between the upper three inches of the column and the lower three inches was weighted by the bulk density of subsoil sands to obtain a specific yield estimate. Specific yield values for subsoil samples from all six study areas are listed in Table 2.

Figure 11. Specific yield of shallow aquifer layers for six local study areas in outwash sands.



SPECIFIC YIELD (Sy)
0
.05
.10
.15
.20
.25
.30
DEPTH BELOW MEAN GROUND SURFACE (feet)
1
2
3
4
5
6
7
16
17
18
Hardwood (S)
Jack Pine (S)
Red Pine (S)
Oak (D)
Jack Pine (D)
Red Pine (D)

TABLE 2

SPECIFIC YIELD VALUES OF SUBSOIL LAYERS

Study Area	Range of Water-Table Depths (Feet)	Specific Yield [1/]
Hardwood (S)	2.0 - 7.0	0.08 - .17
Oak (D)	13.4 - 16.8	.245
Red Pine (S)	4.0 - 7.3	.20 - .256
Red Pine (D)	15.1 - 18.5	.25
Jack Pine (S)	2.8 - 7.3	.10 - .18
Jack Pine (D)	13.1 - 16.6	.235

[1/] Expressed as the decimal ratio of volume of water to volume of sediments.

Computations of Daily Ground-Water Budgets

From the fluctuations of the water table as recorded in each cover-depth situation, a daily recharge-discharge balance sheet was computed for the three shallow study areas. An example of this bookkeeping technique is shown in Table 3 for June 5-20, in the shallow Jack Pine area.

In the three deep water-table areas, the fluctuations of the water table were much more gradual. Recharge from a given storm was found to be distributed over a period of several days to two weeks. In these plots there was no direct evapotranspiration from the ground-water. The budgeting process was simplified accordingly. The rate of seepage flow recession changes very slowly in these plots, therefore, it was possible to compute the recharge and seepage flow volumes by weekly periods.

The daily and weekly imput and drain volumes were totaled for each month and the net change in storage compared to that computed from the periodic change in water level. This can be expressed in equation form as follows:

$$\Delta S = \Delta H \cdot Sy = Rg - RОg - ETg \qquad \text{(VII-2)}$$

The total ET for the month was computed from the gross precipitation minus the net ground-water recharge, where the net recharge was equal to the gross minus ET losses from the saturated zone.

$$ET = P - Rg + ETg \qquad \text{(VII-3)}$$

This analysis is valid only when there is negligible change in soil moisture storage between the beginning and end of the month. In the

TABLE 3

AN EXAMPLE OF GROUND-WATER BUDGET COMPUTATIONS
June 5-15, 1962
Jack Pine (S)

Date	Mean Water Table Depth (ft)	Spec. Yield	Daily ΔH (ft)	ΔHROg (ft)	ROg (ft)	ROg (in)	ΔH- ΔHROG (ft)	Recharge (ft)	Recharge (in)	ETg (ft)	ETg (in)
5	4.63	.13	-.020	-.020	.003	.04	0	0	0	0	0
6	4.65	.13	-.030	-.020	.003	.04	-.010	0	0	.001	.01
7	4.68	.13	-.025	-.020	.002	.02	-.005	0	0	.001	.01
8	4.72	.14	-.050	-.035	.005	.06	-.015	0	0	.003	.04
9	4.77	.14	-.040	-.020	.003	.04	-.020	0	0	.003	.04
10	4.79	.14	-.010	-.020	.003	.04	+.010	.001	.01	0	0
11	4.80	.14	-.000	-.020	.003	.04	+.020	.003	.04	0	0
12	4.81	.14	-.020	-.020	.003	.04	.000	0	0	0	0
13	4.83	.14	-.030	-.020	.003	.04	-.010	0	0	.001	.01
14	4.86	.14	-.030	-.020	.003	.04	-.010	0	0	.001	.01
15	4.91	.14	-.040	-.020	.003	.04	-.020	0	0	.003	.04

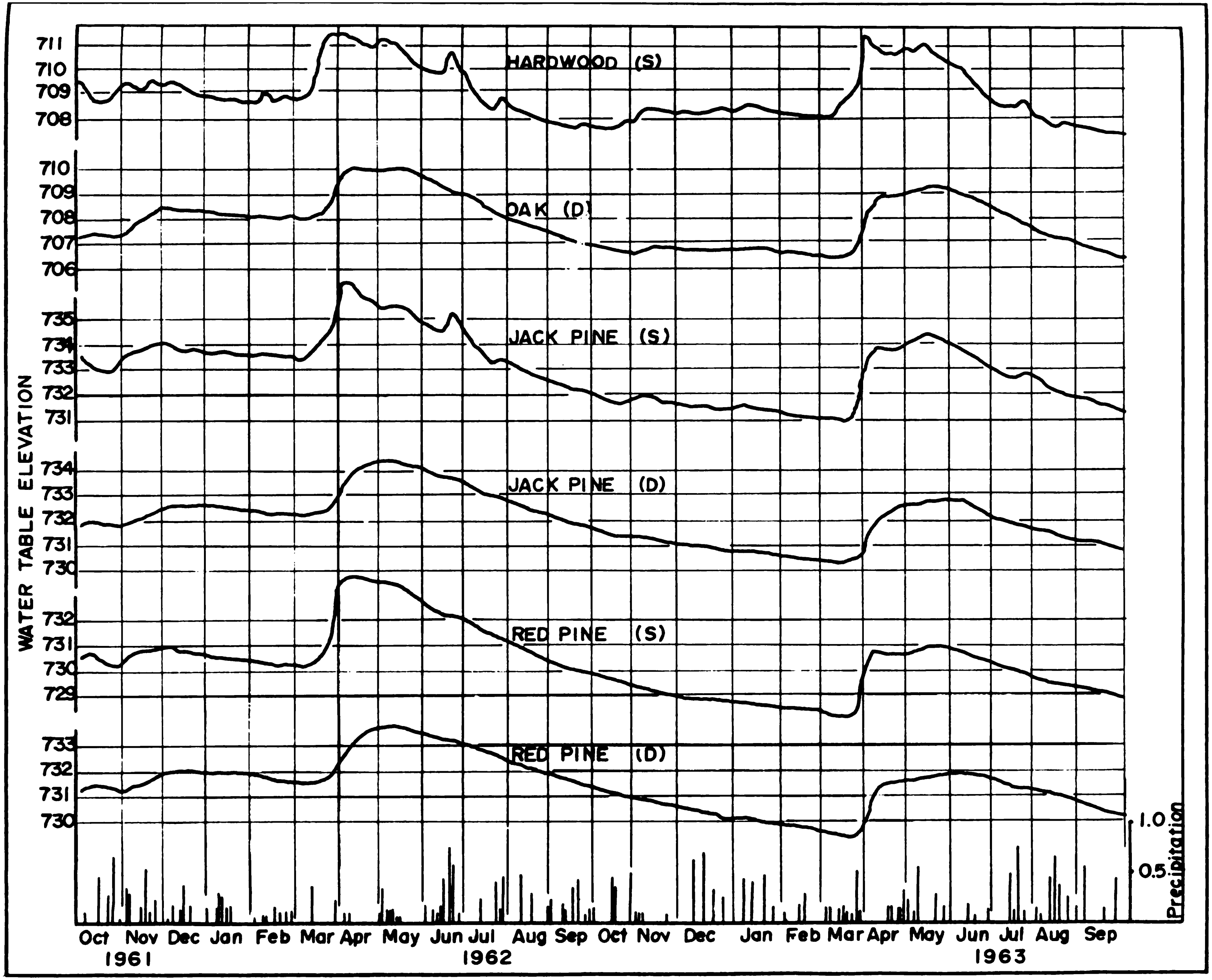
shallow water-table aquifers, this condition was usually met since capillary moisture rise above the water table kept the unsaturated layers near field capacity. Evidence of this situation was seen in the prompt recharge response of the shallow wells in these aquifers to almost every rainfall (Figure 12).

Evapotranspiration in the deeper aquifer areas was estimated for periods between recharge events. The assumption that recharge can only occur when soil moisture deficits are satisfied was not completely justified since low recharge totals were measured from storms which occurred when soils were assumed to be at field capacity by this criterion.

Evaluation of Snow-Melt Recharge

Ground-water recharge from the water released during melting of winter snow made up 40 to 80 percent of the total annual recharge during the two-year period. Since the high permeability of the surface soils on all six study areas permitted infiltration of all melt waters, the recharge of ground-water might be expected to closely parallel the water content of the snowpack. Cumulative recharge during the March-April period was computed for each study area. The water content of the snowpack in each forest cover type was measured during the winter buildup and melting period. During the winter and spring of 1962, these measurements were confined to the five-point snow courses associated with the precipitation network (Figure 6). In the second year, supplemental snow measurements were taken on the study plots where 25 snow cores were weighed, five in the vicinity of each of the five wells in each cover-depth area.

Figure 12. Water-table level fluctuations during two-year study period, mean of five wells in each local study area.



HARDWOOD (S)
OAK (D)
JACK PINE (S)
JACK PINE (D)
RED PINE (S)
RED PINE (D)
WATER TABLE ELEVATION
Precipitation
1.0
0.5
711
710
709
708
706
707
735
734
733
732
731
730
729
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
1961
1962
1963

The total amount of moisture available for recharge during the March-April periods included the snowpack water at the start of the melt, plus rain and snow received during the melt period. Evapotranspiration losses in the early weeks of spring were assumed to be negligible.

CHAPTER VII

RESULTS

Precipitation during the two-year period of this study was very close to the long-term mean of 32.10 inches as measured at Wellston, five miles east of the study area (U.S. Dept. of Commerce, 1962, 1963, 1964). The average at the 12 gauges on the Udell Experimental Forest was 33.11 inches during the 1961-62 water year (Table 4). For the second year this average was only 30.10 inches. The entire study period began with soils near field capacity following 8.75 inches of rainfall in September, 1961. For the remainder of that autumn period, rainfall was above normal. Winter precipitation was above normal until March. Deficient spring rain was followed by abundant June and July precipitation. The water year ended with slightly below normal precipitation.

The 1962-63 water year was marked by deficient rainfall in late fall and late spring. December and March were the only months in which average precipitation was more than an inch above the long-term norm. This second year began with a condition of soil moisture deficiency and ended with an even greater deficiency (Table 5). The two years were characterized by the theoretical computation of the water budget using Thornthwaite's potential evapotranspiration (Thornthwaite and Mather, 1957). The obvious difference was in the autumn recharge period when a water yield of nearly 4.5 inches was indicated during the first year. In the fall of 1962, the excess precipitation above evapotranspiration demands was sufficient only to restore soil moisture to field capacity

TABLE 4

MEAN MONTHLY PRECIPITATION, UDELL EXPERIMENTAL FOREST AND MONTHLY TOTALS ON LOCAL STUDY AREAS

	Normal ppt. Wellston [1/]	Average 12 Udell Stations	Average Hdwd.(S) and Oak(D)	Average Red Pine(S) and Red Pine(D)	Average Jack Pine(S) and Jack Pine(D)
			1961-62 Water Year		
Oct.	3.07	3.37	3.42	3.32	3.26
Nov.	2.97	3.54	3.56	3.44	3.57
Dec.	2.01	2.65	2.79	2.38	2.36
Jan.	2.06	3.49	3.64	3.34	3.54
Feb.	1.55	2.62	2.52	2.38	2.64
Mar.	1.83	1.37	1.49	1.20	1.29
Apr.	2.63	0.92	1.24	0.88	0.88
May	3.08	1.64	1.19	1.92	1.90
Jun.	3.18	4.40	4.36	4.32	3.80
Jul.	2.69	2.99	3.14	2.66	2.94
Aug.	3.33	2.85	2.91	2.76	2.82
Sept.	3.70	3.27	3.40	3.32	3.24
Annual	32.10	33.11	33.66	31.92	32.24
			1962-63 Water Year		
Oct.		3.51	3.42	3.70	3.70
Nov.		0.57	0.56	0.56	0.58
Dec.		3.48	3.37	3.55	3.26
Jan.		2.76	2.63	2.78	2.61
Feb.		1.42	1.43	1.57	1.45
Mar.		2.91	3.00	3.30	3.28
Apr.		2.58	2.60	2.54	2.33
May		2.19	2.19	2.16	2.21
Jun.		1.22	1.25	1.07	1.12
Jul.		3.70	3.67	3.60	3.75
Aug.		3.52	3.56	3.56	3.39
Sept.		2.24	2.06	2.37	2.19
Annual		30.10	29.74	30.76	29.87

[1/] Climatological normal based on period 1931-1960.

TABLE 5

THEORETICAL WATER BALANCE BY MONTHS - THORNTHWAITE & MATHER (1957)

	Mean Monthly Temp. °F	Mean Monthly ppt (in)	Heat Index I	Unadj. Daily PE (in)	Adj. PE Monthly (in)	P-PE (in)	Accum. Pot'l Water Loss (in)	Soil[1/] Moist. Storage (in)	Δ SM Storage (in)	Act. ET (in)	Moist. Deficit (in)	Water Yield (in)
1961-62 Water Year												
Oct.	50.3	3.37	2.93	.08	2.28	+1.09	0	3.00	0	2.28	0	1.09
Nov.	36.3	3.54	0.33	.01	.24	+3.30	0	3.00	0	.24	0	3.30
Dec.	24.7	2.65	0	0	0	+2.65	0	3.00	0	0	0	0
Jan.	17.2	3.49	0	0	0	+3.49	0	3.00	0	0	0	0
Feb.	17.5	2.62	0	0	0	+2.62	0	3.00	0	0	0	0
Mar.	29.8	1.37	0	0	0	+1.37	0	3.00	0	0	0	10.13
Apr.	40.9	0.92	0.98	.03	1.01	-0.09	.09	2.91	-0.09	1.01	0	0
May	57.0	1.64	4.69	.09	3.43	-1.79	1.88	1.57	-1.34	2.98	.45	0
Jun.	65.8	4.40	7.42	.13	5.03	-0.63	2.51	1.26	-0.31	4.71	.32	0
Jul.	65.4	2.99	7.28	.12	4.68	-1.69	4.20	0.70	-0.56	3.55	1.13	0
Aug.	66.2	2.85	7.55	.13	4.68	-1.83	6.03	0.38	-0.32	3.17	1.51	0
Sept.	56.3	3.27	4.50	.09	2.81	+0.46	0	0.84	+0.46	2.81	0	0
Annual	43.9	33.11	35.68		24.16	+8.95				20.75	3.41	14.52
1962-63 Water Year												
Oct.	50.9	3.51	3.08	.07	2.00	+1.51	0	2.45	+1.51	2.00	0	0
Nov.	37.0	0.57	0.41	.02	.48	+0.09	0	2.54	+0.09	0.48	0	0
Dec.	23.8	3.48	0	0	0	+3.48	0	3.00	+0.46	0	0	0
Jan.	13.9	2.76	0	0	0	+2.76	0	3.00	0	0	0	0
Feb.	12.9	1.42	0	0	0	+1.42	0	3.00	0	0	0	0
Mar.	30.7	2.91	0	0	0	+2.91	0	3.00	0	0	0	10.11
Apr.	44.1	2.58	1.56	.04	1.34	+1.24	0	3.00	0	1.34	0	1.24
May	51.0	2.19	3.11	.07	2.67	-0.48	0.48	2.54	-0.46	2.67	0	0
Jun.	67.0	1.22	7.82	.13	5.03	-3.81	4.29	0.21	-2.33	3.55	1.48	0
Jul.	69.1	3.70	8.54	.13	5.07	-1.37	5.66	0.10	-0.11	3.81	1.26	0
Aug.	63.7	3.52	6.72	.11	3.96	-0.44	6.10	0.08	-0.02	3.55	.41	0
Sept.	57.8	2.24	4.92	.09	2.81	-0.57	6.67	0.05	-0.03	2.27	.54	0
Annual	43.5	30.10	36.16		22.93	+6.74				19.67	3.69	11.35

[1/] A field capacity of 3.0" assumed - approximately for Grayling sand soils, with available moisture range of 4 percent and rooting depth of 36 inches.

levels.

Computed actual evapotranspiration was more than one inch greater in the first year, while estimated water yield was more than three inches greater.

Gross Ground-Water Recharge

The total volume of water which was added to ground-water by percolation from rain and melting snow was computed from the daily and weekly aquifer storage changes. The monthly and annual totals for each of the six study areas are listed in Table 6. In every area, the total amount in 1961-62 exceeded that in 1962-63. In general, these annual differences were similar to the predicted difference obtained from the Thornthwaite calculations. A large portion of this difference occurred as autumn recharge.

Total recharge in the Hardwood (shallow) area exceeded that of all other cover-depth conditions. During a major portion of the year, the water table in this plot area is within 18 inches of the soil surface (Figure 12). Capillary moisture rising above the water table maintains this soil at or near field capacity. Consequently, rainfall even in moderate amounts, produces a marked rise in the water-table level. Since the evapotranspiration withdrawals (Table 7) are greatest from these shallow water-table areas, the net recharge differs less than the gross recharge between the deep and shallow counterparts.

Figures 13 and 14 show the monthly gross recharge, net recharge and evapotranspiration loss from ground-water in comparison to the total monthly precipitation. These histograms show that the greatest amount of recharge occurs during the dormant season. In 1962, autumn rainfall

TABLE 6

GROSS GROUND-WATER RECHARGE (Area Inches)

	Hardwood (Shallow)	Oak (Deep)	Jack Pine (Shallow)	Jack Pine (Deep)	Red Pine (Shallow)	Red Pine (Deep)
			1961-62 Water Year			
Oct.	2.99	0.62	1.87	0.23	1.37	0.16
Nov.	2.64	3.83	2.84	2.93	3.10	2.84
Dec.	0.68	0.91	0.65	1.34	0.72	1.38
Jan.	0.20	0.21	0.24	0.30	0.29	0.36
Feb.	0.60	0.35	0.08	0.16	0.30	0.23
Mar.	6.94	6.86	5.08	3.26	5.43	3.05
Apr.	1.07	1.73	1.33	4.32	1.82	4.87
May	1.07	1.61	0.65	0.32	0.48	0.68
Jun.	2.39	0.79	1.85	0.84	0.88	0.34
Jul.	1.67	0.29	0.71	0.37	0.07	0.12
Aug.	0.44	0.02	0.37	0.35	0.19	0.24
Sept.	0.89	0.20	0.18	0.44	0.18	0.24
Annual	21.58	17.41	15.85	14.90	14.83	14.51
			1962-63 Water Year			
Oct.	1.92	0.07	0.49	0.18	0.26	0.16
Nov.	0.41	0.82	0.46	0.41	0.34	0.49
Dec.	0.85	0.28	0.09	0.10	0.35	0.12
Jan.	0.71	0.34	0.18	0.25	0.14	0.08
Feb.	0.08	0	0.02	0	0.12	0
Mar.	7.46	5.36	5.12	1.42	5.44	1.32
Apr.	2.33	2.86	3.19	6.20	3.01	6.55
May	1.80	2.39	1.49	1.48	0.86	2.16
Jun.	0.66	0.24	0.01	0	0.02	0.28
Jul.	1.78	0.29	1.25	0.42	0.68	0.53
Aug.	0.43	0.24	0.41	0.34	0.10	0.12
Sept.	0.31	0	0.02	0.18	0.01	0.08
Annual	18.74	12.89	12.73	10.98	11.33	11.89

TABLE 7

EVAPOTRANSPIRATION DRAIN FROM GROUND-WATER IN
SHALLOW WATER-TABLE AREAS (Area Inches)

Month	Hardwood(S)	Jack Pine(S)	Red Pine(S)
	1961-62 Water Year		
October	0.39	0.16	0.12
November	0.07	0.04	0.01
December			
January			
February			
March			
April	0.04	0.24	0.13
May	0.82	0.56	0.64
June	2.35	0.50	0.65
July	1.32	0.42	0.71
August	0.23	0.06	0.35
September	0.07		0.22
Annual	5.29	1.98	2.83
	1962-63 Water Year		
October	0.01		0.18
November	0.16		0.01
December			
January			
February			
March			
April	0.02	0.06	0.05
May	0.34	0.53	0.32
June	1.38	0.74	0.15
July	1.78	0.64	0.29
August	0.28	0.08	0.20
September	0.17		0.07
Annual	4.14	2.05	1.27

Figure 13. Monthly precipitation, gross and net recharge and evapotranspiration from the saturated zone for six local study areas, 1961-62 water year.

1961-2 WATER YEAR

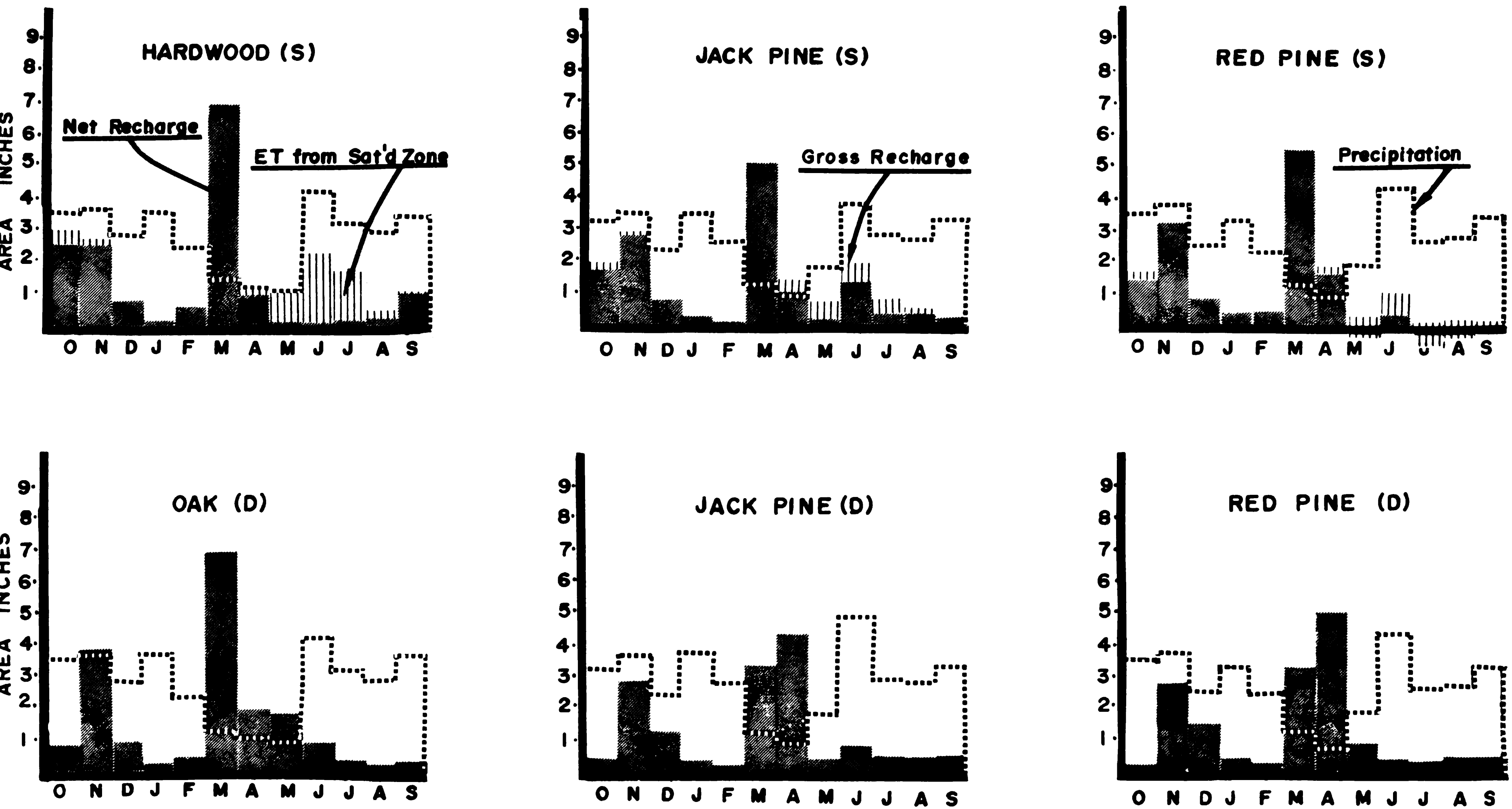
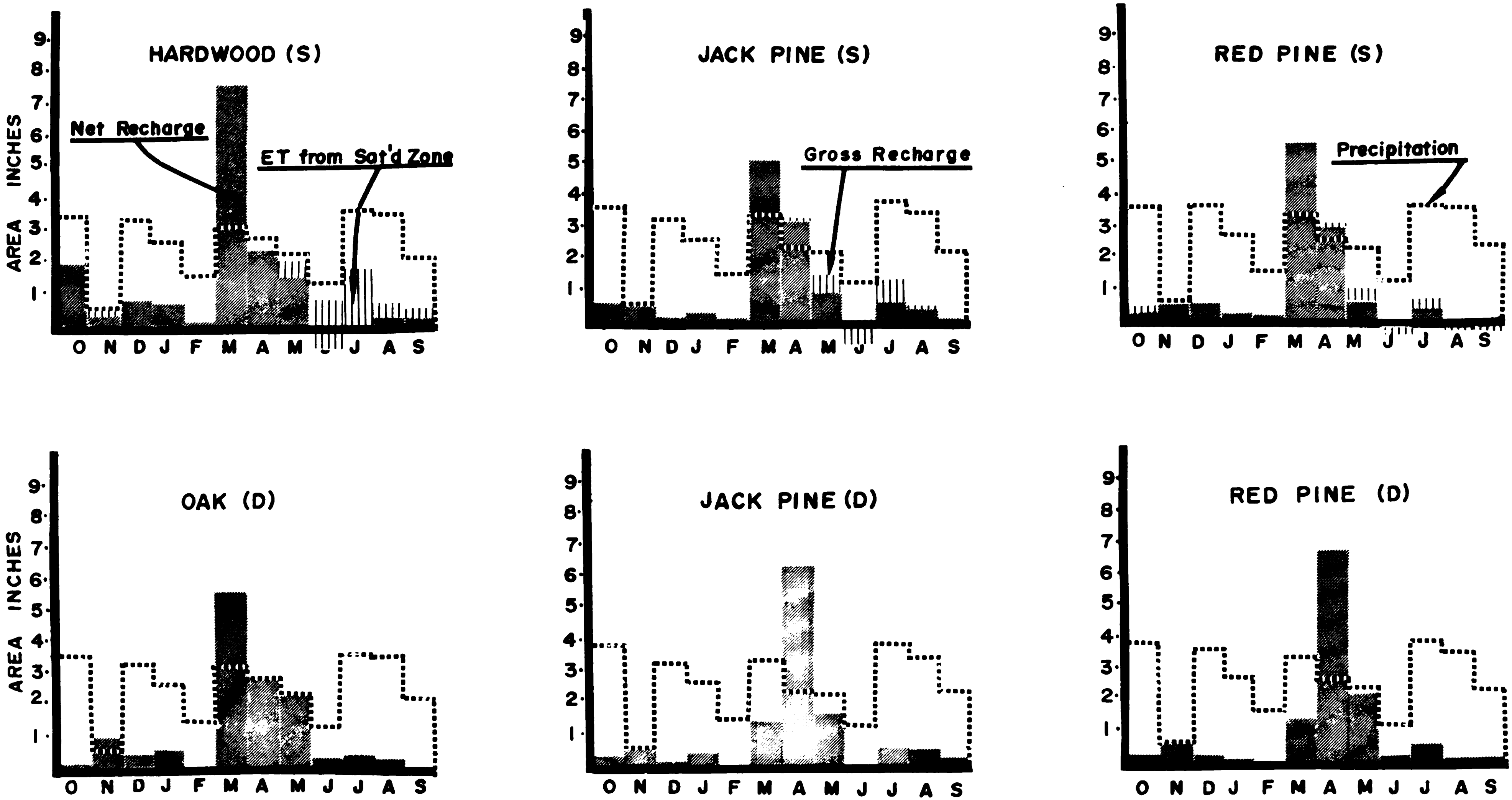


Figure 14. Monthly precipitation, gross and net recharge and evapotranspiration from the saturated zone for six local study areas, 1962-63 water year.

1962-3 WATER YEAR



was not sufficient to produce recharge before winter precipitation began to accumulate in the snowpack.

During both winter periods, continued low temperatures maintained the snowpack until March. At this time, the shallow water-table plots received most of their annual increment of ground-water. Earlier snow melt under the oak plots allowed a larger proportion of this snow water to reach the water table before the end of the month. Insulation of the crowns in two pine areas delayed snow melt until April. The recharge timing differences and the comparative increments from growing season precipition are shown in Figure 15.

The cumulative recharge curves (Figure 16) show these differences in recharge timing in more detail. In the Hardwood (shallow) area, the combination of high water-table levels and low evapotranspiration after leaf fall, produced high rates of recharge in 1961. In the comparative deciduous forests with a deep water table, the recharge was lower by nearly one inch. A part of this difference is compensated for by the evapotranspiration drain of nearly one-half inch on the ground-water beneath the Hardwood (shallow) stand.

During the winter months, recharge from snow melt was slight but both hardwood areas showed greater recharge than the pine areas where brief periods of warm weather had less effect on the snowpack. Differences in the mean water content of the snowpack and the recharge during and following the snow period are discussed below.

Heavy rainfall in mid-June and mid-July produced marked recharge in both shallow Hardwood and Jack Pine areas. At this time, the water table in the Red Pine (shallow) was 4 1/2 to 5 feet below mean ground level. The recharge pattern was very similar to the three deep water table

Figure 15. Weekly increments of gross recharge in six local study areas.

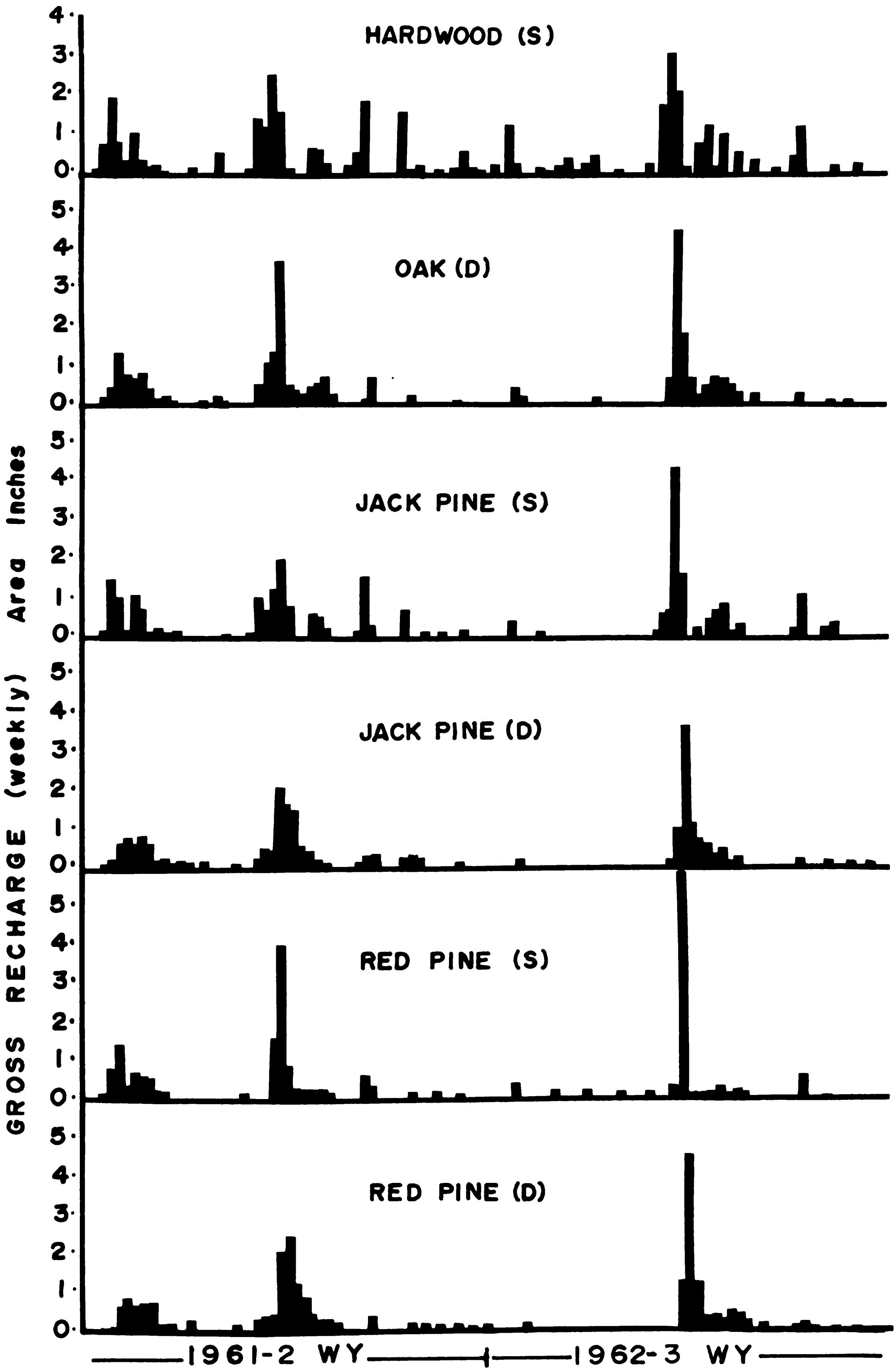
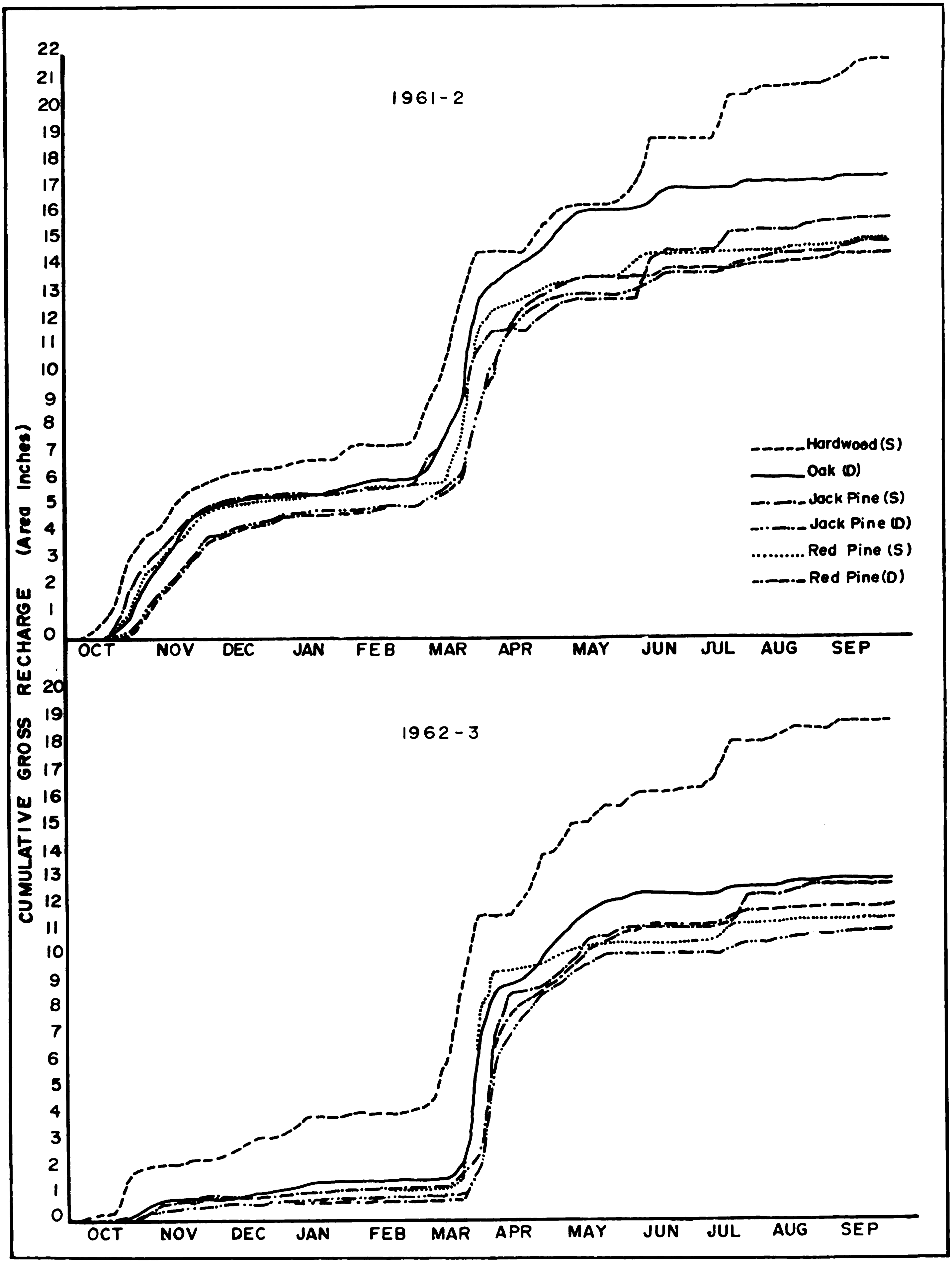

HARDWOOD (S)
OAK (D)
JACK PINE (S)
JACK PINE (D)
RED PINE (S)
RED PINE (D)
GROSS RECHARGE (weekly) Area Inches
0 1 2 3 4
0 1 2 3 4 5
1961-2 WY
1962-3 WY

Figure 16. Cumulative gross recharge in six local study areas by water year.



CUMULATIVE GROSS RECHARGE (Area Inches)
1961-2
1962-3
Hardwood (S)
Oak (D)
Jack Pine (S)
Jack Pine (D)
Red Pine (S)
Red Pine (D)
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP

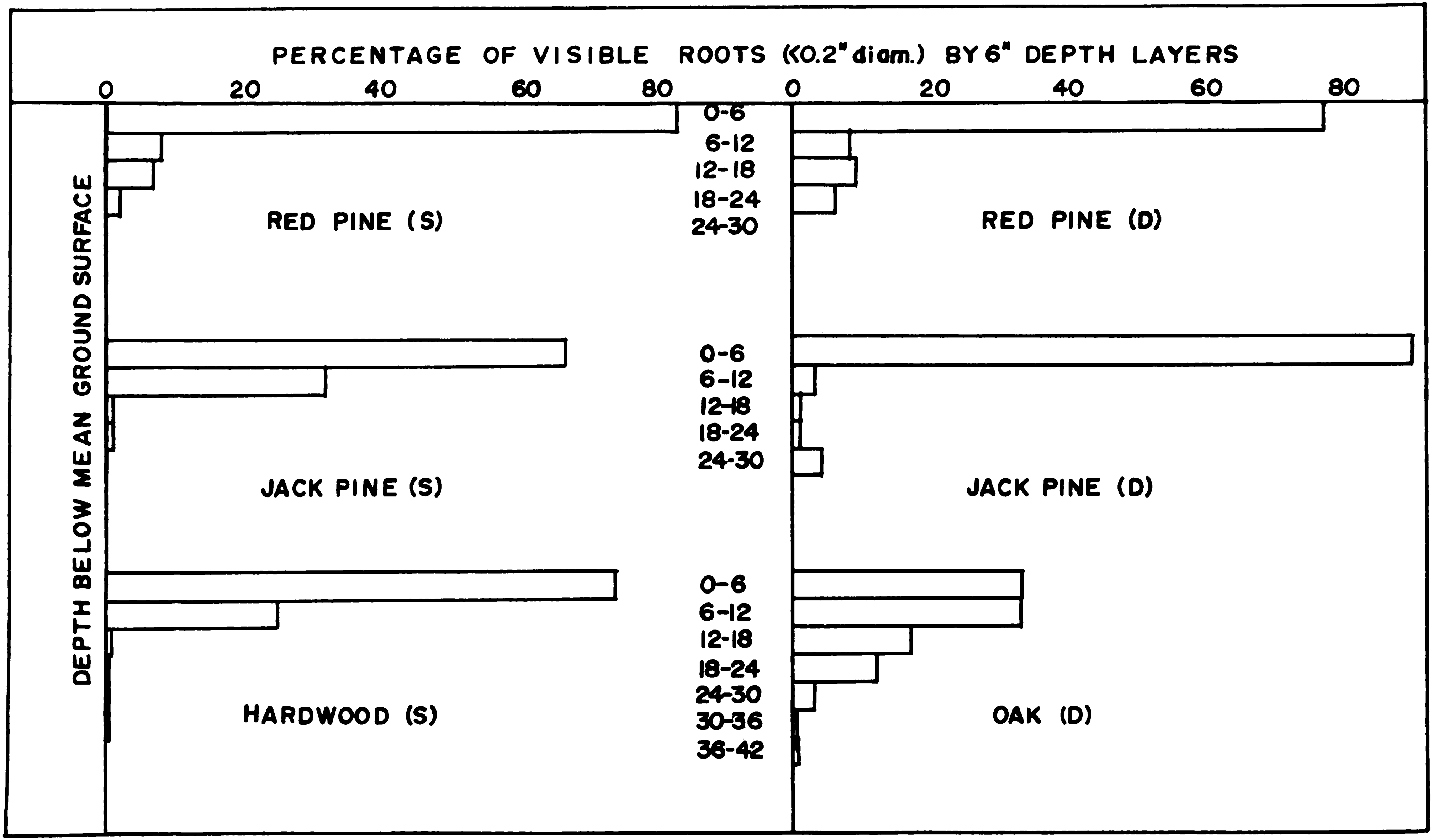
areas which indicates the building up of a soil moisture deficiency above the capillary zone. At the same time, there continued to be a marked diurnal fluctuation in the rate of water-table recession which showed that ET moisture was still being obtained from the ground-water source. Excavated profiles in the three shallow water-table areas provided an explanation for this anamalous response. Fine roots (less than 0.2 inch diameter) were distributed more evenly through the B horizon in the Red Pine (shallow) stand than in the other two shallow water-table types (Figure 17). There is also five-six feet of microtopographic variation in the Red Pine (shallow) area which places approximately one-third of the stand area in a well-drained condition soon after water-table levels drop below their annual peak.

The Oak (deep) area received markedly greater recharge during April and May than was measured in the two deep water-table pine areas. Full hardwood leaf development was not reached until the last week of May. Presumably lower transpiration rates in the Oak accounted for the recharge differences.

In the fall of 1962, only the Hardwood (shallow) area received measureable recharge before the end of November. By that date, the water table in the Jack Pine (shallow) and Red Pine (shallow) areas was well below the root zone.

Both deciduous forest areas showed greater winter recharge during brief winter melting periods. Snow-melt recharge began and ended one to two weeks earlier in these two areas than in the pine areas with comparable ground-water depths. Recharge continued at higher rate under Hardwood stands until leaf development was complete in the first week of June.

Figure 17. Root distribution in relation to depth in six local study areas.


PERCENTAGE OF VISIBLE ROOTS (<0.2" diam.) BY 6" DEPTH LAYERS
0
20
40
60
80
DEPTH BELOW MEAN GROUND SURFACE
0-6
6-12
12-18
18-24
24-30
30-36
36-42
RED PINE (S)
JACK PINE (S)
HARDWOOD (S)
RED PINE (D)
JACK PINE (D)
OAK (D)

Following the prolonged drought period from late May to mid-July, only the Hardwood and Jack Pine (shallow) areas produced heavy recharge from the drought-ending storms with a gross rainfall of 3.3 inches.

In both water years, the two hardwood forest areas produced more gross recharge than any of the pine types. The Jack Pine (shallow) area had the greatest gross recharge of the conifer study areas. During a portion of each growing season, the Red Pine (shallow) area did not have water-table levels sufficiently high to prevent the development of soil moisture deficits. Except during the early part of the growing season, ground-water recharge under this stand was similar to the two deep water-table pine stands.

Evapotranspiration From Ground-Water Supplies

In the shallow ground-water areas, the accelerated rate of water-table recession during the day-light hours indicated evapotranspiration losses (Figure 10). The sum of these daily recessions multiplied by the specific yield of the appropriate aquifer layer is shown for each month and year in Table 7. The Hardwood (shallow) area with the highest average water level during the growing season exhibited the greatest diurnal fluctuations and the greatest annual ground-water losses to evapotranspiration. The rate of ET loss was greatly accelerated after June 1, when the forest was in full leaf.

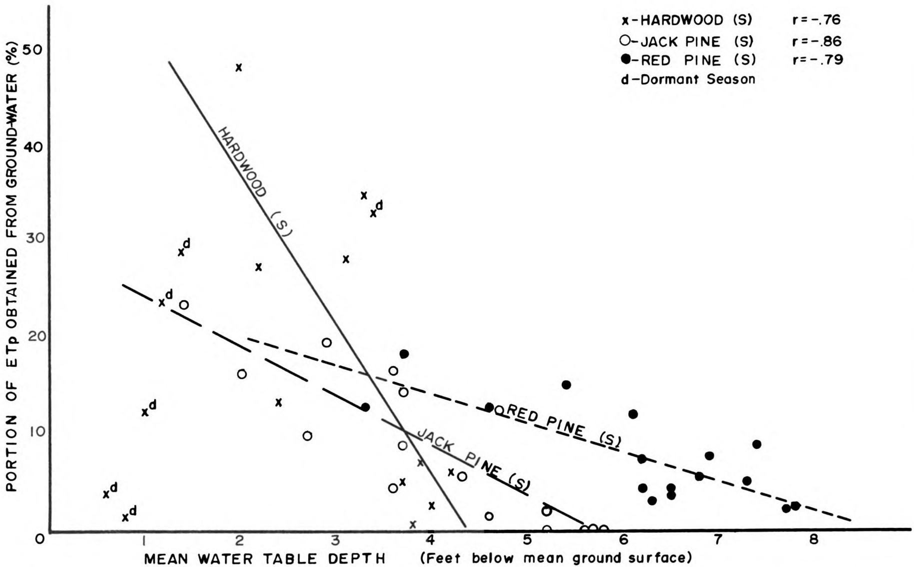
ET losses in the Jack Pine area were minor after July when the water-table level fell below the B horizon. In April, 1962, moisture use was greatest in this area during a low rainfall period. In the following April, cold temperatures and abundant rainfall limited ground-water use for ET.

ET losses were most even throughout the growing season in the Red Pine area. The effect of lower average ground-water levels during the 1962-63 water year was shown in a much lower total water loss (1.26 in 1962-63 vs. 2.82 in 1961-62) under this forest cover.

The comparative effects of ground-water depth on the amount of ET drain from the aquifer is shown in Figure 18. The monthly water losses are plotted as a percentage of the total potential evapotranspiration for that month (See Table 5). By making this conversion, it was possible to compare all monthly periods during the growing season. Separate regression lines were fitted to the monthly observations for each of the three shallow water-table areas. April, May, and November data were excluded from the Hardwood (shallow) analysis. At these times, the principal species were dormant and the ET rates did not fit the trends which were evident for the remainder of the snow-free period. These data are indicated by the subscript "d" on Figure 18.

It is evident from this figure that ground-water losses to ET cease when water-table levels drop below 4.5 feet in the Hardwood and below 5.5 feet in the Jack Pine. In the Red Pine area, the slope of the regression line is less steep. No clear cutoff point was evident from the data obtained during the two years of study. Obviously ground-water losses to ET become negligible at water-table depths below eight feet. Due to the microtopographic conditions mentioned earlier, only a portion of the trees on this area ever obtained ground-water during the study period. Conversely, some low lying sections may be able to derive capillary moisture from the saturated zone when the average depth is greater than eight feet.

Figure 18. Monthly evapotranspiration from the saturated zone as a percentage of potential evapotranspiration in relation to water-table depth.


x-HARDWOOD (S) r=-.76
O-JACK PINE (S) r=-.86
●-RED PINE (S) r=-.79
d-Dormant Season
HARDWOOD (S)
JACK PINE (S)
RED PINE (S)
PORTION OF ETp OBTAINED FROM GROUND-WATER (%)
MEAN WATER TABLE DEPTH (Feet below mean ground surface)
0
10
20
30
40
50
1
2
3
4
5
6
7
8

Net Ground-Water Recharge

A comparison of the actual effectiveness of the six study areas as water producers is shown in Table 8. The amounts of ground-water utilized for ET has been subtracted from the gross recharge figures. It is evident that both deciduous forest areas yielded more water for seepage flow than did any of the pine areas. The greatest difference was 5.4 inches (45%) between the Red Pine (shallow) and the Oak (deep) during the first year. Both deep pine areas produced 2.5 - 3 inches less than the deep Hardwood area.

Among the shallow water-table types, the Hardwood area yielded 2.4 inches (17%) more than the Jack Pine and 4.3 inches (35%) more than the Red Pine in the first year.

All areas showed reductions in net recharge during the second year. These differences, ranging from a 1.7 inch reduction in the Hardwood (shallow) to a 4.5 inch reduction under the Oak (deep), were doubtless affected by the soil moisture deficit which existed at the start of the second water year. In the shallow plots this deficit was less severe and the reduction in net recharge, over that due to the difference in precipitation, was not as large as the reduction in their deep water-table counterparts.

The negative net recharge values in the shallow water-table areas during June, 1963, indicated a net loss from storage during this low rainfall period. The Red Pine (shallow) area showed a net loss during several other growing season months resulting from low gross recharge and a continual, though small, utilization of ground-water. In this respect, the deeper rooted red pine was consistantly the highest water use area. Although water-table levels were higher, on the average,

TABLE 8

NET GROUND-WATER RECHARGE (Area Inches)

	Hardwood (Shallow)	Oak (Deep)	Jack Pine (Shallow)	Jack Pine (Deep)	Red Pine (Shallow)	Red Pine (Deep)
			1961-62 Water Year			
Oct.	2.60	0.62	1.71	0.23	1.25	0.16
Nov.	2.57	3.83	2.80	2.93	3.09	2.84
Dec.	0.68	0.91	0.65	1.34	0.72	1.38
Jan.	0.20	0.21	0.24	0.30	0.29	0.36
Feb.	0.60	0.35	0.08	0.16	0.30	0.23
Mar.	6.94	6.86	5.08	3.26	5.43	3.05
Apr.	1.03	1.73	1.09	4.32	1.69	4.87
May	0.25	1.61	0.09	0.32	-0.16	0.68
Jun.	0.04	0.79	1.35	0.84	0.23	0.34
Jul.	0.35	0.29	0.29	0.37	-0.64	0.12
Aug.	0.21	0.02	0.31	0.35	-0.16	0.24
Sept.	0.82	0.20	0.18	0.44	-0.04	0.24
Annual	16.29	17.41	13.87	14.90	12.00	14.51
			1962-63 Water Year			
Oct.	1.91	0.07	0.49	0.18	0.08	0.16
Nov.	0.25	0.82	0.46	0.41	0.33	0.49
Dec.	0.85	0.28	0.09	0.10	0.35	0.12
Jan.	0.71	0.34	0.18	0.25	0.14	0.08
Feb.	0.08	0	0.02	0	0.12	0
Mar.	7.46	5.36	5.12	1.42	5.44	1.32
Apr.	2.31	2.86	3.13	6.20	2.96	6.55
May	1.46	2.39	0.96	1.48	0.54	2.16
Jun.	-0.72	0.24	-0.73	0	-0.13	0.28
Jul.	0	0.29	0.61	0.42	0.39	0.53
Aug.	0.15	0.24	0.33	0.34	-0.10	0.12
Sept.	0.14	0	0.02	0.18	-0.06	0.08
Annual	14.60	12.89	10.68	10.98	10.06	11.89
Difference	-1.69	-4.52	-3.19	-3.92	-1.94	-2.62

in the Jack Pine (shallow), averaging 4.04 feet in comparison to 6.17 feet below mean ground surface during the two growing seasons, the more restricted rooting depth of the Jack Pine limited moisture use and allowed for greater net recharge.

One of the principal factors in the low net 1962-63 recharge of all types, was the lack of autumn rainfall. Only the Hardwood (shallow) area received a considerable amount of recharge above the ET usage during October. Rainfall late in October resulted in 0.8 inch of recharge under the Oak in November, while producing only one-half this amount in the pine types.

There was clear evidence of earlier transpiration demands in the conifers in the relative amounts of May recharge in both years. Delayed drainage of snow-melt waters in the deep water-table plots obscured this relationship in April in the monthly totals, but was evident in the cumulative recharge curves (Figure 16).

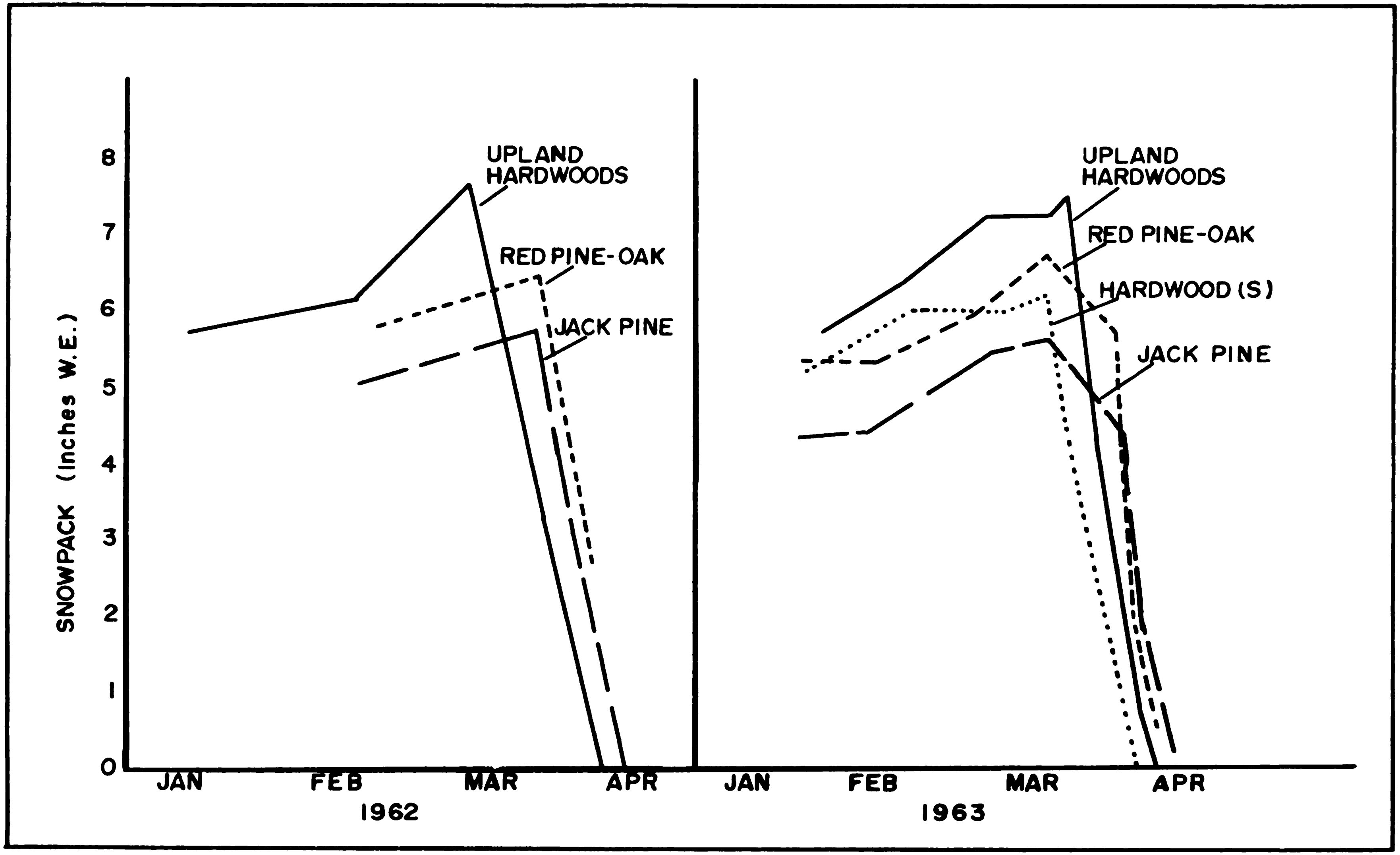
Snowpack Accumulation and Spring Recharge

McGuinness (1941) has stressed the important role of snow-melt waters in the recharge of ground-water in the Lower Peninsula of Michigan. Coming during a period of low evapotranspiration losses and at a time when soil moisture is at or near field capacity, the water in the melting snowpack is available for runoff or recharge depending on the infiltration capacity of the soil, topography and soil frost conditions. In sand soils of the Udell Experimental Forest, surface runoff from snow melt is negligible even when the soils are frozen. Probably this is due to a combination of spotty soil frost patterns (Striffler, 1959) and gentle relief. It is obvious from the monthly and the cumulative annual recharge patterns that a large portion of the total recharge increment resulted from snow melt in both years of this study.

The winters of 1961-62 and 1962-63 were periods of continual snowpack accumulation with only minor melting periods prior to the spring breakup. The maximum water content of the snowpack during each winter was determined for the three cover types (Figure 19). Consistant differences in the amounts of water stored on the ground were inversely related to the dormant season crown densities. The highest snowpack water equivalent values were found under deciduous stands which have low (10%) crown densities in the dormant season. This was true in the well-drained sections of the forest. In shallow water-table hardwoods, the snowpack was melted at the ground-line and the maximum water equivalent never reached the 7.6 and 7.4 inch values which were measured under upland oaks and aspen in 1962 and 1963, respectively. The early winter recharge which resulted from this mid-winter melting was most obvious in the winter of 1963 as is shown in the Hardwood (shallow) cumulative recharge curve (Figure 16).

The mean of 25 snow samples taken in this area on six dates in the later half of the winter, are shown in Figure 19. From January 28, to February 18, during a period of very low temperatures, the snowpack in the high water-table hardwoods accumulated at the same rate as that in the well-drained portions of the hardwood forest. Between the next two sampling dates, the water equivalent of the upland snowpack increased 0.8 inch, while that in the Hardwood (shallow) area declined 0.1 inch. During this time, the wells in the shallow water-table portions showed a recharge of 0.5 inches, while the Oak (deep) received no measureable input.

Figure 19. Average snowpack water equivalent values by forest cover type.



SNOWPACK (Inches W.E.)
0
1
2
3
4
5
6
7
8
UPLAND HARDWOODS
RED PINE-OAK
JACK PINE
JAN
FEB
MAR
APR
1962
UPLAND HARDWOODS
RED PINE-OAK
HARDWOOD (S)
JACK PINE
JAN
FEB
MAR
APR
1963

The Jack Pine areas, with a uniform crown density of approximately 82 percent, accumulated the lowest snowpack. The maximum water equivalent in both deep and shallow water-table zone was 5.8 inches in 1962 and 5.6 inches in 1963. Apparently the water-table levels in the shallow pine areas were sufficiently deep so that the latent-heat of the ground-water did not induce melting. There also may be less opportunity for mid-winter melting due to slower ripening of the snowpack beneath the conifer crowns.

The Red Pine areas, with an intermediate crown density of about 65% in winter, contained a maximum snowpack of 6.5 inches in 1962 and 6.7 inches in 1963. These values, intermediate to the two conditions mentioned previously, were identical in both deep and shallow water-table lands in 1963. During this winter in which intensive snow sampling was carried out in the six study areas, the snowpack was found to be very irregular, having patches and bands with water equivalent values as high as 8.5 inches in the holes created by the deciduous oak component of the stands. In comparison, the snowpack beneath Hardwoods and Jack Pine was regularly distributed except for major aspect differences.

The portion of gross annual recharge which resulted from winter precipitation is shown on an expanded time scale in Figure 20. The earlier melting which occurs under the open Hardwood cover is best illustrated by comparing the recharge timing of the three shallow water-table areas. Recharge in the deep water-table zones shows the same timing difference, but all recharge patterns are delayed by the time required for percolation.

Snow-melt recharge had ended in all the shallow water-table areas by April 12. The total recharge in these areas is compared in

Figure 20. Cumulative ground-water recharge during winter and snow-melt periods in six local study areas.

and snow-melt

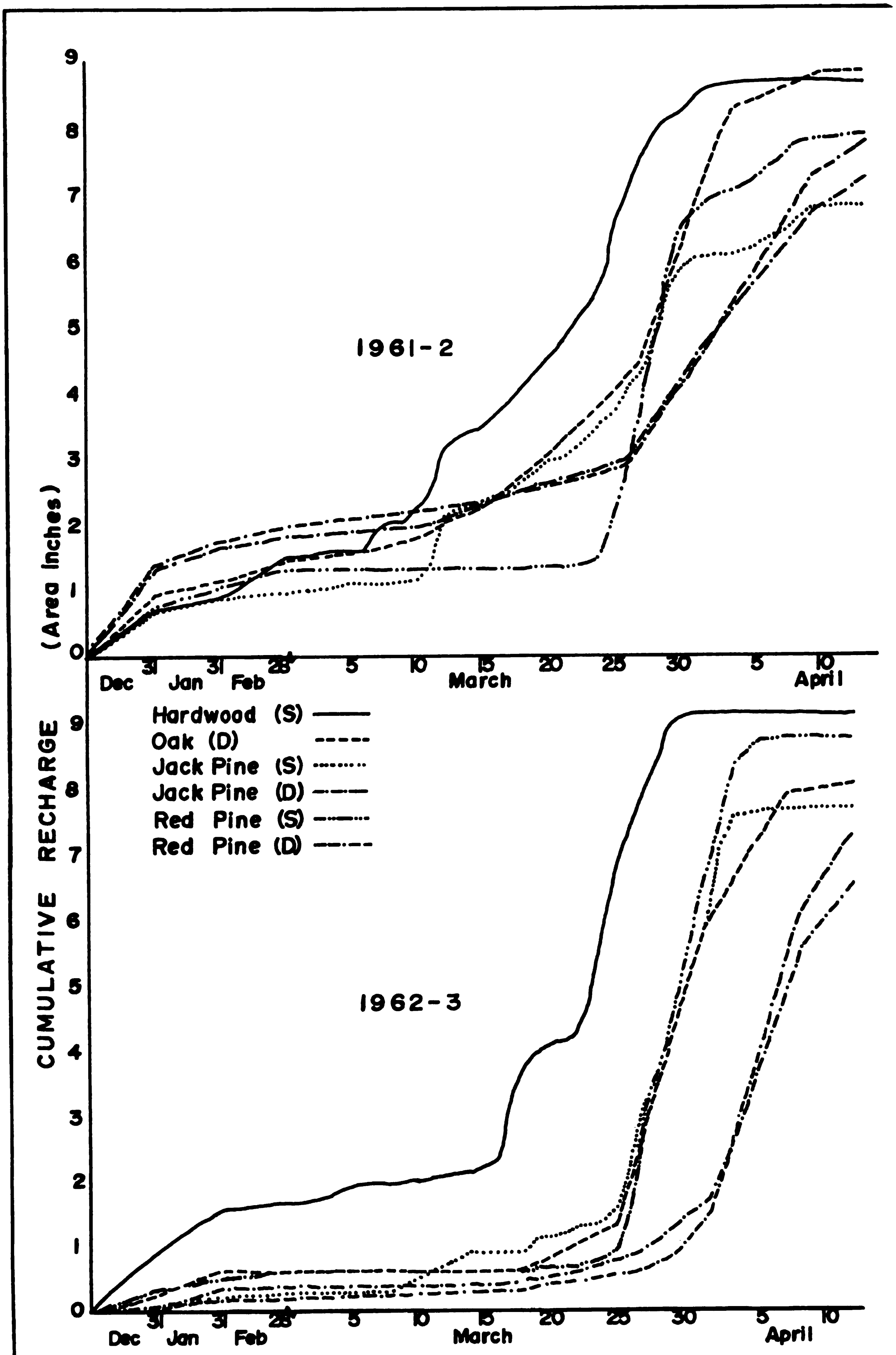


Table 9.

These recharge values correspond to the differences in snowpack accumulation. Total recharge in the Red Pine (shallow) area in 1962 appears anamolously high when the difference in precipitation is considered. As was explained earlier, the location of these plots near a strip of sparsely wooded private land may have resulted in inflow due to more rapid recharge in the open land. Short periods of altered ground-water flow patterns were noted during both recharge periods in the Red Pine (shallow) vicinity. Appropriate corrections were made in the inflow-outflow balance to the extent permitted by weekly and monthly measurements of surrounding wells. Nevertheless, the precision of the gravity flow recession rate estimate, which was basic to this analysis, was least accurately determined during this period of rapidly changing water-table levels.

The total snow-melt recharge in the deep water-table areas is not easily separated because of the longer delay in recharge response in the wells. The percolation of autumn rainfall caused greater recharge in all three deep areas during December of 1961 than in any of the shallow areas. It is unlikely that a greater portion of the early snowfall melted on these better drained sites during this period. Recharge from the spring melt continued throughout April and into early May. Rainfall during the spring months also contributed some recharge so that there was no clear end point to the snow-melt contribution. Figure 20 shows that, on April 12, of each year, the total recharge in these deep areas, though still increasing, was of the same relation as that shown by the shallow water-table areas. The Oak (deep) had received the greater amount of recharge, partly due to the earlier snow melt. The Red Pine

TABLE 9

WINTER AND SNOW-MELT RECHARGE,
MAXIMUM SNOWPACK AND WINTER PRECIPITATION
BY COVER TYPE IN THE SHALLOW WATER-TABLE ZONE

	1961-62			1962-63		
	Dec-Mar ppt(in)	Max SP WE(in)	Total Recharge (in)	Dec-Mar ppt (in)	Max SP WE(in)	Total Recharge (in)
Hdwd (S)	10.46	7.6 [1/]	8.73	10.43	7.4	9.14
Jack Pine(S)	9.83	5.8	6.84	10.60	5.6	7.70
Red Pine (S)	9.30	6.5	7.95	11.20	6.7	8.79

[1/] Snowpack data from well-drained hardwood area used for comparison to all-winter buildup in conifers.

(deep) was intermediate. The Jack Pine (deep) has the least accumulated winter and spring recharge.

These six case histories show a consistant pattern in which higher crown densities produce lower snowpacks and lower ground-water increments following snow melt. Except for the slightly greater winter transpiration which may be expected in conifers, the principal cause for these differences must be greater interception losses from the denser crowns. Numerous reports have shown that less snow accumulates under dense conifer crowns (Hart, 1963; Lull and Rushmore, 1960; Weitzman and Bay, 1958). This analysis has demonstrated a measureable difference in water yield associated with these snowpack differences.

In 1961-62, the recharge received from winter precipitation accounted for from 49 to 66 percent of the total net recharge for the entire water year. This was a year of abundant autumn rainfall. Recharge during the 1962-63 water year was much more dependent on snow water. Sixty-one to 88 percent of the net annual recharge came during the winter and early spring. Because of their longer transpiration period, conifer stands, in general, received less recharge during spring and autumn. Winter recharge made up a larger portion of the annual total and in these cover types the winter precipitation contributed less to ground-water supplies than it did in the deciduous forests.

Evapotranspiration

Estimates of the total annual evapotranspiration in each of the six cover-depth conditions were computed from the formula:

$$ET = P - Rg + ETg - \Delta SM \qquad \text{(VII-1)}$$

where ΔSM is the change in soil moisture storage between the beginning and the end of the water year. The 1961-62 period started with soils at field capacity following heavy rainfall in late September, 1961. The ground-water recharge increments in the autumn of 1962 showed that only in the Hardwood (shallow) area were the soils near field capacity at the end of September. The soil moisture deficit in the other five areas was not measured directly. Using the accumulated soil moisture deficit which was indicated by the Thornthwaite computation for September 30, the total annual ET values were computed. For the 1962-63 water year, the difference between the calculated deficit on October 1, 1962, and September 30, 1963, was used. The annual ET values computed by this method are shown in Table 10.

The shallow pine areas had the highest evapotranspiration rates in both years, corresponding to their low net recharge values (Table 8). The deep water-table pines used from 0.3 to 2.5 inches less than their shallow counterparts. The hardwood forests were consistantly lower in total water use than the pines. Surprisingly, the shallow water-table Hardwood area used less water for ET than the well-drained Oak area. This can be explained partly as a function of rooting depth. The shallow root development in the poorly-drained mineral soil must produce lower ET rates when the water table is lowered below the two-foot level.

Monthly evapotranspiration during the growing season was computed from the precipitation, net recharge and soil moisture storage changes (Tables 11 and 12). In the absence of on-site measurements of soil moisture storage, monthly changes in storage were computed from the theoretical depletion indicated by Thornthwaite's water balance method. In the deep water-table areas, it was also necessary to estimate the

TABLE 10

TOTAL ANNUAL EVAPOTRANSPIRATION (in Inches) BY FOREST COVER TYPE AND WATER-TABLE DEPTH CONDITION

Water Year	Cover Type					
	Hardwood(S)	Oak(D)	Jack P.(S)	Jack P.(D)	Red P.(S)	Red P.(D)
1961-62	17.37	18.41	20.53	19.50	22.08	19.57
1962-63	15.14	17.64	20.08	19.78	21.49	19.66

Table 11. Monthly hydrologic budgets for six local study areas utilizing changes in soil moisture status predicted by Thornthwaite's formula, 1961-62 water year.

STUDY AREA	P_{pt}	R_g	RO	ET_g	NET R_g	ET_s	TOTAL ET	S_g	S_s	SP	W_g	E_d	TOTAL Ann. ET
						OCTOBER 1961							
Hdwd(S)	3.12	2.99	2.26	0.39	2.60	0.13	0.82	+0.31	0	0	0	-	
Oak (D)	3.12	0.62	1.08	0	0.62	2.80	1.20_t	-0.46	0	0	1.60	-	
J. Pine(S)	3.26	1.87	2.47	0.16	1.71	1.39	1.55	-0.76	0	0	0	-	
J. Pine(D)	3.26	0.23	0.94	0	0.23	3.03	2.28_t	-0.71	0	0	0.75	-	
R. Pine(S)	3.32	1.37	2.36	0.12	1.25	1.95	1.71_t	-1.11	0	0	0.36	-	
R. Pine(D)	3.32	0.16	1.06	0	0.16	2.00	2.00_t	-0.90	0	0	1.16	-	
						NOVEMBER 1961							
Hdwd(S)	3.56	2.61	2.28	0.07	2.57	0.92	0.99	+0.29	0	0	0	-	
Oak (D)	3.56	3.83	1.06	0	3.83	-0.27	0.60_t	+2.77	0	0	0.73	-	
J. Pine(S)	3.57	2.81	1.82	0.04	2.80	0.73	0.77	+0.98	0	0	0	-	
J. Pine(D)	3.57	2.93	0.91	0	2.93	0.64	1.00_t	+2.02	0	0	0.39	-	
R. Pine(S)	3.41	3.10	1.57	0.01	3.09	0.34	0.71_t	+1.52	0	0	0	-	
R. Pine(D)	3.41	2.84	1.06	0	2.84	0.60	0.70_t	+1.78	0	0	1.06	-	
						DECEMBER 1961							
Hdwd(S)	2.79	0.68	1.16	0	0.68	0	0	-0.48	0	2.11	0	-	
Oak (D)	2.79	0.91	1.13	0	0.91	0	0	-0.22	0	2.61	0	-	
J. Pine(S)	2.36	0.65	1.39	0	0.65	0	0	-0.74	0	1.71	0	-	
J. Pine(D)	2.36	1.34	0.89	0	1.34	0	0	+0.45	0	1.41	0	-	
R. Pine(S)	2.38	0.72	1.37	0	0.72	0	0	-0.65	0	1.66	0	-	
R. Pine(D)	2.38	1.38	1.15	0	1.38	0	0	+0.23	0	2.06	0	-	
						JANUARY 1962							
Hdwd(S)	3.64	0.20	0.59	0	0.20	0	0	-0.39	0	5.55	0	-	
Oak (D)	3.64	0.21	0.79	0	0.21	0	0	-0.58	0	6.04	0	-	
J. Pine(S)	3.54	0.24	0.76	0	0.24	0	0	-0.52	0	5.01	0	-	
J. Pine(D)	3.54	0.30	0.67	0	0.30	0	0	-0.37	0	4.65	0	-	
R. Pine(S)	3.34	0.29	0.74	0	0.29	0	0	-0.45	0	4.71	0	-	
R. Pine(D)	3.34	0.36	0.79	0	0.36	0	0	-0.43	0	5.04	0	-	
						FEBRUARY 1962							
Hdwd(S)	2.52	0.60	0.70	0	0.60	0	0	-0.10	0	7.47	0	-	
Oak (D)	2.52	0.35	0.72	0	0.35	0	0	-0.37	0	8.21	0	-	
J. Pine(S)	2.64	0.08	0.34	0	0.08	0	0	-0.26	0	7.57	0	-	
J. Pine(D)	2.64	0.16	0.65	0	0.16	0	0	-0.49	0	7.13	0	-	
R. Pine(S)	2.38	0.30	0.71	0	0.30	0	0	-0.44	0	6.79	0	-	
R. Pine(D)	2.38	0.23	0.72	0	0.23	0	0	-0.49	0	7.19	0	-	
						MARCH 1962							
Hdwd(S)	1.49	6.94	3.71	0	6.94	0	0	+3.23	0	---2.02---		-	
Oak (D)	1.49	6.86	1.12	0	6.86	0	0	+5.74	0	2.84		-	
J. Pine(S)	1.29	5.08	0.88	0	5.08	0	0	+4.20	0	3.78		-	
J. Pine(D)	1.29	3.26	0.84	0	3.26	0	0	+2.42	0	5.16		-	
R. Pine(S)	1.20	5.43	-1.61	0	5.43	0	0	+7.07	0	2.56		-	
R. Pine(D)	1.20	3.05	0.90	0	3.05	0	0	+2.15	0	5.34		-	
						APRIL 1962							
Hdwd(S)	1.24	1.07	2.00	0.04	1.03	0.17	0.21	-0.97	0	0	0	2.02	
Oak (D)	1.24	1.73	1.56	0	1.73	-0.49	0.20_t	+0.17	0	0	---2.15---		
J. Pine(S)	0.88	1.33	1.68	0.24	1.09	-0.15	0.74_t	-0.59	0	0	0	2.83	
J. Pine(D)	0.88	4.32	0.78	0	4.32	-3.44	0.70_t	+3.54	-0.50	0	0	1.52	
R. Pine(S)	0.88	1.82	0.53	0.13	1.69	-0.94	0.63_t	+1.16	-0.25	0	0	1.37	
R. Pine(D)	0.88	4.87	0.78	0	4.87	-3.99	0.70_t	+4.09	-0.50	0	0	1.15	
						MAY 1962							
Hdwd(S)	1.19	1.07	1.90	0.82	0.25	0.12	0.94	-1.65	0	0	0	-	
Oak (D)	1.19	1.61	2.11	0	1.61	-0.42	0.90_t	-0.80	0	0	0	0.83	
J. Pine(S)	1.90	0.65	1.52	0.56	0.09	1.25	3.00	-1.43	-1.19	0	0	-	
J. Pine(D)	1.90	0.32	1.27	0	0.32	1.58	3.00	-0.95	-1.42	0	0	-	
R. Pine(S)	1.92	0.18	1.51	0.61	-0.16	1.44	3.00	-1.67	-0.92	0	0	-	
R. Pine(D)	1.92	0.68	1.14	0	0.68	1.24	3.00	-0.46	-1.76	0	0	-	

STUDY AREA	P_{pt}	R_g	RO	ET_g	NET R_g	ET_s	TOTAL ET	S_g	S_s	SP	W_g	E_d	TOTAL Ann. ET
						JUNE 1962							
Hdwd(S)	4.36	2.39	1.25	2.35	0.04	1.97	4.32	-1.21	-	-	-	-	
Oak (D)	4.36	0.79	3.07	0	0.79	3.57	3.88	-2.28	-0.31	-	-	-	
J. Pine(S)	3.80	1.85	1.87	0.50	1.35	1.95	2.76	-0.52	-0.31	-	-	-	
J. Pine(D)	3.80	0.84	2.11	0	0.84	2.96	3.27	-1.27	-0.31	-	-	-	
R. Pine(S)	4.32	0.88	1.87	0.65	0.23	3.44	4.40	-1.64	-0.31	-	-	-	
R. Pine(D)	4.32	0.34	2.02	0	0.34	3.98	4.29	-1.68	-0.31	-	-	-	
						JULY 1962							
Hdwd(S)	3.14	1.67	1.72	1.32	0.35	1.47	2.79	-1.37	-	-	-	-	
Oak (D)	3.14	0.29	2.82	0	0.29	2.85	3.41	-2 53	-0.56	-	-	-	
J. Pine(S)	2.94	0.71	2.23	0.42	0.29	2.23	2.93	-1.94	-0.28	-	-	-	
J. Pine(D)	2.94	0.37	2.96	0	0.37	2.57	3.13	-2.59	-0.56	-	-	-	
R. Pine(S)	2.66	0.07	1.51	0.71	-0.64	2.59	3.86	-2.15	-0.56	-	-	-	
R. Pine(D)	2.66	0.12	1.92	0	0.12	2.54	3.10	-1.80	-0.56	-	-	-	
						AUGUST 1962							
Hdwd(S)	2.91	0.44	1.10	0.23	0.21	2.47	2.70	-0.89	0	-	-	-	
Oak (D)	2.91	0.02	2.08	0	0.02	2.89	3.21	-2.06	-0.32	-	-	-	
J. Pine(S)	2.82	0.37	1.75	0.06	0.31	2.45	2.83	-1.44	-0.32	-	-	-	
J. Pine(D)	2.82	0.35	1.87	0	0.35	2.47	2.79	-1.52	-0.32	-	-	-	
R. Pine(S)	2.76	0.19	1.49	0.35	-0.16	2.57	3.24	-1.65	-0.32	-	-	-	
R. Pine(D)	2.76	0.24	1.89	0	0.24	2.54	2.86	-1.65	-0.32	-	-	-	
						SEPTEMBER 1962							
Hdwd(S)	3.40	0.89	1.07	0.07	0.82	2.51	2.58	-0.25	0	-	-	-	
Oak (D)	3.40	0.20	1.13	0	0.20	3.20	2.74	-0.93	+0.46	-	-	-	
J. Pine(S)	3.24	0.18	1.28	0	0.18	3.06	2.60	-1.10	+0.46	-	-	-	
J. Pine(D)	3.24	0.44	1.96	0	0.44	2.80	2.34	-1.52	+0.46	-	-	-	
R. Pine(S)	3.32	0.18	1.38	0.22	-0.04	3.14	2.90	-1.42	+0.46	-	-	-	
R. Pine(D)	3.32	0.24	2.14	0	0.24	3.08	2.62	-1.90	+0.46	-	-	-	
						TOTAL (1961-62 Water Year)							
Hdwd(S)	33.66	21.58	19.74	5.29	16.29	10.06	15.35	-3.45	0	-	-	2.02	17.37
Oak (D)	33.66	17.41	18.97	0	17.41	15.41	16.14	-1.55	-0.73	-	-	0.83	16.97
J. Pine(S)	32.24	15.85	18.00	1.98	13.87	13.56	17.18	-4.12	-1.64	-	-	2.83	20.01
J. Pine(D)	32.24	14.86	15.85	0	14.86	16.36	18.51	-0.99	-2.65	-	-	1.52	20.03
R. Pine(S)	31.92	14.83	13.43	2.83	12.00	16.33	20.45	-1.43	-1.90	-	-	1.37	21.82
R. Pine(D)	31.92	14.51	15.55	0	14.51	16.78	19.27	-1.04	-2.99	-	-	1.15	20.42

S_g = periodic change in ground water storage

S_s = periodic change in soil moisture storage

SP = snow pack (W.E.)

W_g = gravitational water in vadose zone

E_d = dormant season evaporation loss

t = estimated ET values from Thornthwaite formula

Table 12. Monthly hydrologic budgets for six local study areas utilizing changes in soil moisture status predicted by Thornthwaite's formula, 1962-63 water year.

STUDY AREA	P_{pt}	R_g	RO	ET_g	NET R_g	ET_s	TOTAL ET	S_g	S_s	SP	W_g	E_d	TOTAL Ann. ET
						OCTOBER 1962							
Hdwd(S)	3.42	1.92	0.50	0.01	1.91	1.50	1.51	+1.41	0	0	0	-	
Oak (D)	3.42	0.07	0.65	0	0.07	3.35	1.28	-0.58	+1.51	0	0.56	-	
J. Pine(S)	3.70	0.49	0.85	0	0.49	3.21	1.70	-0.36	+1.13	0	0.38	-	
J. Pine(D)	3.70	0.18	1.06	0	0.18	3.52	2.01	-0.88	+1.18	0	0.33	-	
R. Pine(S)	3.70	0.26	1.06	0.18	0.08	3.44	2.11	-0.98	+1.23	0	0.28	-	
R. Pine(D)	3.70	0.16	1.37	0	0.16	3.54	2.03	-1.21	+1.08	0	0.43	-	
						NOVEMBER 1962							
Hdwd(S)	0.56	0.41	0.60	0.16	0.25	0.15	0.31	-0.35	0	0	0	-	
Oak (D)	0.56	0.82	0.76	0	0.82	-0.26	0.30_t	+0.06	0	0	0	-	
J. Pine(S)	0.58	0.46	1.00	0	0.46	0.12	0.50_t	-0.52	0	0	0	-	
J. Pine(D)	0.58	0.41	1.06	0	0.41	0.17	0.50_t	-0.65	0	0	0	-	
R. Pine(S)	0.56	0.34	1.00	0.01	0.33	0.22	0.50_t	-0.67	0	0	0	-	
R. Pine(D)	0.56	0.49	1.54	0	0.49	0.07	0.50_t	-1.05	0	0	0	-	
						DECEMBER 1962							
Hdwd(S)	3.37	0.85	0.65	0	0.85	-	-	+0.20	0	2.52	0	-	
Oak (D)	3.37	0.28	0.41	0	0.28	-	-	-0.13	0	3.09	0	-	
J. Pine(S)	3.26	0.09	0.65	0	0.09	-	-	-0.56	0	3.17	0	-	
J. Pine(D)	3.26	0.10	0.77	0	0.10	-	-	-0.67	0	3.16	0	-	
R. Pine(S)	3.55	0.35	1.02	0	0.35	-	-	-0.67	0	3.20	0	-	
R. Pine(D)	3.55	0.12	1.03	0	0.12	-	-	-0.91	0	3.43	0	-	
						JANUARY 1963							
Hdwd(S)	2.63	0.71	0.72	0	0.71	-	-	-0.01	0	4.44	0	-	
Oak (D)	2.63	0.34	0.34	0	0.34	-	-	0	0	5.38	0	-	
J. Pine(S)	2.61	0.18	0.54	0	0.18	-	-	-0.36	0	5.60	0	-	
J. Pine(D)	2.61	0.25	0.65	0	0.25	-	-	-0.40	0	5.52	0	-	
R. Pine(S)	2.78	0.14	0.68	0	0.14	-	-	-0.54	0	5.84	0	-	
R. Pine(D)	2.78	0.08	0.76	0	0.08	-	-	-0.68	0	6.13	0	-	
						FEBRUARY 1963							
Hdwd(S)	1.43	0.08	0.56	0	0.08	-	-	-0.48	0	5.79	0	-	
Oak (D)	1.43	0	0.34	0	0	-	-	-0.34	0	6.81	0	-	
J. Pine(S)	1.45	0.02	0.43	0	0.02	-	-	-0.41	0	7.03	0	-	
J. Pine(D)	1.45	0	0.67	0	0	-	-	-0.67	0	6.97	0	-	
R. Pine(S)	1.57	0.12	1.02	0	0.12	-	-	-0.90	0	7.29	0	-	
R. Pine(D)	1.57	0	0.72	0	0	-	-	-0.72	0	7.70	0	-	
						MARCH 1963							
Hdwd(S)	3.00	7.46	2.10	0	7.46	-	-	+5.36	0	0	0	1.33	
Oak (D)	3.00	5.36	0.42	0	5.36	-	-	+4.94	0	0	---4.45---		
J. Pine(S)	3.28	5.12	0.34	0	5.12	-	-	+4.78	0	-------------5.19---			
J. Pine(D)	3.28	1.42	0.85	0	1.42	-	-	+0.57	0	-------------8.83---			
R. Pine(S)	3.30	5.44	0.70	0	5.44	-	-	+4.74	0	-------------5.15---			
R. Pine(D)	3.30	1.32	0.94	0	1.32	-	-	+0.38	0	-------------9.68---			
						APRIL 1963							
Hdwd(S)	2.60	2.33	3.20	0.02	2.31	0.27	0.29	-0.89	0	0	0		
Oak (D)	2.60	2.86	0.79	0	2.86	-0.26	0.30	+2.07	0	0	---3.89---		
J. Pine(S)	2.33	3.19	1.12	0.06	3.13	-0.86	1.40_t	+2.01	0	0	0	2.93	
J. Pine(D)	2.33	6.20	0.72	0	6.20	-3.87	1.40_t	+5.48	0	0	---3.56---		
R. Pine(S)	2.54	3.01	1.13	0.05	2.96	-0.47	1.40_t	+1.83	0	0	0	3.28	
R. Pine(D)	2.54	6.55	0.82	0	6.55	-4.01	1.40_t	+5.73	0	0	---4.27---		
						MAY 1963							
Hdwd(S)	2.19	1.80	2.39	0.34	1.46	0.39	0.73	-0.93	0	-	-	1.33	
Oak (D)	2.19	2.39	1.74	0	2.39	-0.20	0.70_t	+0.65	0	-	-	2.99	
J. Pine(S)	2.21	1.49	1.10	0.53	0.96	0.72	1.65	-0.14	-0.40	-	-	2.93	
J. Pine(D)	2.21	1.48	0.96	0	1.48	0.73	1.70	+0.52	-0.40	-	-	3.00	
R. Pine(S)	2.16	0.86	0.29	0.32	0.54	1.30	1.62	+0.25	0	-	-	3.28	
R. Pine(D)	2.16	2.16	1.20	0	2.16	0	1.60	+0.96	-0.40	-	-	3.07	

STUDY AREA	P_{pt}	R_g	RO	ET_g	NET R_g	ET_s	TOTAL ET	S_g	S_s	SP	W_g	E_d	TOTAL Ann. ET
						JUNE 1963							
Hdwd(S)	1.25	0.66	1.68	1.38	-0.72	0.59	2.97	-2.40	-1.00	-	-	-	
Oak (D)	1.25	0.24	2.58	0	0.24	1.01	3.34	-2.34	-2.33	-	-	-	
J. Pine(S)	1.12	0.01	1.49	0.74	-0.73	1.11	3.41	-2.22	-1.59	-	-	-	
J. Pine(D)	1.12	0	1.56	0	0	1.12	3.45	-1.56	-2.33	-	-	-	
R. Pine(S)	1.07	0.02	1.32	0.15	-0.13	1.05	3.53	-1.45	-2.33	-	-	-	
R. Pine(D)	1.07	0.28	1.26	0	0.28	0.79	3.12	-0.98	-2.33	-	-	-	
						JULY 1963							
Hdwd(S)	3.67	1.78	1.20	1.78	0	1.89	3.67	-1.20	0	-	-	-	
Oak (D)	3.67	0.29	2.56	0	0.29	3.38	3.49	-2.27	-0.11	-	-	-	
J. Pine(S)	3.75	1.25	1.90	0.64	0.61	2.50	3.14	-1.29	0	-	-	-	
J. Pine(D)	3.75	0.42	1.72	0	0.42	3.33	3.44	-1.30	-0.11	-	-	-	
R. Pine(S)	3.60	0.68	1.50	0.29	0.39	2.92	3.32	-1.11	-0.11	-	-	-	
R. Pine(D)	3.60	0.53	1.82	0	0.53	3.09	3.18	-1.29	-0.11	-	-	-	
						AUGUST 1963							
Hdwd(S)	3.56	0.43	1.12	0.28	0.15	3.13	3.41	-0.97	0	-	-	-	
Oak (D)	3.56	0.24	2.21	0	0.24	3.32	3.32	-1.97	0	-	-	-	
J. Pine(S)	3.39	0.41	1.49	0.08	0.33	2.98	3.06	-1.16	0	-	-	-	
J. Pine(D)	3.39	0.34	1.75	0	0.34	3.05	3.05	-1.41	0	-	-	-	
R. Pine(S)	3.56	0.10	1.16	0.20	-0.10	3.46	3.66	-1.26	0	-	-	-	
R. Pine(D)	3.56	0.12	1.69	0	0.12	3.44	3.44	-1.57	0	-	-	-	
						SEPTEMBER 1963							
Hdwd(S)	2.06	0.31	0.70	0.17	0.14	1.75	1.92	-0.56	0	-	-	-	
Oak (D)	2.06	0	1.30	0	0	2.06	2.06	-1.30	0	-	-	-	
J. Pine(S)	2.19	0.02	0.98	0	0.02	2.17	2.17	-0.96	0	-	-	-	
J. Pine(D)	2.19	0.18	1.03	0	0.18	2.01	2.01	-0.85	0	-	-	-	
R. Pine(S)	2.37	0.01	1.20	0.07	-0.06	2.36	2.43	-1.26	0	-	-	-	
R. Pine(D)	2.37	0.08	1.25	0	0.08	2.29	2.29	-1.17	0	-	-	-	
						TOTAL (1962-63 Water Year)							
Hdwd(S)	29.74	18.74	15.42	4.14	14.60	-	14.81	-0.82	-1.00	-	-	1.33	16.14
Oak (D)	29.74	12.89	14.10	0	12.89	-	14.79	-1.21	-0.93	-	-	2.99	17.78
J. Pine(S)	29.87	12.73	11.89	2.05	10.68	-	17.06	-1.19	-0.89	-	-	2.93	19.99
J. Pine(D)	29.87	10.98	12.80	0	10.98	-	17.56	-1.82	-1.66	-	-	3.00	20.56
R. Pine(S)	30.76	11.33	12.07	1.27	10.06	-	18.57	-2.02	-1.21	-	-	3.28	21.85
R. Pine(D)	30.76	11.89	14.40	0	11.89	-	17.56	-2.51	-1.76	-	-	3.07	20.63

S_g = periodic change in ground water storage

S_s = periodic change in soil moisture storage

SP = snow pack (W.E.)

W_g = gravitational water in vadose zone

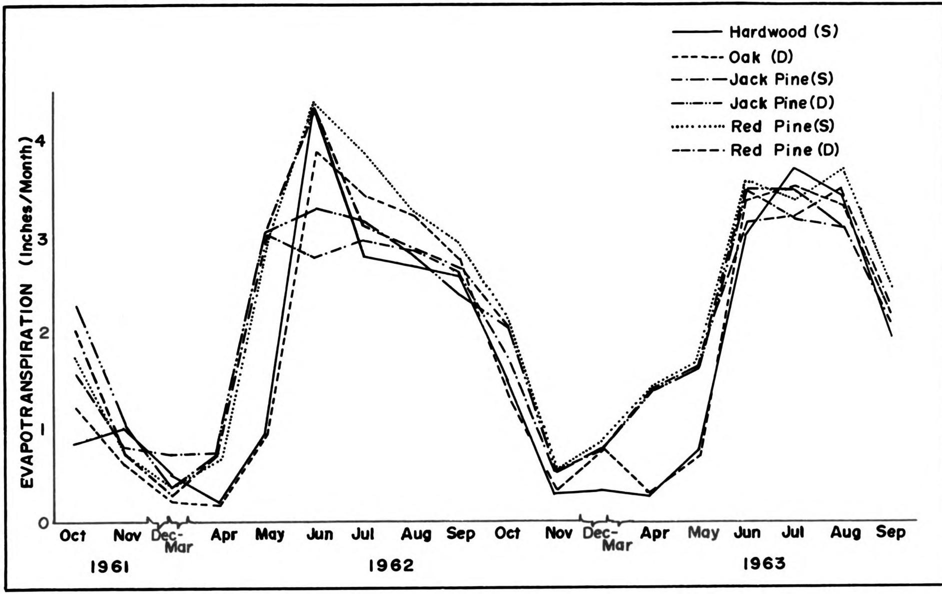
E_d = dormant season evaporation loss

t = estimated ET values from Thornthwaite formula volumes of percolating moisture which has not yet reached the water table. This approach is admittedly arbitrary. However, the computed values for the period from May to September in both water years was little affected by the problem of delayed percolation. The patterns of evapotranspiration shown in Figure 21 are illustrative of the early use of water by conifers and the concentration of evapotranspiration into the three summer months in the hardwood forests.

A more detailed picture of the comparative rates of moisture use in wet and dry periods was obtained by analysing each period between recharge events in the three shallow water-table areas. Theoretically, the unsaturated soil moisture status is at the same field capacity level at the end of such a recharge event. If this were actually the case, a storm coming only one or two days after another recharge producing storm should produce a recharge input nearly equal to the total throughfall. Many such instances during the two growing seasons demonstrated that this was not strictly true. Soil moisture is evidently depleted and recharged in irregular horizontal patterns, so that portions of the area produce recharge while others still exhibit soil moisture deficits. Reports on the variations in soil moisture conditions during the growing season have shown by direct measurement that the opportunity for groundwater recharge varies over even a localized area (Striffler, 1961; Lull and Axely, 1958).

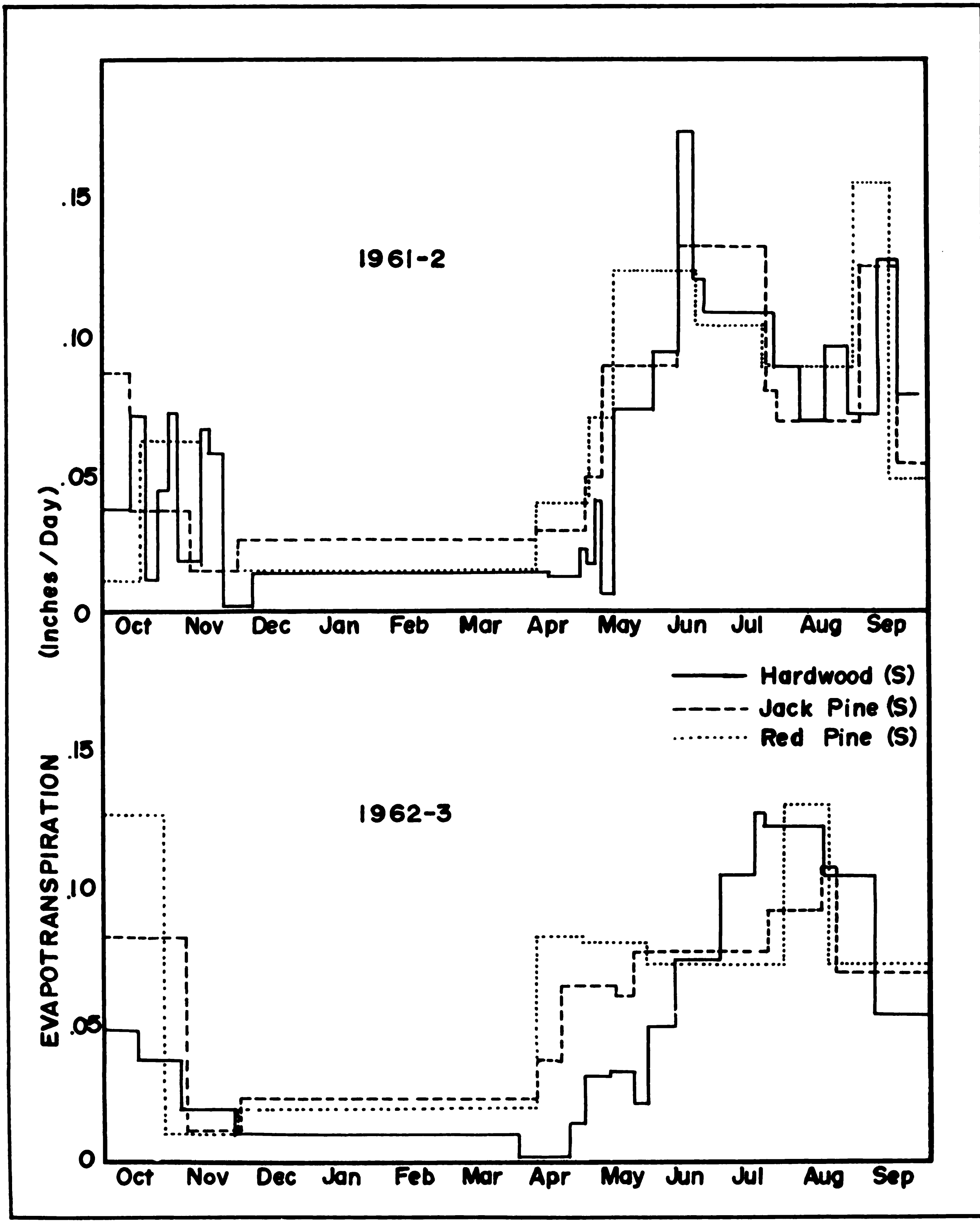
In spite of these discrepancies, a pattern of evapotranspiration in the three cover types emerged from this analysis (Figure 22). During both growing seasons, the conifer types began rapid evapotranspiration use in mid-April. The hardwood forest moisture use for ET was delayed four to six weeks, until the time of leaf development. During late

Figure 21. Monthly evapotranspiration for six local study areas.



Hardwood (S)
Oak (D)
Jack Pine(S)
Jack Pine(D)
Red Pine(S)
Red Pine (D)
EVAPOTRANSPIRATION (Inches/Month)
0
1
2
3
4
Oct
Nov
Dec-Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec-Mar
Apr
May
Jun
Jul
Aug
Sep
1961
1962
1963

Figure 22. Daily evapotranspiration for three shallow water-table study areas, average rates for periods between ground-water recharge events.

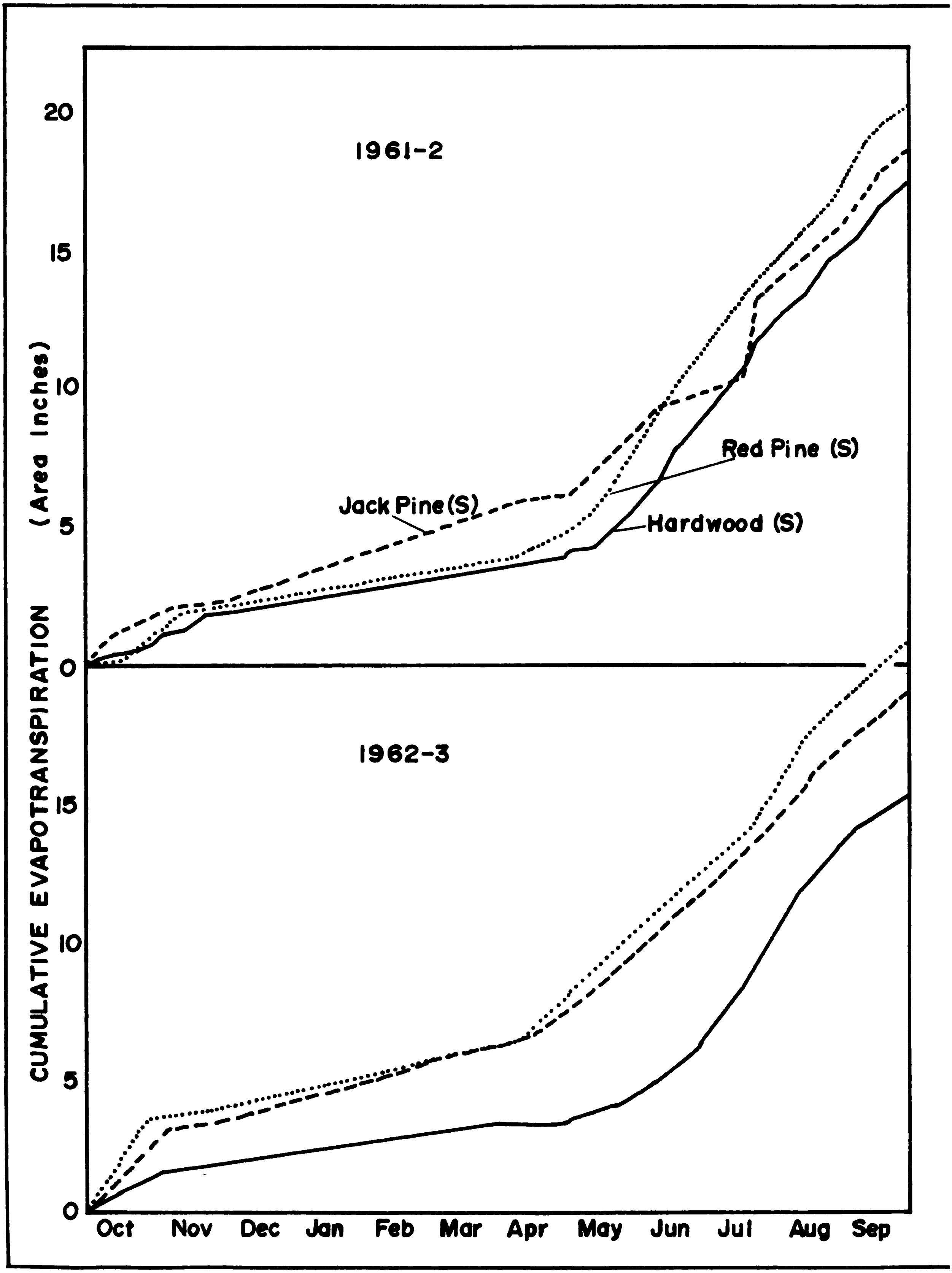

1961-2
1962-3
EVAPOTRANSPIRATION (Inches / Day)
0
.05
.10
.15
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Hardwood (S)
Jack Pine (S)
Red Pine (S)

June and early July, the maximum ET rate was greatest in the Hardwood stand. In the autumn of 1962, a higher rate of moisture use was evident in the conifers, although the late November period showed use in the Hardwood area to be slightly higher. This is but one example of the irregularities in the calculated ET pattern which arise from the soil moisture deficits which remained at the time the period-ending recharge occurred. Many of the irregularities disappeared when the periodic ET losses were accumulated to obtain the annual totals (Figure 23). The apparent lag in ET under Jack Pine in July is another example of the soil moisture deficit error. Both the lower dormant season ET rates and the shorter growing season are evident in the slopes of the cumulative curves for the Hardwood cover type.

No estimate of soil moisture deficits was included in the latter periodic ET calculation. The greatest resulting error occurred at the end of the first water year, and at the beginning of the second. According to the Thornthwaite calculation, the 1961-62 water year ended with a soil moisture deficit of over two inches. If measurements of this deficit were available, the rate of moisture use for late September, 1962, would be greater and those for October, 1962, would be lower. The greatest effect would be in the Red Pine (shallow) area with the deepest water table and the greatest opportunity for a soil moisture deficit to develop. A somewhat lesser deficit would be expected in the Jack Pine (shallow) area and very little deficit in the Hardwood (shallow) area.

In the absence of in situ measurements of the soil moisture status during the study period, the best statement which can be made on evapotranspiration is: the patterns of evapotranspiration use

Figure 23. Cumulative evapotranspiration for three shallow water-table areas based on computed evapotranspiration between ground-water recharge events.


1961-2
1962-3
CUMULATIVE EVAPOTRANSPIRATION (Area Inches)
20
15
10
5
0
15
10
5
0
Jack Pine(S)
Red Pine (S)
Hardwood (S)
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep

follow those shown in Figures 21 and 22, although the total annual consumptive use is probably in excess of the indicated amounts. These annual totals closely approximate those shown in Table 10.

Ground-Water Yield to Seepage Flow

An estimate of the rate of water-table recession caused by the drainage of the aquifer by seepage flow was basic to the computation of all the previous water budget items. These recession rates were determined for a single point in the extensive water-table aquifer, the individual recording well location. In the budgeting operation, daily and weekly changes in storage due to seepage flow were computed by multiplying the predicted recession rate by the appropriate specific yield value. These "runoff" values were accumulated for each month and for each water year (Table 13).

Total annual seepage flow from the six local study areas was generally in the same ratio as net recharge. The Hardwood (shallow) area contributed the greatest amount to seepage flow. In 1961-62, the Oak area was the second largest contributor. The Jack Pine (shallow) area was highest of the conifer areas in 1961-62, but lowest in 1962-63. This difference was due to the high water-table conditions at the start of the 1961-62 water year. During the fall of 1961, this Jack Pine area, located near the water-table divide, was drained rapidly by seepage flow. In the 1962-63 water year, the water table was lower in this area in the dormant season and the seepage loss was much less.

All areas except the Red Pine (deep) showed a net loss from storage during the period from October 1, 1961, to October 1, 1962 (Figure 12). During the second water year, this Red Pine (deep) area

TABLE 13

MONTHLY LOSSES FROM AQUIFER STORAGE TO SEEPAGE FLOW, BY COVER TYPE AND DEPTH (Area Inches)

	Hardwood (Shallow)	Oak (Deep)	Jack Pine (Shallow)	Jack Pine (Deep)	Red Pine (Shallow)	Red Pine (Deep)
			1961-62 Water Year			
Oct.	2.26	1.08	2.47	0.94	2.36	1.06
Nov.	2.28	1.06	1.82	0.91	1.57	1.06
Dec.	1.16	1.13	1.39	0.89	1.37	1.15
Jan.	0.59	0.79	0.76	0.67	0.74	0.79
Feb.	0.70	0.72	0.34	0.65	0.74	0.72
Mar.	3.71	1.12	0.88	0.84	-1.64	0.90
Apr.	2.00	1.56	1.68	0.78	0.53	0.78
May	1.90	2.41	1.52	1.27	1.51	1.14
Jun.	1.25	3.07	1.87	2.11	1.87	2.02
Jul.	1.72	2.82	2.23	2.96	1.51	1.92
Aug.	1.10	2.08	1.75	1.87	1.49	1.87
Sept.	1.07	1.13	1.28	1.96	1.38	2.14
Annual	19.74	18.97	18.00	15.85	13.43	15.55
			1962-63 Water Year			
Oct.	0.50	0.65	0.85	1.06	1.06	1.37
Nov.	0.60	0.76	1.00	1.06	1.00	1.54
Dec.	0.65	0.41	0.65	0.77	1.02	1.03
Jan.	0.72	0.34	0.54	0.65	0.68	0.76
Feb.	0.56	0.34	0.43	0.67	1.02	0.72
Mar.	2.10	0.42	0.34	0.85	0.70	0.94
Apr.	3.20	0.79	1.12	0.72	1.13	0.82
May	2.39	1.74	1.10	0.96	0.29	1.20
Jun.	1.68	2.58	1.49	1.56	1.32	1.26
Jul.	1.20	2.56	1.90	1.72	1.50	1.82
Aug.	1.12	2.21	1.49	1.75	1.16	1.69
Sept.	0.70	1.30	0.98	1.03	1.20	1.25
Annual	15.42	14.10	11.89	12.80	12.07	14.40

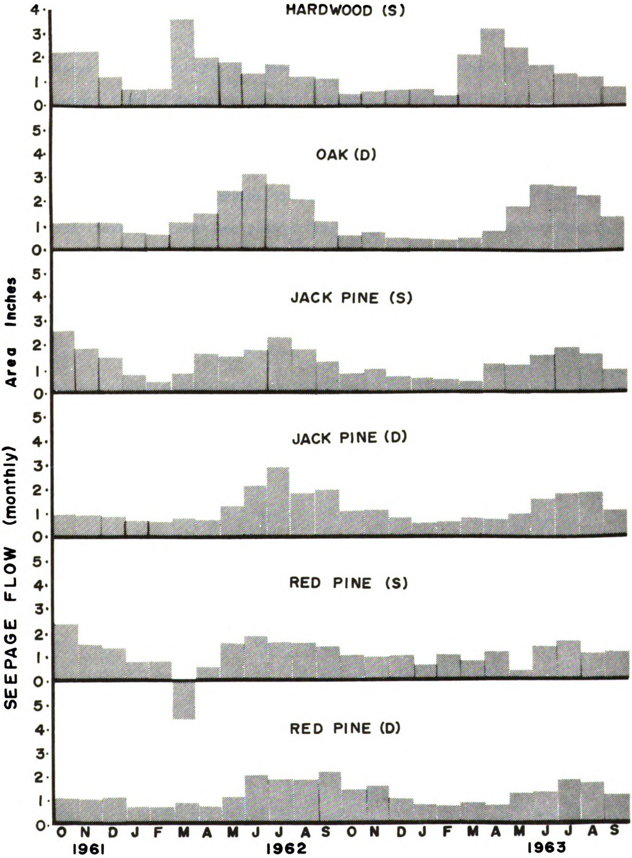
had a greater storage loss than the other areas. This storage loss, plus the net recharge for the year, resulted in a greater seepage flow than occurred in any area except the Hardwood (shallow).

The timing of maximum seepage flow losses in the six study areas provides some measure of their relative contribution to stream-flow during the year. The deeper water-table areas and those located most distant from the streams have later maximum recession from seepage (Figure 24). Continual drainage during the winter months provides a steady contribution to stream-flow during the snowpack period.

In the Red Pine (shallow) area, the proximity of open lands which had earlier snow melt than the conifer area, produced subsurface inflow during early spring. In March, 1962, this inflow was sufficient to more than counterbalance the drainage from the area. The net seepage flow for that month resulting in a gain in storage which was recorded as negative seepage flow. As was explained in the description of the study area, a drainage ditch which conducts high water-table flow northeastward toward Pine Creek, passes by the eastern border of the Red Pine (shallow) study area. There are numerous hardwood and bog-type swamps along the ground-water basin divide which runs southeast from the Udell Hills. When these swamps are flooded in the spring, surface flow is produced in this ditch to the extent required for complete influent seepage. In 1962, surface flow extended to the north section line of Section 20, T21N, R14W. Influent seepage produced an addition to ground-water storage beneath the Red Pine (shallow) study area. The net seepage loss from storage was reduced accordingly during the month of April.

All areas are affected by the evapotranspiration rates in shallow water-table lands. The Oak (deep) area is particularly influenced by the

Figure 24. Monthly losses from aquifer storage to seepage flow for six local study areas.


HARDWOOD (S)
OAK (D)
JACK PINE (S)
JACK PINE (D)
RED PINE (S)
RED PINE (D)
SEEPAGE FLOW (monthly) Area Inches
O N D J F M A M J J A S O N D J F M A M J J A S
1961
1962
1963

accelerated water-table gradient which results when water levels in the hardwood swamp to the north are lowered in June and July. Whereas recharge is apparently a function of cover type and water-table depth, seepage flow is dependent on the position of the particular area in the basin, the recharge and discharge behavior in adjacent portions of the aquifer and the timing of percolation recharge within the study area itself. When these complexities are considered, seepage flow losses from these six local sections of the aquifer cannot be simply added to obtain a basin drainage volume. Use of these local analyses of seepage loss is nevertheless valid for derivation of the local water budget.

CHAPTER VIII

DISCUSSION OF WATER BUDGET RESULTS

Analysis of the two water years, 1961-62 and 1962-63 has produced measures of comparative recharge of ground-water supplies beneath three contrasting forest cover types. In general, the deciduous forest types produced greater amounts of net ground-water recharge than the coniferous types. In the first water year (1961-62), the mean addition to ground-water supplies in the four pine areas was 18 percent less than the mean for the two hardwood areas. In the 1962-63 water year, the conifers yielded 21 percent less than the hardwoods. The mean differences for the two years was 2.9 inches (15.3 vs. 12.4).

The mean difference in winter recharge, attributable to snow melt, was 0.9 inches. In the Jack Pine areas where crown densities remained high throughout the year, the decrease was greater, 1.2 inches less for the mean of the two water years. Under this forest type, winter and spring melt recharge differences accounted for 46 percent of the difference in total annual net recharge. In the Red Pine areas this portion of the water year accounted for only 16 percent of the mean annual difference.

Cumulative curves of both annual recharge and annual evapotranspiration illustrated the effects of longer transpiration periods in the conifer stands (Figures 16 and 23). The greater use of moisture for evapotranspiration in the Red Pine-Oak areas is presumeably due to the deeper rooting depths and, hence, larger soil moisture storage capacities in the root zone. Investigations of the comparative rooting depths in the Udell Experimental Forest (Figure 17) support the findings of DeByle and Place (1959). In sand soils, jack pine roots are concentrated in the surface six to eight inches of soil. Mixed Oak and Red Pine stands had deeper rooting which help to explain both the high evapotranspiration rates and the ability of these stands to obtain water from the saturated zone at greater depths than the other types.

An earlier investigation by the author of soil moisture depletion patterns in red pine and oak forests near the Udell Experimental Forest, showed that an opportunity existed for ground-water recharge differences during the spring and fall months (Urie, 1959). Using the soil moisture levels which were measured during the 1958 growing season, precipitation during the period was found to exceed field capacities on sufficient occasions to produce 3.3 inches of recharge under oak forests and only 1.5 inches of recharge under red pine plantations. The greatest difference during the April to October study period occurred prior to leaf development in the oak forests. The present study substantiates these indications; recharge was greater in the hardwood forests in both spring periods.

The mean annual difference in net recharge during the snow-free periods was 2.7 inches between the two red pine areas and the two hardwood areas. Thus, 82 percent of the recharge effect occurred during the rainfall months. A lesser difference, 1.5 inches, was measured between hardwoods and jack pine. Since precipitation was reasonably well distributed throughout the two-year period and both years were near the mean annual rainfall, these recharge effects of forest cover may also approach the long-term norm. Continued measurements will be needed to substantiate this.

The effects of ground-water depths were illustrated by the timing of recharge and the comparative rate of evapotranspiration drain. Because of differences in soil profile development and water-table regimen in the three shallow water-table plots, the observed differences in root penetration cannot be explained simply as species differences. Regardless of these interacting effects, there was a clear relationship between the moisture drained and ground-water depths. Sharp cutoff levels were found in the Hardwood and Jack Pine (shallow) areas. In the Red Pine (shallow) area, the diurnal acceleration of the rate of water-table decline continued at a very slow but measureable pace to the lowest well levels occurring during the study period.

The short history of water-table-level trends which has been accumulated in the Udell area (Figure 12) shows that the mean annual ground-water levels in the Red Pine (shallow) were lower than in the other shallow types. The deeper root development in this forest type may be due to these lower levels. In the deep water-table areas, the red pine rooting depth is also greater than in jack pine under similar drainage conditions. Unfortunately, there was no available red pine plantation on AuGres soils, such as existed in the extensive Jack Pine (shallow) area. The explanation for different recharge-evapotranspiration balances between these two pine types is not at hand. It is apparent, however, that the two areas are different in their hydrologic behavior. The Jack Pine (shallow) pattern of ET drain on ground-water is more like that of the Hardwood (shallow) area. Both have short periods of rapid use while ground-water levels are high. The conifer areas are alike in showing earlier ET drain than the Hardwoods.

Both pine types utilized more water than hardwoods for evapotranspiration in the shallow water-table position, 0.7 inches in Jack Pine and 2.2 inches in Red Pine. No definite effect was found between the two hardwood study areas. It was apparent from observations of soil conditions that soil moisture deficits were rare in the Hardwood (shallow) area. The inter-recharge evapotranspiration patterns (Figure 22) show that, for brief periods early in the summer, the daily rate of evapotranspiration is very high in this type. The seasonal decline in ground-water levels must result in a drop in the withdrawals from the saturated zone, for the diurnal fluctuations were almost non-detectable by August of both years. Satterlund (1960) found northern hardwood forests in Michigan's Upper Peninsula could use ground-water only to 30-inch depths. This study was also carried out in an area of shallow water tables where root penetration was doubtless inhibited by saturated soils during much of the year.

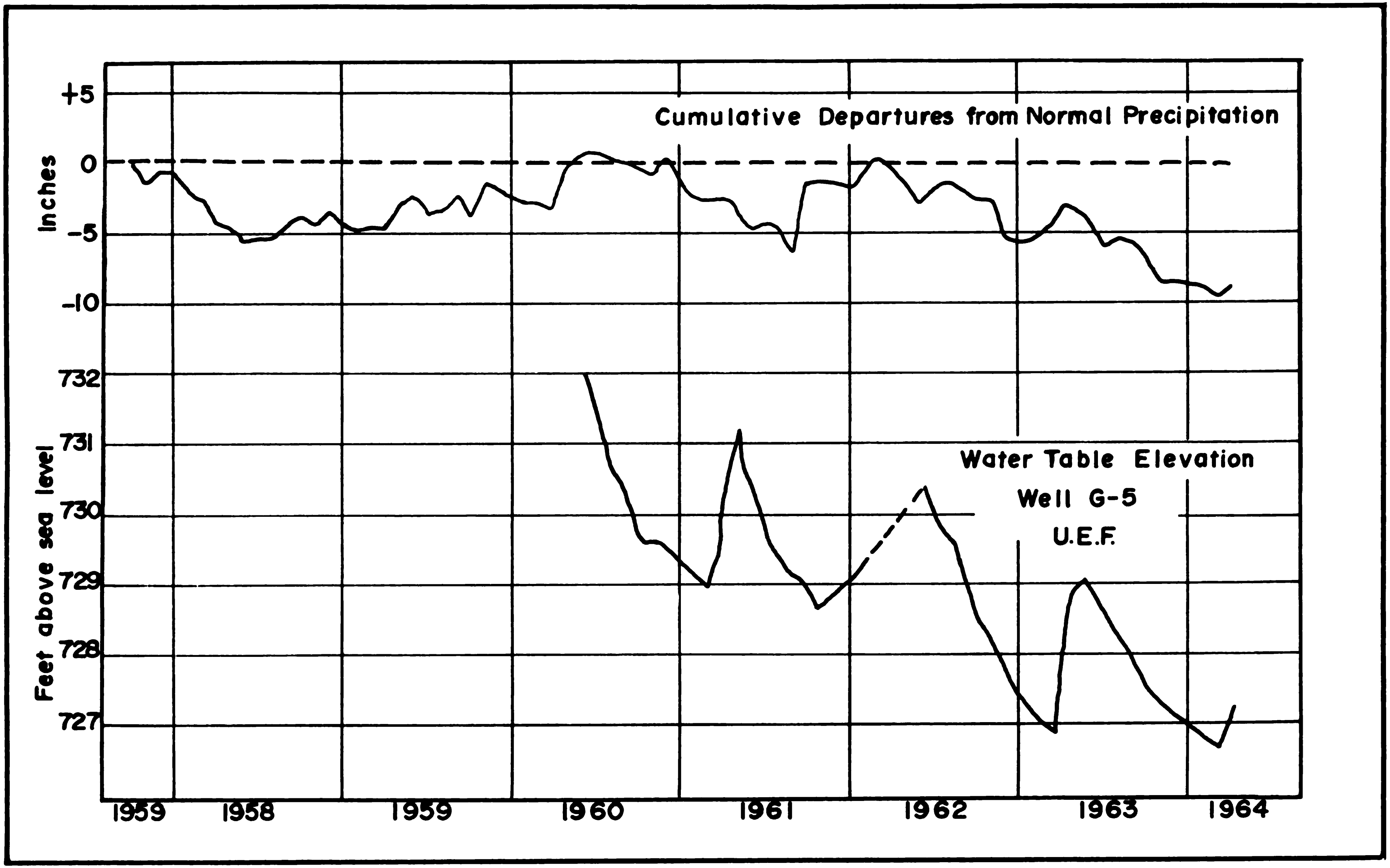
There are species, stocking level and distribution differences, between the two hardwood study areas (Table 1). Since these differences are also characteristic of the change from well-drained to poorly-drained sands on the entire Udell Forest, the water budgets, if true in themselves, are valid measures of these two drainage conditions under existing native forests.

The two water-year periods which were included in this analysis did not differ greatly in total precipitation. Despite this similarity, the water yield which was obtained as net ground-water recharge was 20 percent less in the second water year (mean of all six areas). The recharge difference is partly due to the difference in antecedent soil moisture conditions. In 1961, October 1 was a date on which water tables were high and soils were at field capacity levels. The following water year began with a soil moisture deficit of two or three inches.

In 1961-62, there was normal or above normal precipitation during the fall and winter months. In 1962-63, there was no appreciable recharge before the snowpack began to accumulate. A higher proportion of the annual precipitation fell during the growing season in 1962-63. Accordingly, the rates of total evapotranspiration were similar in both years. Summer rainfall produced little ground-water recharge; this was reflected in the low total for the second year.

Moisture removed from ground-water by evapotranspiration reduced the amount of net recharge. In 1961-62, water-table levels were higher than in the following year, especially in the autumn and spring. The rate of ET drain was directly related to the height of the water table. This tended to reduce the net recharge during the year of higher water yields. The influence of water-table height on the evapotranspiration vector can be predicted to the extent that annual water-table trends are predictable. Drecher (1957) showed a high correlation of water-table levels with a five-year running average of precipitation. In deeper water-table conditions, the trends may reflect longer term precipitation conditions, (Wenzel, 1936). The relatively short history of Udell ground-water conditions corresponds to cumulative departures from normal precipitation (Figure 25).

Figure 25. Water-table elevation on eastern outwash plain, Udell Experimental Forest, in relation to cumulative departures from normal precipitation.



Cumulative Departures from Normal Precipitation
Inches
+5
0
-5
-10
Water Table Elevation
Well G-5
U.E.F.
Feet above sea level
732
731
730
729
728
727
1959
1958
1959
1960
1961
1962
1963
1964

CHAPTER IX

SUMMARY

The objectives of this study were:

1. To develop methods for measuring the hydrologic budget of definable cover type areas in highly infiltrable sands.

2. To compare the net water yield (or net ground-water recharge) and evapotranspiration for three forest conditions common to the northern part of Michigan's Southern Peninsula.

3. To determine the effect of water-table depth under these forest cover types on the evaporation loss and, thus, on the net water yield.

The first objective was met in that a method was developed for obtaining the water budget for a localized sector of a broad water-table aquifer. Once such a method became available, from measurements of ground-water recharge, seepage flow losses and evapotranspiration drain, it was then possible to compare cover types now on the lands. It will also be possible to evaluate the hydrologic effects of future forest management practices. The need for such a method is obvious from the heterogeneous pattern of cover conditions within the large drainage basins characteristic of this northern portion of Michigan.

The first step in developing the required analysis was an objective separation of the components of water-table fluctuations. Except for temporary rises due to barometric pressure changes, wind effects (Parker and Stringfold, 1950), and entrapped air beneath a percolating wetting front (Lee, 1934), recharge by percolated precipitation water was the only cause for positive changes in well levels.

Declining well levels resulted from one, and sometimes two, processes. Seepage flow produced a continual change in storage which could be predicted from indications of the inflow-outflow balance in the local study area. Secondary recessions due to evaporation losses from the saturated zone occurred during the growing season in shallow water-table areas.

The separation of these two recession vectors was possible because of diurnal fluctuations in the rate of water-table decline. The nocturnal rate of recession should be approximately that predicted from the slopes of the water table (Figure 9). Agreements between these independent measures of the recession rate due to seepage flow, indicated that local recession because of evapotranspiration drain in shallow water-table areas did not induce appreciably accelerated inflow during the daylight hours.

On the other hand, low evapotranspiration rates in the Hardwood (shallow) area, although partially explained by shorter growing seasons and shallow root penetration, suggested that the seepage flow and evapotranspiration drain may not have been entirely separated. With this exception, the techniques utilized in this analysis provided an adequate method for the separation of the components of water-table fluctuations.

Conversion of these separate trends in well levels to a measure of the volume of water was accomplished by multiplying the head changes for the well area by the specific yield values.

The method for obtaining the specific yield values for the shallow water-table aquifers was essentially that described by Olmsted and Hely (1962) as Method "A." As was pointed out by these authors, the short-term coefficient of storage, which they called the gravity yield, is ordinarily less than the specific yield. Olmsted and Hely solved the equation.

$$Yg = \frac{\Delta Sg}{\Delta Hg} \qquad (X-1)$$

where Yg is their gravity yield (a dimentionless ratio), ΔSg is the change in ground-water storage in a given period in area inches, and ΔHg is the corresponding increase in ground-water storage in inches, by computing the integral of base-flow recession during the dormant season. In the Udell Hills study, no stream-flow data was available. Recharge inputs were used for the Sg term. The resulting gravity yield values varied inversely with the degree of soil profile development.

In the deep water-table aquifers, specific yield values were obtained by draining undisturbed sample cores. Following initial saturation, the cores were drained for 48 hours with the base of the core maintained at water-table level. The height of capillary rise in medium sands is 12-35 centimeters (4.7 to 13.8 inches) (Harr, 1962). Examination of the undisturbed cores after drainage showed capillary rise in the Udell samples to be approximately 12 inches. Specific yield determinations were made from the upper and lower three inches of these 24-inch columns. The upper sample was well above the height of maximum capillary rise. The lower sample was almost completely within the lower 20% of the capillary zone where saturation is relatively high (Taylor, 1948).

To the extent which the two-inch diameter cores were actually representative of undisturbed aquifer materials, acceptable gravity yield values were determined in this manner.

In these deeper aquifers, where there was only one major cycle of water-table fluctuations each year, the drainage period was sufficiently long so that the gravity yield probably closely approximated the specific yield. In the shallow water-table areas, there were more frequent alternating recharge and drainage cycles. In these areas, the use of a constant specific (or gravity) yield value for a given aquifer layer is less justified. However, in view of the much greater variations due to the degree of soil profile development, the estimated mean specific yield for a daily recharge or recession event was probably little affected by the minor changes due to time of drainage.

The second objective was the determination of the hydrologic budget for three representative forest types. In the deep water-table areas this was accomplished as soon as a method for measuring the volume of recharge was developed. Periodic evapotranspiration was then determined from the difference between recharge and precipitation. In shallow water-table areas, the net recharge remaining after evapotranspiration from the saturated zone was equated with water yield. Total evapotranspiration was the sum of precipitation which did not reach the saturated zone plus the volume of water removed from the saturated zone.

The precision of the gross and net recharge determinations could not be checked directly. Comparisons with the periodic water yield and evapotranspiration predicted by Thornthwaite's empirical formula were reasonably close in the pine areas. In the hardwood areas, the water yields were higher in the spring months, indicating that potential evapotranspiration rates were not reached until full leaf development was attained.

These analyses showed that dormant season recharge is proportional to the amount of crown cover during this period. The computed snow-melt recharge was related to the maximum snowpack accumulated beneath the crown canopy.

The effects of water-table depth were shown by the well records from the three shallow water-table plots. Although the overall relationships between cover types were not apparent due to differences in soil conditions, water-table regimes and rooting depths, there were consistant decreases in evaporative ground-water losses with lowering water-table levels. Ground-water depletion due to evapotranspiration ceased when water-table depths were lowered to 4.5 feet in the Hardwood (shallow) area and to 5.5 feet in the Jack Pine (shallow) area. The lower limit of evaporation effect was related to the depth of rooting.

The bookkeeping required for these computations was tedious and time consuming. This was especially true of the shallow water-table wells where daily accounting was used. Since the routine is a sequence of arithmetic operations once the well record is interpreted, the entire procedure is amenable to machine computation. A logical extension of the present study will be the development of a computer program to reduce daily well changes, precipitation, diurnal fluctuations and grid well observations of water-table slope conditions to periodic water budget values. Desirable refinements of the empirical methods used here would be:

1. Incorporation of gravity yield functions which are dependent on depth of the water table and the time of drainage.

2. Numerical analysis of current grid well data to obtain a mathematical solution of the second derivative of the water-table elevation for use in predicting the seepage flow recession.

Stallman (1956) has described methods for utilizing well levels from a regularly spaced grid to obtain positive and negative accretions to storage. Where the transmissibility and specific yield are known, these methods can be applied directly to obtain periodic water budgets. At the present time, only localized estimates are available for the aquifers of the Udell Experimental Forest. Extention of the water budgets, as computed in the present study, depends on the availability of these aquifer constants. As these become available, the periodic water yield will be computed and related to stream-flow in the bordering channels. The effects of forest cover conditions and ground-water depths reported here will form an important part of this broader study.

LITERATURE CITED

Childs, E. C.
1960. The nonsteady state of the water table in drained land. Journal of Geophysical Research. 65: 780-782.

DeByle, N.V. and I. C. M. Place
1959. Rooting habits of oak and pine on Plainfield sand in central Wisconsin. University of Wisconsin Forestry Research Note No. 44. Madison, Wisconsin. 2 pp.

Dils, Robert E. and John L. Arend
1956. Snow accumulation under red pine of different stand densities in Lower Michigan. U.S. Dept. of Agr., Forest Service, Lake States Forest Experiment Station, Technical Note No. 460, St. Paul, Minnesota. 2 pp.

Drecher, William J.
1955. Some effects of precipitation on ground-water in Wisconsin. Wisconsin Geological Survey Information Circular No. 1. Madison, Wisconsin. 17 pp.

Ferris, John G.
1959. Ground water. pp. 127-191, In: Hydrology by Chester O. Wisler and Ernest F. Brater. John Wiley and Sons, New York. 2nd edition. 408 pp.

Harr, Milton E.
1962. Ground-water and seepage. McGraw-Hill Book Company, Inc. New York. 315 pp.

Hart, George
1963. Snow and frost conditions in New Hampshire under hardwood and pines and in the open. Journal of Forestry. 61: 287-289.

Hazen, Allen
1892. Experiments upon the purification of seepage and water at the Lawrence Experiment Station. Massachusetts State Board of Health, 23rd Annual Report, 1891. pp. 428-434.

Holstener, Jørgensen, H.
1961. An investigation of the influences of various tree-species and the ages of the stands on the level of the ground-water table in forest tree stands in Bergentved. "Det forstlige Forsøgovoensen i Danmark." 27: 237-480. Danish with English summary.

King, F. H.
1898. Principles and conditions of the movements of ground-water. U.S. Geological Survey, 19th Annual Report, Part 2. pp. 59-294.

Kittredge, Joseph
1948. Forest influences. McGraw-Hill Book Company, Inc. New York. 394 pp.

Lee, Charles H.
1934. The interpretation of water-levels in wells and test-holes. Transactions, American Geophysical Union. 15: 540-554.

Lemmon, Paul E.
1956. A spherical densiometer for estimating forest overstory density. Forest Science. 2: 314-320.

Lull, H. W. and J. H. Axely
1958. Forest soil moisture relationships in the coastal plain sands of southern New Jersey. Forest Science. 4: 1-19.

Lull, Howard W. and Francis M. Rushmore
1960. Snow accumulation and melt under certain forest conditions in the Adirondacks. U.S. Dept. of Agr., Forest Service, Northeast Forest Experiment Station, Station Paper 138. Upper Darby, Pennsylvania. 16 pp.

McGuinness, C. L.
1941. The importance of snow in relation to ground-water recharge. Central States Snow Conference, Michigan State College. Proceedings. Lansing, Michigan. 1: 166-172.

____
1963. The role of ground-water in the national water situation. U.S. Dept. of Interior. Geological Survey Water Supply Paper 1800. Washington, U.S. Government Printing Office.

Meinzer, O. E. and N. D. Stearns
1929. A study of ground-water in the Pomperaug Basin, Connecticut, with special reference to intake and discharge. U.S. Geological Survey Water Supply Paper 597-B. pp. 73-146.

Meinzer, Oscar Edward
1932. Outline of methods for estimating ground-water supplies. U.S. Geological Survey Water Supply Paper 638-C. pp. 99-144.

Olmsted, F. H. and A. G. Hely
1962. Relation between ground-water and surface-water in Brandywine Creek Basin, Pennsylvania. U.S. Geological Survey Professional Paper 417-A. pp. A-1 - A-21.

Parker, G. G. and V. T. Stringfield
1950. Effects of earthquakes, trains, tides, winds and atmospheric pressure changes on water in the geologic formations of southern Florida. Economic Geology. 45(5): 441-460.

Rasmussen, W. C. and G. E. Andreasen
1959. Hydrologic budget of the Beaverdam Creek Basin, Maryland. U.S. Geological Survey Water Supply Paper 1472. pp. 59-168.

Satterlund, Donald Robert
1960. Some interrelationships between ground-water and swamp forests in the western upper peninsula of Michigan. University Microfilms, Inc. Ann Arbor, Michigan. 171 pp.

Schicht, R. J. and W. C. Walton
1961. Hydrologic budgets for three small watersheds in Illinois. Report of Investigation 40. Illinois State Water Survey, Urbana, Illinois. 40 pp.

Smith, W. O.
1961. Mechanism of gravity drainage and its relation to specific yield of uniform sands. U.S. Geological Survey Professional Paper 402-A. pp. A-1 - A-12.

Society of American Foresters
1954. Forest cover types of North America. Society of American Foresters, Washington, D.C. 67 pp.

Stallman, Robert W.
1956. Numerical analysis of regional water levels to define aquifer hydrology. Transactions, American Geophysical Union. 37(4): 451-460.

Striffler, W. D.
1959. Effects of forest cover on soil freezing in northern Lower Michigan. U.S. Dept. of Agr., Forest Service, Lake States Forest Experiment Station, Station Paper 76. 16 pp.

Striffler, William D.
1961. Intensity of soil moisture sampling is affected by depth and vegetative cover. U.S. Dept. of Agr., Forest Service, Lake States Forest Experiment Station, Technical Note No. 603. St. Paul, Minnesota. 2 pp.

Taylor, D. W.
1948. Fundamentals of soil mechanics. John Wiley and Sons, Inc. New York. 700 pp.

Thornthwaite, C. W. and J. R. Mather
1957. Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology. Vol. X, No. 3. Centerton, N. J. 311 pp.

Todd, David Keith
1959. Ground-water hydrology. John Wiley and Sons, Inc. New York. 336 pp.

Troxell, H. C.
1936. The diurnal fluctuations in the ground-water and the flow of the Santa Anna River and its meaning. Transactions, American Geophysical Union. 17: 498-501.

U.S. Dept. of Commerce, Weather Bureau
1962. Climatological Data, Michigan, Annual Summary 1961. 76(13): 184-194.

U.S. Dept. of Commerce, Weather Bureau
1963. Climatological Data, Michigan, Annual Summary 1962. 77(13): 190-199.

U.S. Dept. of Commerce, Weather Bureau
1964. Climatological Data, Michigan, Annual Summary 1963. 78(13): 188-197.

Urie, Dean H.
1959. Pattern of soil moisture depletion varies between red pine and oak stands in Michigan. U.S. Dept. of Agr., Forest Service, Lake States Forest Experiment Station, Technical Note No. 564. 2pp.

Weitzman, Sidney and Roger R. Bay
1958. Winter snow and water supply. The Conservation Volunteer, Minnesota Dept. of Conservation. 21(126): 45-48.

Wenzel, Leland K.
1936. Several methods of studying fluctuations of ground-water levels. Transactions, American Geophysical Union. 17: 400-405.

White, Walter N.
1932. A method of estimating ground-water supplies based on discharge by plants and evaporation from soil. U.S. Geological Survey Water Supply Paper 659-A. 105 pp.