

EVAPOTRANSPIRATION AND THE  
WILSON CREEK WATER BUDGET

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## ABSTRACT

This study was undertaken as an attempt to estimate evapotranspiration or consumptive use by "natural" vegetation along the Manitoba Escarpment using semi-empirical methods.

The Wilson Creek Experimental Watershed was chosen as the study unit and is representative of the environment along the Manitoba Escarpment.

The study was composed of two parts. Firstly, the Wilson Creek water budget was calculated on a monthly basis for the period of study May to September, 1965 to 1971. Secondly, Class "A" Pan evaporation, the Blaney-Criddle formula, the Meyer formula, the Thornthwaite formula, the Penman formula, and the energy budget were used to calculate potential evapotranspiration for the same period of study. The potential evapotranspiration was compared to the actual evapotranspiration as calculated from the water budget. Monthly and seasonal coefficients were derived for each of the six semi-empirical methods which allow conversion of their potential evapotranspiration estimates to actual evapotranspiration.

## ACKNOWLEDGEMENTS

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# TABLE OF CONTENTS

	Page
TITLE PAGE .....	i
ABSTRACT .....	ii
ACKNOWLEDGEMENTS .....	iii
TABLE OF CONTENTS .....	iv
LIST OF TABLES .....	vi
LIST OF FIGURES .....	viii
CHAPTER I INTRODUCTION .....	1
CHAPTER II THE HYDROLOGIC CYCLE AND WATER BUDGET .....	3
CHAPTER III THE WILSON CREEK EXPERIMENTAL WATERSHED .....	6
Location .....	7
Climate .....	7
Topography .....	9
Geology .....	9
Soils .....	13
Vegetation .....	13
CHAPTER IV INSTRUMENTATION .....	22
CHAPTER V THE WILSON CREEK WATER BUDGET .....	29
Precipitation .....	29
Streamflow .....	31
Change in Snow Storage .....	32
Change in Soil Moisture Storage .....	34
Groundwater Outflow .....	37
Change in Groundwater Storage .....	42
Surface Water Storage .....	48
Evapotranspiration .....	48
Checking the Water Budget .....	49
CHAPTER VI ALTERNATE METHODS OF ESTIMATING	
EVAPOTRANSPIRATION .....	57
Pan Evaporation .....	58
Blaney Criddle Formula .....	59
Meyer Formula .....	61
Thornthwaite Formula .....	64
Penman Formula .....	66
Energy Budget .....	71

	Page
CHAPTER VII DISCUSSION OF RESULTS .....	75
CHAPTER VIII CONCLUSIONS .....	87
SELECTED BIBLIOGRAPHY .....	89
APPENDIX 1 SOIL MOISTURE DATA .....	92
APPENDIX 2 WATERTABLE WELL HYDROGRAPHS 1965-1971 .....	102
APPENDIX 3 DATA FOR THE BLANEY-CRIDDLE FORMULA .....	125
APPENDIX 4 DATA FOR THE MEYER FORMULA .....	128
APPENDIX 5 DATA FOR THE PENMAN FORMULA .....	131
APPENDIX 6 DATA FOR THE ENERGY BUDGET .....	135

## LIST OF TABLES

Table		Page
1	Summary Of The Soil Classification Of The Wilson Creek Watershed .....	15
2	Engineering Interpretations Of The Soil Observations In The Wilson Creek Watershed .....	16
3	Vegetation Of Wilson Creek Project .....	18
4	Precipitation .....	30
5	Streamflow .....	30
6	Change In Soil Moisture Storage .....	38
7	Change In Groundwater Storage .....	47
8	Change In Bald Hill Reservoir Storage .....	47
9	1965 Water Budget .....	50
10	1966 Water Budget .....	51
11	1967 Water Budget .....	52
12	1968 Water Budget .....	53
13	1969 Water Budget .....	54
14	1970 Water Budget .....	55
15	1971 Water Budget .....	56
16	Class "A" Pan Evaporation .....	60
17	Class "A" Pan Coefficients .....	60
18	Blaney-Criddle Consumptive - Use Factors .....	62
19	Blaney-Criddle Crop Coefficients .....	62
20	Meyer Formula ( $e_s - e_a$ ) (1+0.10u) .....	65
21	Meyer Formula Coefficients .....	65
22	Thornthwaite Potential Evapotranspiration .....	67
23	Thornthwaite Coefficients .....	67

Table		Page
24	Penman Potential Evapotranspiration .....	72
25	Penman Coefficients .....	72
26	Energy Budget Potential Evapotranspiration .....	74
27	Energy Budget Coefficients .....	74
28	Summary Of Coefficients And Correlation Coefficients " $\rho$ " .....	76
1.1	Soil Moisture Zones For 1965-1970 .....	93
1.2	Soil Moisture Zones For 1971 .....	93
3.1	Monthly Percentage Of Annual Daytime Hours .....	126
3.2	Blaney-Criddle Formula Data .....	127
4.1	Saturation Vapour Pressure Over Water And Over Ice, In Millibars .....	129
4.2	Meyer Formula Data .....	130
5.1	Mid Monthly Intensity Of Solar Radiation ( $R_A$ ) On A Horizontal Surface In M.M. Of Water Evaporated Per Day .....	132
5.2	Values of $\sigma T_A^4$ For Various Temperatures .....	133
5.3	Penman Formula Data .....	134
6.1	Energy Budget Data .....	136

## LIST OF FIGURES

Figure		Page
1	The Hydrologic Cycle .....	4
2	Location Of The Wilson Creek Experimental Watershed .....	8
3	Map Showing Topography And Geologic Cross-Section	10
4	Geologic Cross-Section A-A' .....	11
5	Surficial Geology Of The Wilson Creek Watershed ..	12
6	Soils Of The Wilson Creek Watershed .....	14
7	Vegetation Of The Wilson Creek Watershed .....	17
8	Instrumentation In The Wilson Creek Watershed ....	23
9	Piezometer And Well Locations In The Wilson Creek Watershed .....	26
10	Piezometer And Well Locations In And Adjacent To The Wilson Creek Watershed .....	27
11	Watertable Contour Map And Location Of Geologic Cross-Section O-P .....	40
12	Geologic Cross-Section O-P .....	41
13	Energy Balance Over A Vegetational Surface .....	69
14	Cumulative Measured And Computed Evapotranspiration For 1965 .....	77
15	Cumulative Measured And Computed Evapotranspiration For 1966 .....	78
16	Cumulative Measured And Computed Evapotranspiration For 1967 .....	79
17	Cumulative Measured And Computed Evapotranspiration For 1968 .....	80
18	Cumulative Measured And Computed Evapotranspiration For 1969 .....	81
19	Cumulative Measured And Computed Evapotranspiration For 1970 .....	82

Figure		Page
20	Cumulative Measured And Computed Evapotranspiration For 1971 .....	83
5.1	Temperature Vs $\Delta$ .....	133

# CHAPTER I

## INTRODUCTION

"Evapotranspiration of water by plants means, broadly, the amount of water required to produce the mature crop. The implication is that such water has been 'used' or is no-longer directly available to man. It has been either stored in the plant tissues, or converted to vapour and discharged into the atmosphere where it re-enters the familiar hydrologic cycle and eventually appears again somewhere on the earth as precipitation" (Gray, 1970).

It is essential that the water requirements and consumptive use of water by plants be known in planning for soil conservation, irrigation, and conservation of water supplies. In order to see if it is possible to arrive at a realistic estimate of evapotranspiration by various methods, this study was undertaken on the Wilson Creek drainage basin.

The methods used to determine the evapotranspiration in the Wilson Creek basin are:

1. Water Budget method.
2. Measurement from Class "A" evaporation pan.
3. Blaney-Criddle formula.
4. Meyer formula.
5. Thornthwaite formula.
6. Penman formula.
7. Energy budget.

The water budget method provides an estimate of the actual evapotranspiration or consumptive use of plants. The other methods produce estimates of potential evapotranspiration, that is, the amount of water a given plant, in given condition, will use in evaporation and transpiration if sufficient water is available in the soil to meet the demand. Coefficients must be applied to these other methods to arrive at actual evapotranspiration.

This study undertakes to determine these coefficients and the strength of correlation of each coefficient.

Many factors operate singly or in combination to influence the amount of water consumed by vegetation. The more important of the natural influences are climate, water supply, soils and topography.

All of the components of the water budget and the estimates of evapotranspiration as calculated from the other methods are in inches of water over the entire watershed and/or acre-feet.

The period of study consists of the growing season, May to September, for the seven year period, 1965-1971.

## CHAPTER II

### THE HYDROLOGIC CYCLE AND WATER BUDGET

The hydrologic cycle is the descriptive term applied to the general circulation of water from the oceans to the atmosphere, to the ground, and back to the oceans again (Linsley et. al., 1949). Figure 1 is a simplified diagrammatic expression of the hydrologic cycle.

The quantities of water going through a hydrologic cycle may be calculated in terms of a water budget. A water budget may be stated in the simplified hydrologic equation:

$$\text{INFLOW} = \text{OUTFLOW} + \text{CHANGE IN STORAGE.} \quad (1)$$

The items in the hydrologic equation are as follows:

INFLOW: (1) precipitation, (2) surface inflow,  
(3) groundwater inflow.

OUTFLOW: (1) surface outflow, (2) groundwater outflow  
(3) evapotranspiration.

CHANGE IN STORAGE: change in

(1) groundwater, (2) soil moisture, moisture in the root zone above the groundwater table,  
(3) snow cover, (4) surface reservoir water and depression storage.

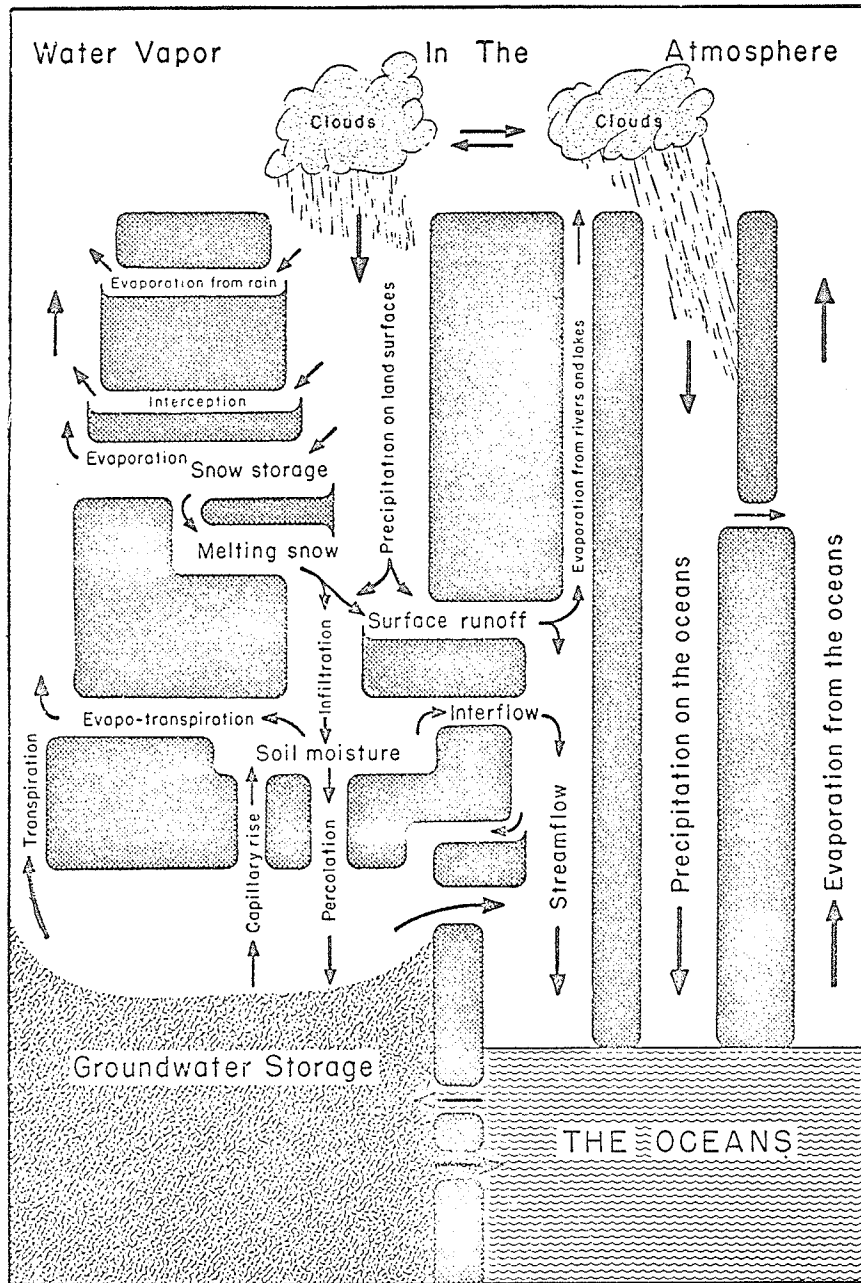


FIGURE 1

THE HYDROLOGIC CYCLE

(SOURCE: LINSLEY ET AL, 1949)

The water budget, or water balance, method is a measurement of continuity of flow of water. This holds true for any time interval and applies to any drainage basin.

For drainage basins where there is no water movement between adjacent units, this becomes the general hydrologic budget equation:

$$P = E_T + S \pm \Delta S_{ns} \pm \Delta S_{ms} \pm \Delta G_{ws} \pm \Delta S_s + G_{wo} \quad (2)$$

where

$P$  = precipitation, the total input of water into the unit;

$E_T$  = total evapotranspiration loss from the unit;

$S$  = surface outflow from the unit;

$\Delta S_{ns}$  = net change in snow cover;

$\Delta S_{ms}$  = net change in soil moisture in storage;

$\Delta G_{ws}$  = net change in groundwater in storage;

$\Delta S_s$  = net change in surface water storage;

$G_{wo}$  = groundwater outflow from the unit.

The sign convention used in Equation 2 is such that an increase in any of the storage terms is positive and a decrease in any storage term is negative.

## CHAPTER III

### THE WILSON CREEK EXPERIMENTAL WATERSHED

The Manitoba Escarpment, which includes the eastern slopes of the Riding Mountain, is of pre-glacial origin, and extends from the Pembina Hills near the United States border, to the Pasquia Hills some 300 miles to the northwest.

During periodic floods, the streams, which drain the escarpment, pick up large quantities of silt, shale, and debris from the steep mountain valleys. This material is then deposited in the channels leading away from the toe of the escarpment, where slopes are much more gradual. This process of erosion, deposition and overbank flooding has continued for thousands of years and has resulted in the formation along the base of the escarpment of a band of rich, arable land.

As settlement and development of this fertile land progressed, increasingly severe problems of flooding and erosion control were encountered.

In 1957, the Wilson Creek Experimental Watershed project was instituted to investigate and remedy headwater causes of flooding and erosion on agricultural land lying below the Manitoba Escarpment. MacKay and Stanton (1964) have provided a more detailed description of the history of erosion and sedimentation in the area.

### LOCATION

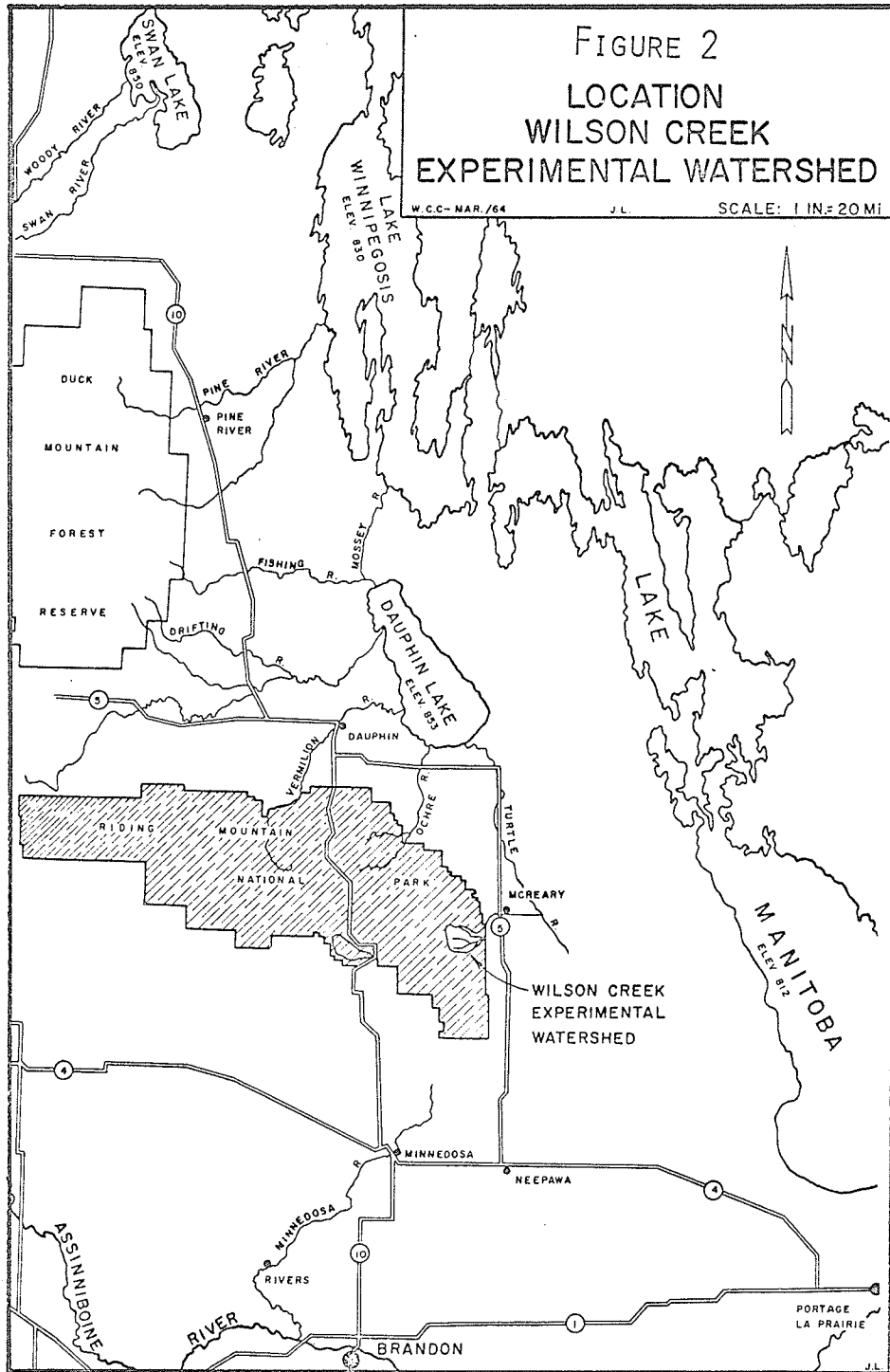
The 8.5 square mile (5440 acres) watershed is located on the eastern slopes of the Riding Mountain in Township 20, Range 16 W.P.M., some 150 miles north and west of Winnipeg (Figure 2).

### CLIMATE

The watershed is located in a generally sub-humid climate. The annual air temperature cycle in the watershed ranges from  $-45^{\circ}\text{F}$  to  $+110^{\circ}\text{F}$  with a mean of about  $30^{\circ}\text{F}$ . The average annual precipitation is about 18 inches. Since 1959, the average total precipitation for the period of study, May to September, has been 14.55 inches. The average temperature since 1961 for the period of study has been approximately  $55^{\circ}\text{F}$ .

Throughout the general escarpment region the summer precipitation often occurs during sharp, intense thunderstorms. These are usually centered over the higher portion of the escarpment and often are extremely local.

According to MacKay (1970), runoff from the watershed occurs as a result of the melting of the winter snowpack, and precipitation from; frontal storms in the late spring and early summer, convective storms during the early and middle summer, and mild frontal storm activity in the late summer and fall.



## TOPOGRAPHY

The headwaters of the watershed lie at elevations up to 2450 feet above sea level. The lower part of the basin descends to approximately 1100 feet in a distance of four miles (Figure 3). The middle watershed is deeply incised and cut by a large number of drains and coulees, tributary to the main watercourses. The main streams are cut into the bedrock shale in deep, V-shaped valleys four to five hundred feet deep (MacKay and Stanton, 1964).

## GEOLOGY

The Post-Paleozoic formations in the Riding Mountain area of the Manitoba Escarpment range in age from Jurassic to Upper Cretaceous. Siliceous shale bedrock in the upper reaches of the watershed is overlain by thick deposits of glacial drift, which are composed mainly of calcareous till (Figure 4). The surficial form of the drift above the 2300 foot contour is that of stagnation moraine with abundant hummocks and closed depressions. From approximately the 1800 foot to the 1500 foot contour, the creek banks are formed predominantly of slumped shale, alluvium, and colluvium, with occasional outcrops of relatively undisturbed Cretaceous shale units (Figure 5). The lower portion of the watershed is composed mainly of alluvial deposits (McCullough, 1972).

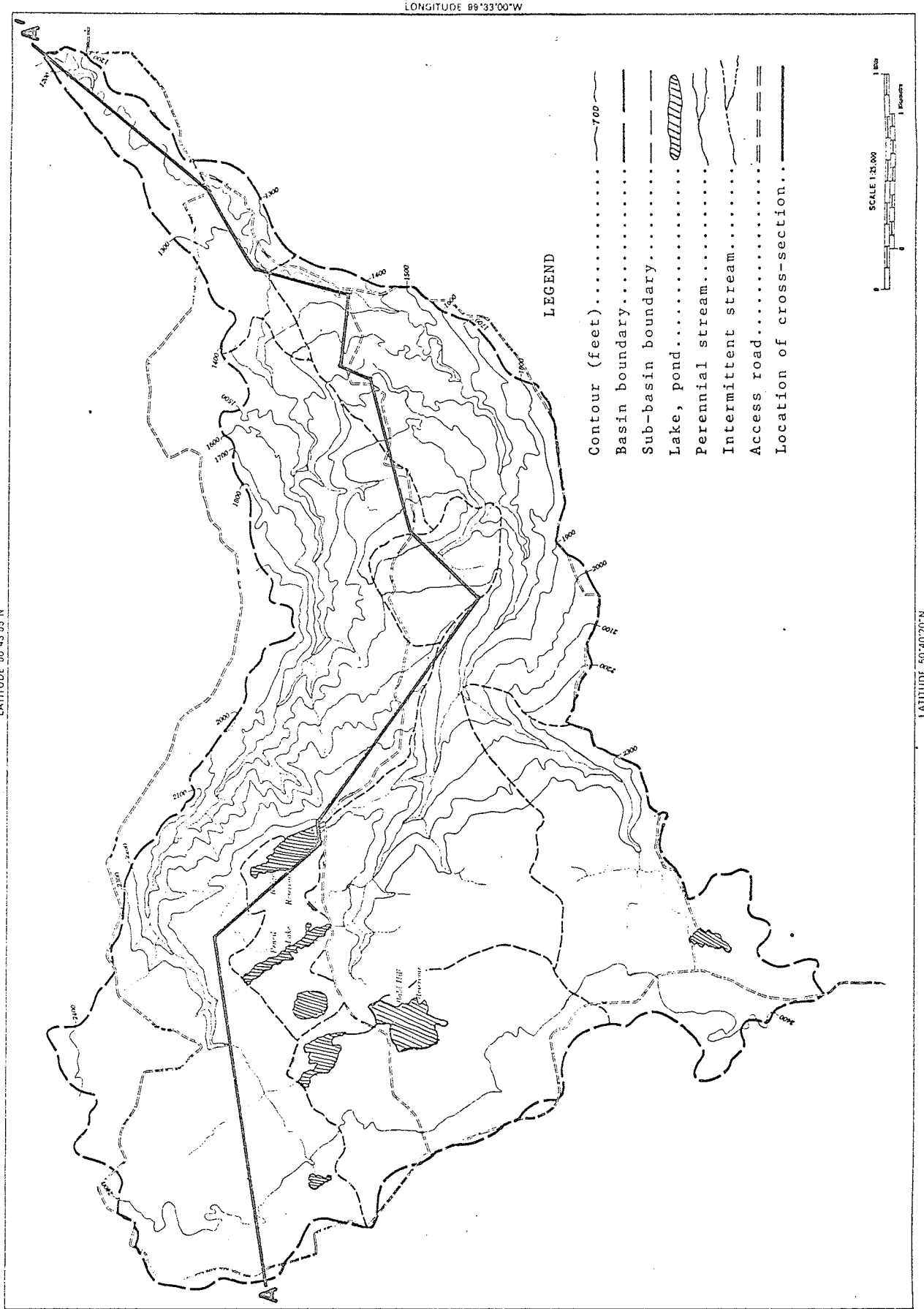


FIGURE 3 MAP SHOWING TOPOGRAPHY AND GEOLOGIC CROSS-SECTION

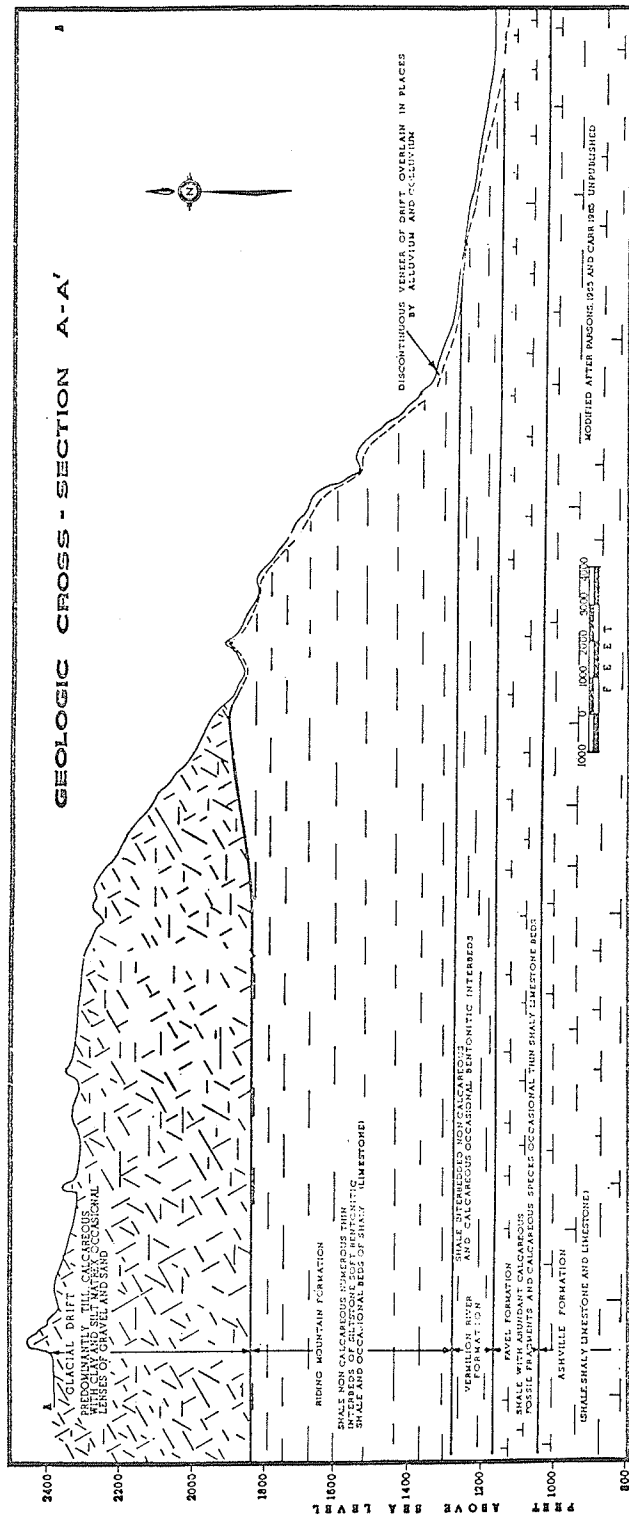


FIGURE 4 GEOLOGIC CROSS-SECTION A-A'

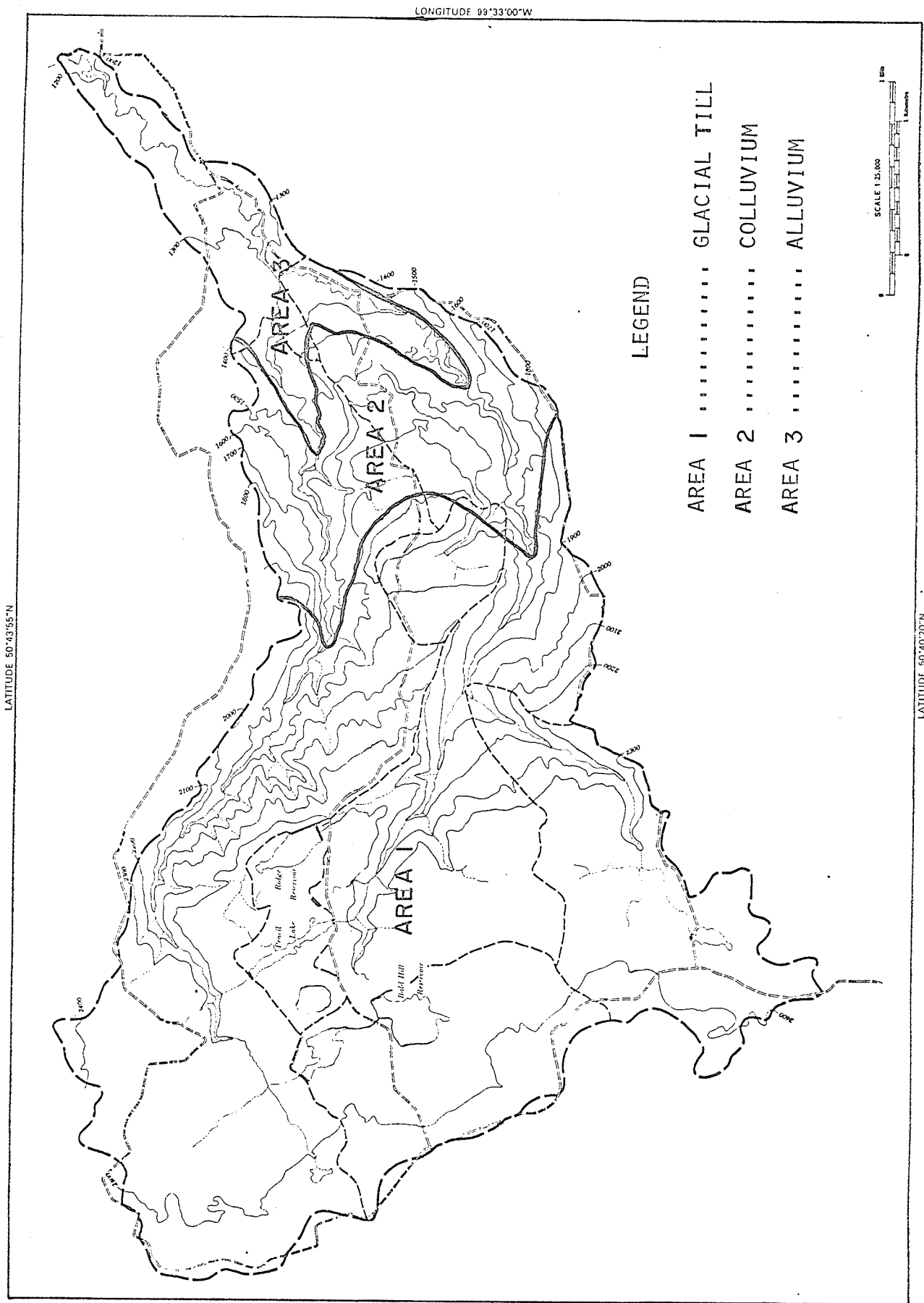


FIGURE 5 SURFICIAL GEOLOGY OF THE WILSON CREEK WATERSHED

## SOILS

A detailed reconnaissance soil survey of the watershed was undertaken in 1958. Ten soil types were identified and mapped during the survey (Figure 6). A detailed description of the soils is given in Tables 1 and 2.

## VEGETATION

Both broad and detailed studies have been made of the existing vegetation cover of the watershed by Ritchie (1958). These have involved both field studies and air photo interpretation in defining the boundaries of four main vegetation areas (Figure 7).

The area designated as "OM" on the upland is an open decadent forest of hardwoods and spruces with areas of browsed shrub cover.

Area "M" on the upper escarpment slopes is a closed cover of mixed forest, made up chiefly of white birch and aspen poplar with local stands of coniferous trees.

Area "m" represents the middle to lower steep part of the catchment. This is occupied by young stands of deciduous trees, dominated by white birch and aspen poplar.

The forested part of the lowland plain (area "ML") abutting on the escarpment bears a mixed young forest with a varied assortment of conifers and hardwoods (MacKay and Stanton, 1964).

A detailed list of vegetation will be found in Table 3.

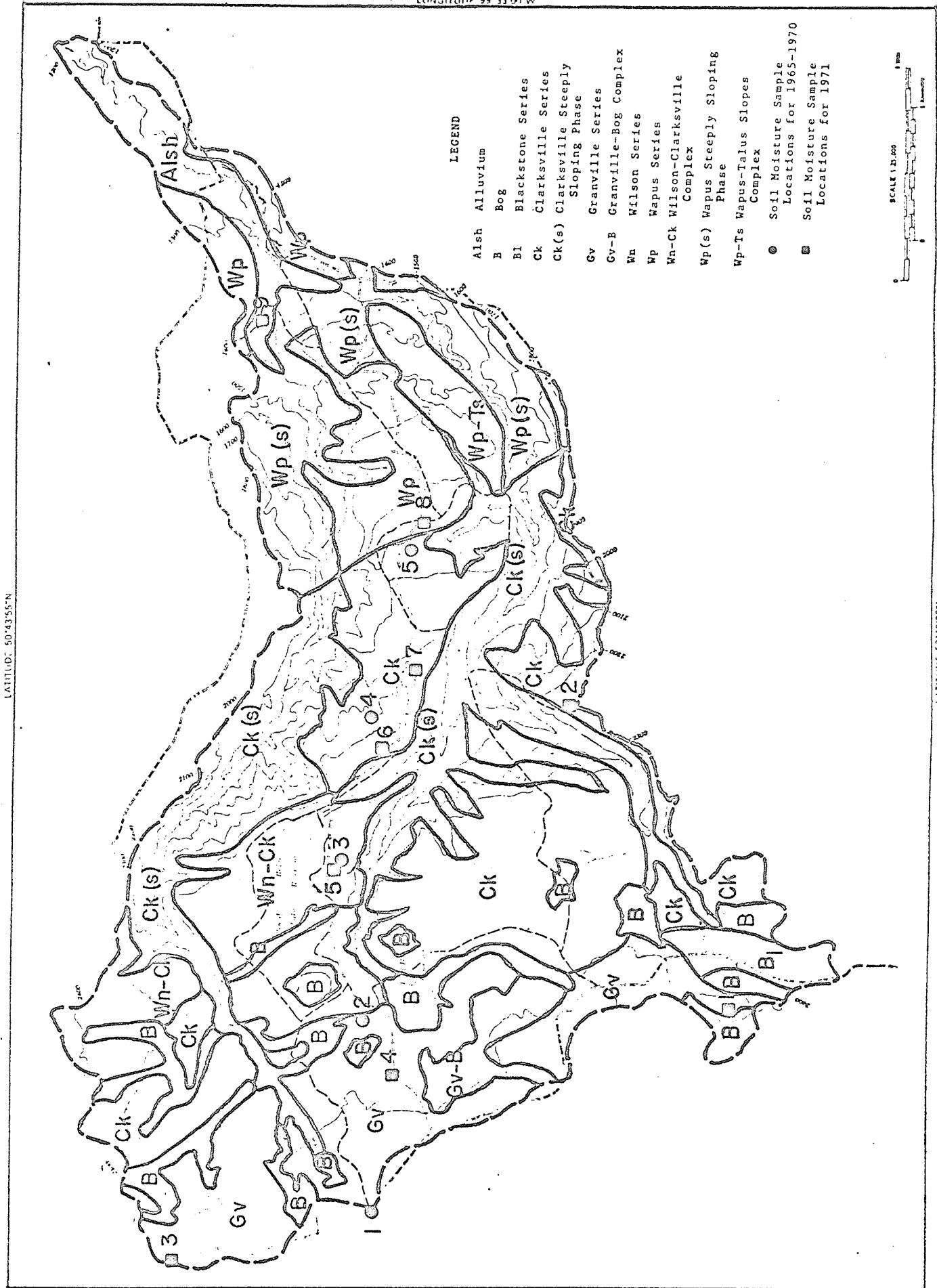


FIGURE 6 SOILS OF THE WILSON CREEK WATERSHED

TABLE 1

## SUMMARY OF THE SOIL CLASSIFICATION FOR THE WILSON CREEK WATERSHED

Map Symbol	Soil	Soil Sub-Group	Soil Parent Material	Soil Drainage	Topography
Alsh	Alluvium	Alluvial Soil	Recent alluvium composed mainly of shale fragments	Imperfectly drained	Level to gently sloping
B	Bog	Organic Soil	Mixed peat deposits over 30 inches thick	Very poorly drained	Level to depressional
El	Blackstone series	Orthic Grey Wooded	Clay textured glacial till of moderate to low lime content	Moderately well to well-drained	Irregular, gently to moderately sloping
Ck	Clarksville series	Orthic Grey Wooded	Loam textured glacial till of moderate to low lime content	Well-drained	Irregular, gently to moderately sloping
Ck(s)	Clarksville, steeply sloping phase	Orthic Grey Wooded	Loam textured glacial till of moderate to low lime content	Somewhat excessively drained	Very steeply sloping
Cv	Cranville series	Orthic Grey Wooded	Clay loam textured glacial till of moderate lime content	Well-drained	Irregular, gently to moderately sloping
Ts	Talus Slopes	Regosol	Exposed banks of hard, grey shale with weathered surface	Excessively drained	Very steeply sloping
Wn	Wilson series	Podzolized Grey Wooded	Loam textured glacial till of moderate to low lime content	Well-drained	Irregular, gently to steeply sloping
Wp	Wapus series	Orthic Grey Wooded	Glacial till and outwash composed mainly of shale fragments	Somewhat excessively drained	Irregular, gently to steeply sloping
Wp(s)	Wapus, steeply sloping phase	Orthic Grey Wooded	Glacial till and outwash composed mainly of shale fragments	Excessively drained	Very steeply sloping

(SOURCE: PRATT AND POYSER, UNPUBLISHED)

TABLE 2

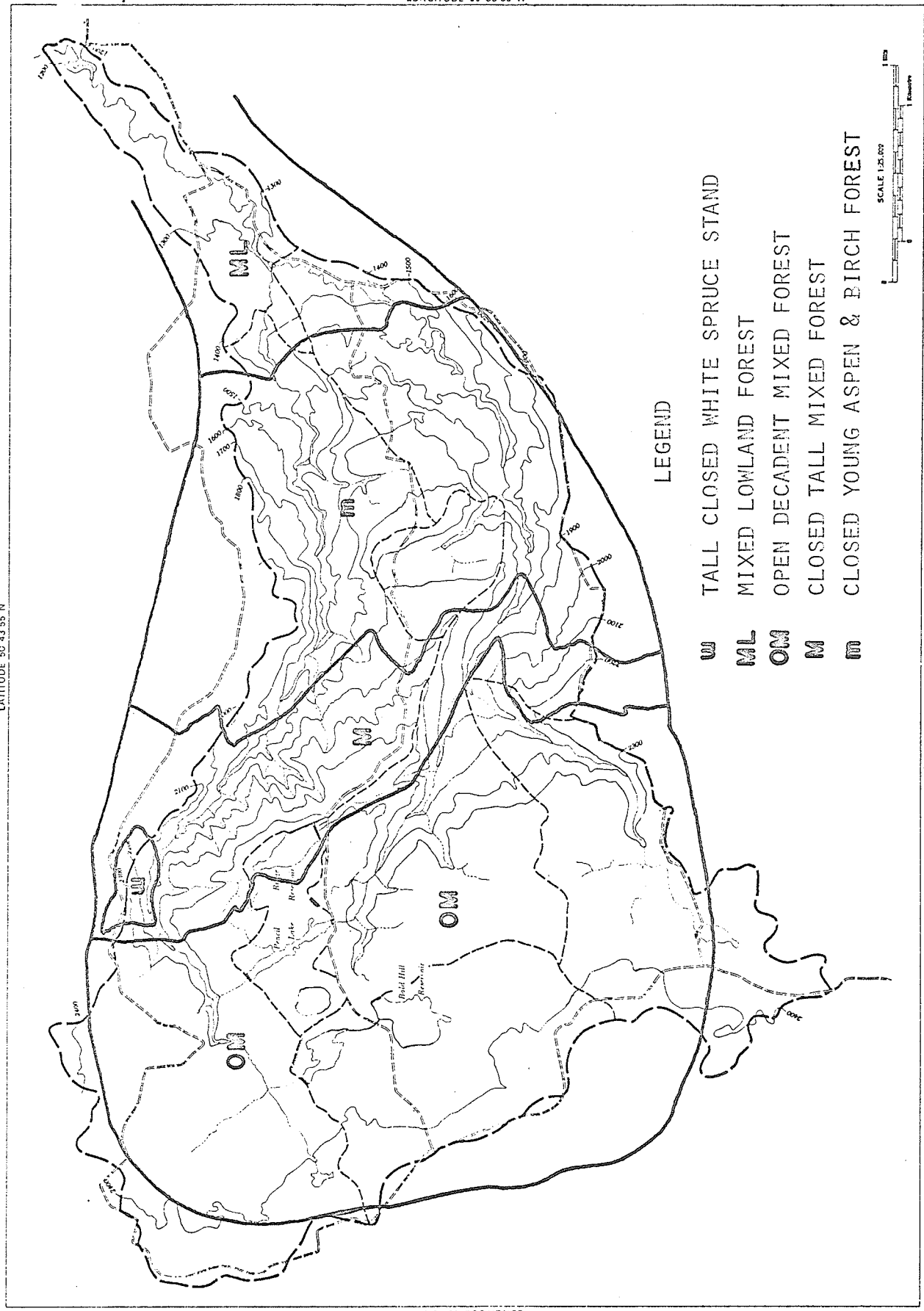
ENGINEERING INTERPRETATIONS OF SOIL OBSERVATIONS IN THE WILSON CREEK WATERSHED

Soil	Textural Profile	Water Holding Capacity	Internal Drainage	Runoff	Percent Slope	Shrinkage - Swellage Potential
Alluvium (Alsh)	Stratified, shaly sand and gravel with some finer layers	Moderately low	Rapid, sometimes impeded by high water table	Slow	0 - 5	Low
Bog (B)	Organic material to a depth of 30 inches or more variable below	Very high	Impeded by high water table	Ponded	0 - 0.5	--
Blackstone (B <sub>1</sub> )	0 - 6" - clay loam 6 - 20" - heavy clay 20" + - clay	High	Very slow	Medium	2 - 10	Very high
Clarksville (Ck)	0 - 12" - loam 12 - 24" - clay loam 24" + - shaly loam	Medium	Medium	Slow	2 - 15	Moderately low
Clarksville, steeply sloping phase (Ck (s))	0 - 8" - loam 8 - 16" - clay loam 16" + - shaly loam	Medium	Medium	Rapid	15 - 100	Moderately low
Granville (Gv)	0 - 8" - loam 8 - 20" - heavy clay loam 20" + - clay loam	Moderately high	Medium	Medium	2 - 15	Medium
Talus Slopes (Ts)	0 - 6" of shale flakes underlain by shale bedrock	Low	Very rapid	Slow	15 - 100	Low
Wilson (Wn)	0 - 14" - sandy loam 14 - 35" - clay loam 35" + - loam	Medium	Medium	Slow	2 - 15	Moderately low
Wapus (Wp)	0 - 20" - very fine sandy loam 20 - 40" - clay loam 40" + - shale fragments	Moderately low	Rapid	Slow	2 - 15	Low
Wapus, steeply sloping phase (Wp (s))	0 - 15" - very fine sandy loam 15 - 30" - clay loam 30" + - shale fragments	Moderately low	Rapid	Slow	15 - 100	Low

(SOURCE: PRATT AND POYSER, UNPUBLISHED)

LONGITUDE 99°33'00"W

LATITUDE 50°43'55"N



LEGEND

- W TALL CLOSED WHITE SPRUCE STAND
- ML MIXED LOWLAND FOREST
- OM OPEN DECADENT MIXED FOREST
- M CLOSED TALL MIXED FOREST
- m CLOSED YOUNG ASPEN & BIRCH FOREST

FIGURE 7 VEGETATION OF THE WILSON CREEK WATERSHED

TABLE 3Vegetation of Wilson Creek Project  
(According to Dr. J.C. Ritchie)Area "O.M."Tree Layer (discontinuous)

<i>Picea glauca</i>	white spruce
<i>Picea mariana</i>	black spruce
<i>Betula papyrifera</i>	white birch
<i>Populus tremuloides</i>	aspen
<i>Populus balsamifera</i>	black poplar
<i>Pinus Banksiana</i>	jack pine

Tall Shrub Layer (continuous)

<i>Corylus cornuta</i>	hazel
<i>Alnus rugosa</i>	speckled alder

Short Shrubs and Herbs

<i>Ribes hirtellum</i>	low wild gooseberry
<i>Rosa acicularis</i>	prickly rose
<i>Viburnum edule</i>	low-bush cranberry
<i>Symphoricarpus albus</i>	snowberry
<i>Elymus innovatus</i>	hairy wild rye
<i>Aralia nudicaulis</i>	wild sarsparilla
<i>Mertensia paniculata</i>	tall lungwort
<i>Lathyrus ochroleucus</i>	cream coloured vetchling
<i>Fragaria virginiana</i>	strawberry
<i>Lycopodium annotinum</i>	stiff club moss
<i>Galium septentrionalis</i>	bedstraw
<i>Equisetum sylvaticum</i>	woodland horsetail
<i>Osmorhiza claytoni</i>	
<i>Rubus idaeus</i>	

Within the alder thickets the following are characteristic of the ground cover:

<i>Mertensia paniculata</i>	
<i>Ribes tristis</i>	swamp red current
<i>Dryopteris cristata</i>	crested shield fern
<i>Carex bebbii</i>	
<i>Galium triflorum</i>	sweet scented bedstraw
<i>Circaea alpina</i>	small enchanters nightshade
<i>Equisetum sylvaticum</i>	

Area "M"

(a) In this area is the only stand of continuous closed white spruce in the watershed. (Area "w" on map). Trees range from 80 to 100 feet in height and are from 150 to 250 years old. Associated vegetation is as follows:

Shrubs

<i>Corylus cornuta</i>	
<i>Rubus idaeus</i>	
<i>Alnus crispa</i>	green alder
<i>Rosa acicularis</i>	
<i>Symphoricarpos albus</i>	
<i>Ribes hirtellum</i>	

Herbs

<i>Aralia nudicaulis</i>	
<i>Actaea rubra</i>	red baneberry
<i>Elymus innovatus</i>	
<i>Rubus pubescens</i>	dewberry
<i>Milium effusum</i>	
<i>Mertensia paniculata</i>	
<i>Dasiphora trachycaulon</i>	cinquefoil
<i>Galium triflorum</i>	

(b) Closed Aspen (Tall). This has a well developed shrub layer dominated by hazel, alder and mountain maple.

Smaller shrubs, herbs and grasses are as follows:

<i>Diervilla lonicera</i>	bush honeysuckle
<i>Milium effusum</i>	
<i>Mertensia paniculata</i>	
<i>Galium septentrionalis</i>	
<i>Oryzopsis asperifolia</i>	white grained mountain rice
<i>Galium triflorum</i>	
<i>Osmorhiza longistylis</i>	smooth sweet cicely
<i>Lathyrus ochroleucus</i>	
<i>Dryopteris spinulosa</i>	
<i>Actaea rubra</i>	
<i>Anemone riparia</i>	

(c) Closed, tall mixed forest.

White birch, white spruce and aspen are dominant in the mixed forest with shrubs, hazel, alder and mountain maple. Ground vegetation is similar to that found under the closed aspen above.

Area "m"

In this area are found younger more vigorous stands of deciduous trees, with the coniferous element decreasing significantly. This area can conveniently be divided into north facing slopes, interflaves and south facing slopes.

(a) Following are the more characteristic and common shrubs and herbs found under white birch, with black and white spruce on north facing slopes:

Aralia nudicaulis	
Linnaea borealis v. americana	twin flower
Cornus canadensis	bunch berry
Disporum trachycarpum	fairy bells
Mitella muda	bishops cap
Diervilla lonicera	
Rubus pubescens	
Ranunculus acris	tall buttercup
Viola rugulosa	Western Canada violet
Pyrola asarifolia	pink wintergreen
Osmorhiza claytoni	
Maianthemum canadense	2-leaved Solomon Seal

(b) The interfluve area is dominantly young aspen regenerating vegetatively. Beneath the aspen are the following:

Shrubs

Acer spicatum	mountain maple
Corylus cornuta	
Cornus stolonifera	red ozier dogwood
Viburnum Rafinesqueanum	downy arrow-wood

Small Shrubs and Herbs

Aralia nudicaulis	
Steironema ciliata	fringed loosestrife
Agrimonia striata	agrimony
Galium triflorum	
Fragaria virginiana	
Diervilla lonicera	
Symphoricarpos albus	
Rosa acicularis	

(c) South Facing Slopes These slopes may again be divided into three categories.

- (i) slopes which have a continuous vegetative cover made up largely of grassland communities with varying proportions of shrubs and trees
- (ii) slopes whose cover of vegetation is disintegrating and where incipient erosion is prevalent
- (iii) slopes which have been completely or almost completely denuded.

There is ample evidence of heavy browsing and tracking of wildlife on these slopes. At the summits the commoner plants found are:

Eleagnus commutata	wolf willow
Corylus cornuta	
Shepherdia canadensis	buffalo berry
Viburnum Rafinesqueanum	
Amelanchier alnifolia	saskatoon

Area "m"

On the brow of the slopes the following are found:

*Quercus macrocarpa*  
*Amelanchier alnifolia*  
*Rosa acicularis*  
*Populus tremuloides*

On the slopes proper are found:

<i>Amelanchier alnifolia</i>	
<i>Eleagnus commutata</i>	
<i>Petalostemon candidum</i>	white prairie clover
<i>Glycyrrhiza lepidota</i>	wild licorice
<i>Monarda fistulosa</i>	wild bergamot
<i>Stipa spartea</i>	porcupine grass
<i>Bromus purgans</i>	Canada brome
<i>Astragalus canadensis</i>	Canadian milk vetch
<i>Danthonia spicata</i>	poverty oat grass
<i>Artemisia frigida</i>	pasture sage
<i>Rosa acicularis</i>	
<i>Symphoricarpos occidentalis</i>	western snowberry
<i>Muhlenbergia racemosa</i>	marsh muhly
<i>Muhlenbergia cuspidata</i>	prairie muhly
<i>Solidago nemoralis v. decemflora</i>	showy golden rod
<i>Houstonia longifolia</i>	long leaved bluets
<i>Campanula rotundiflora</i>	harebell
<i>Penstemon gracilis</i>	lilac flowered beard tongue

In these grassland communities on steep slopes there is abundant evidence that the disintegration of the turf of vegetation is initiated by path cutting of the hoofed animals.

Area "ML"

In this region many of the alluvial deposits are occupied by more or less pure stands of Balsam Fir (*Abies balsamea*). Regeneration here is good. Other trees found are cottonwood, green ash and elm. Ground vegetation is as follows:

<i>Aralia nudicaulis</i>	
<i>Rubus pubescens</i>	
<i>Cornus canadensis</i>	bunch berry
<i>Linnaea borealis v. americana</i>	
<i>Pleurozium scheriberi</i>	
<i>Galium triflorum</i>	
<i>Fragaria virginiana</i>	
<i>Pyrola asarifolia</i>	
<i>Maianthemum canadense</i>	
<i>Disporum trachycaulon</i>	
<i>Oryzopsis asperifolia</i>	
<i>Ptilium crista-castrensis</i>	
<i>Galium septentrionalis</i>	
<i>Dicranum rugosum</i>	
<i>Rhytidiadelphus triquetrus</i>	
<i>Peltigera apthosa</i>	
<i>Rosa acicularis</i>	
<i>Mnium affine</i>	
<i>Eurhynchium strigosum</i>	

## CHAPTER IV

### INSTRUMENTATION

Precipitation was measured by a network of 35 standard rain gauges distributed within and adjacent to the watershed (Figure 8). The rain gauge network has remained essentially the same since 1965 except for station #35 which was added in the spring of 1971.

Streamflow was measured by means of a stage recording weir equipped with a Stevens Type A recorder located at the exit of Wilson Creek from the watershed (Figure 8). The recorded stage was checked daily by a staff and any necessary adjustments were subsequently made. Rating curves were prepared yearly from discharge measurements made with a Price current meter.

Data necessary for the calculation of evapotranspiration have been recorded since 1965 at the weather station located at rain gauge #32 (Figure 8). Air temperature and relative humidity were measured and recorded by a hygrothermograph inside a standard shelter 4.5 feet above the ground. Maximum and minimum thermometers were also used to record air temperatures.

Wind speed was measured by a three-cup type of anemometer at a reference height of ten meters. The wind is

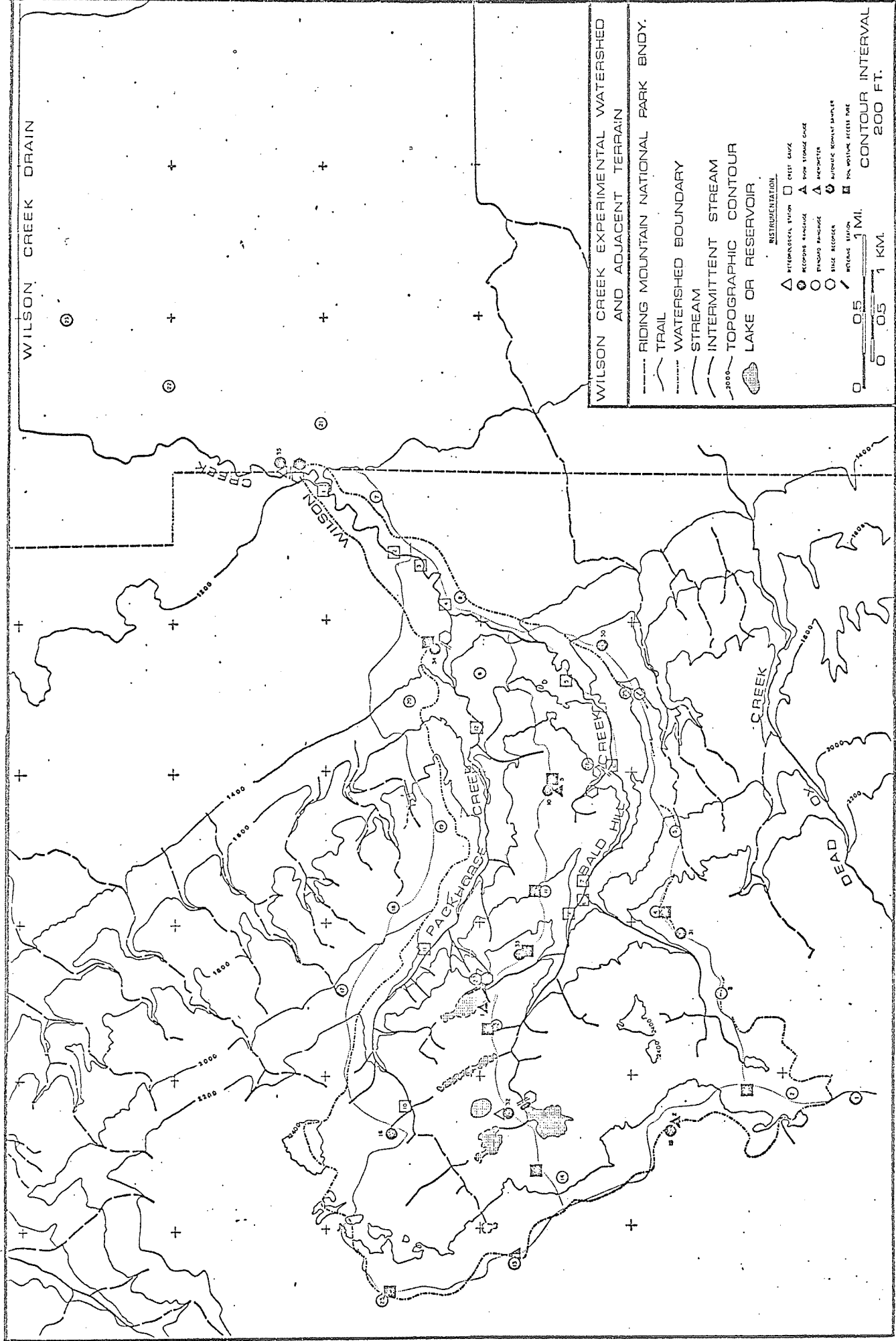


FIGURE 8 INSTRUMENTATION IN THE WILSON CREEK WATERSHED

recorded at the previous site of the weather station at rain gauge #13 because of its superior location.

Evaporation measurements were taken daily by means of a Class "A" evaporation pan, also known as the Class "A" land pan. The pan is 4 feet in diameter and 10 inches deep.

During the spring of 1971, a second weather station became operational near the Wilson Creek weir at the lower end of the watershed. This included an evaporation pan, an anemometer, a hygograph, a thermograph and maximum and minimum thermometers among various other instruments.

A CSIRO net radiometer has been recording radiation from the sun since 1969.

The winter snowpack was measured during snow surveys taken each year between March 11 and March 14. The snow surveys analysed average snow depth and average water content by means of a Mount Rose snow sampling kit. Eleven snow courses were sampled in and adjacent to the watershed.

The stage in the Bald Hill Reservoir was recorded by means of a Stevens Type A recorder and checked by means of a staff gauge. A stage-storage curve for the reservoir had been prepared by M. Sydor in 1969.

In the summers of 1964 and 1965, the Geological Survey of Canada drilled five wells and established eleven piezometers in the watershed. The water levels in wells GS-1, GS-2 and GS-5 were recorded weekly. These wells were subsequently fitted with a Type "F" water level recorder, the charts being replaced once a month. During the summer of 1969, an additional 45 nests of wells and piezometers were installed in and adjacent to the watershed by F.W. Schwartz. Twenty-eight more nests were added to the network in the summer of 1970. Ten of the wells were fitted with spring-wound type "F" water level recorders which require the charts to be changed weekly. An additional 9 nests of piezometers were installed outside of the watershed along a 12 mile line running northeast from the basin outlet. Ten nests were installed during the summer of 1971 by G. McCullough. The groundwater program at the end of the summer of 1971 consisted of 78 watertable wells and 157 piezometers (Figures 9 and 10). Water levels were recorded weekly from May to September.

Since 1965, an estimate of the moisture content of the soil has been taken at more or less weekly intervals. From 1965-1970, the test procedure made use of a one-inch

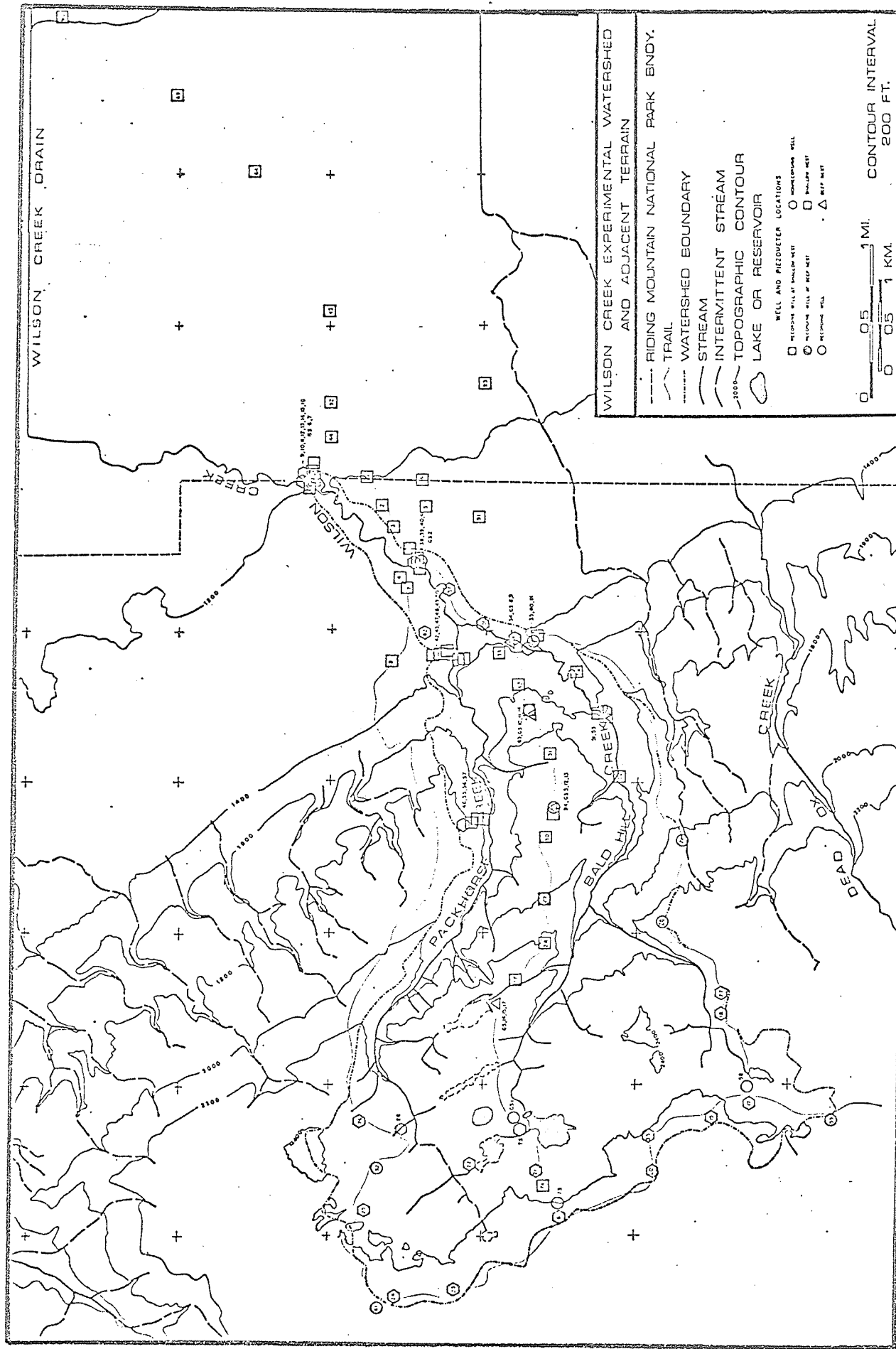


FIGURE 9 PIEZOMETER AND WELL LOCATIONS IN THE WILSON CREEK WATERSHED

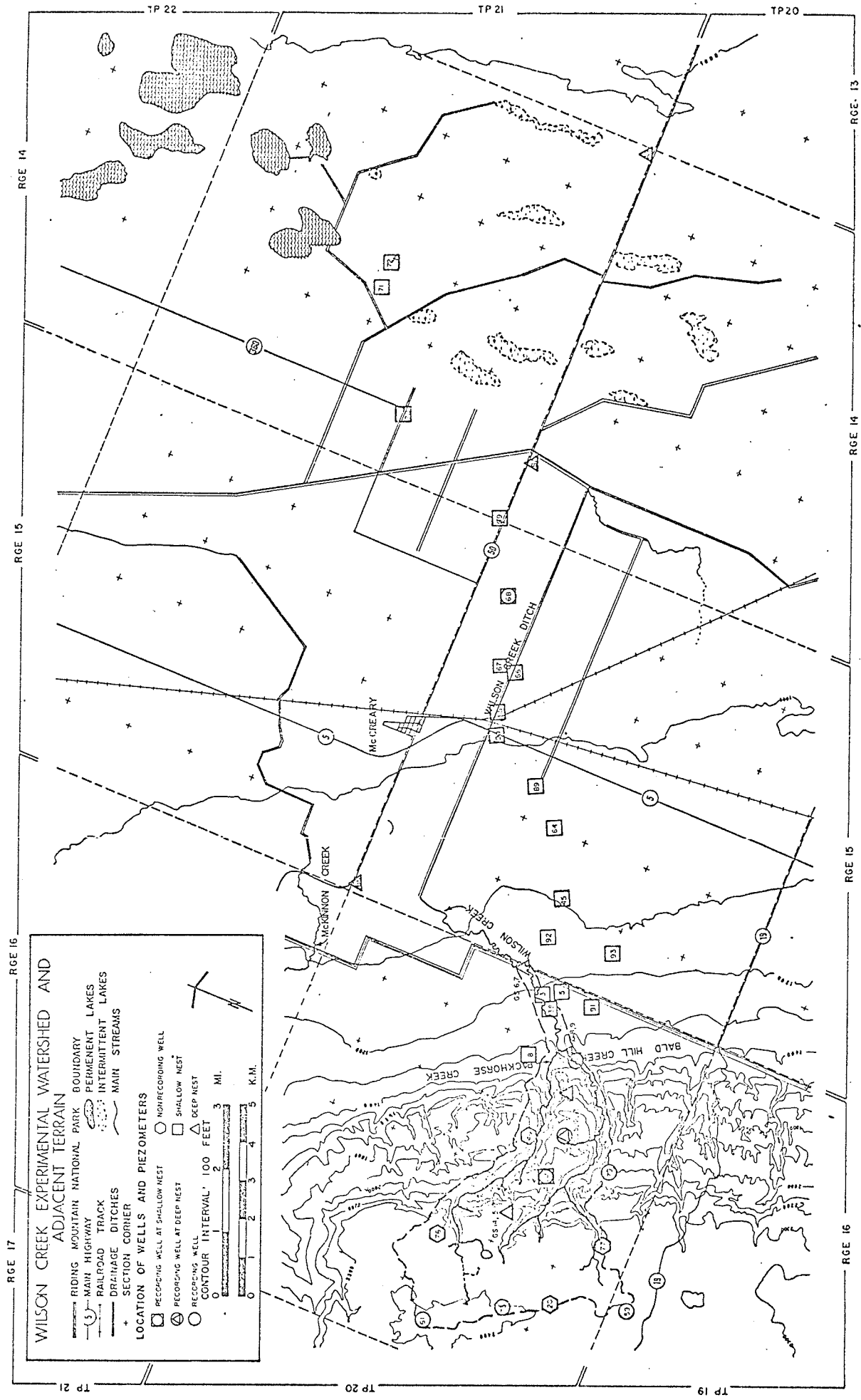


FIGURE 10 PIEZOMETER AND WELL LOCATIONS IN AND ADJACENT TO THE WILSON CREEK WATERSHED

tube sampler to take soil samples at increments of six inches to a depth of three feet. The moisture content of each sample was estimated by feel and recorded. These tests were made at five stations (Figure 6). During the summer of 1971, a NEA neutron probe with a BASC battery scaler was used to determine soil moisture. Readings were taken at depths of 12 inches, 24 inches, and 36 inches. These readings were taken at 9 stations (Figure 6).

## CHAPTER V

### THE WILSON CREEK WATER BUDGET

#### PRECIPITATION

The daily readings of the 35 standard rain gauges were averaged to obtain daily and subsequently total monthly values of precipitation over the watershed. With such a large number of observation points, the method of averaging the data rather than weighting each data point should introduce negligible error. The monthly values of precipitation for the period of study may be found in Table 4.

The months of May, 1969 and June, 1969 differ from the other months during the period of study in that both end with a large amount of precipitation falling during the last week of each month. Preliminary water budget calculations indicated that this large input, with the resulting increase in storage, would cancel or even negate any estimate of evapotranspiration for the two months. To eliminate this effect, the months of May, June and July, 1969 were rearranged into the periods May 1-28, May 29-June 24, and June 25-July 31. Each period ends immediately before a large rainfall or begins with the rainfall. The other components of the water budget were also calculated for the modified intervals, excepting evapotranspiration which was recalculated for the original monthly intervals.

TABLE 4  
PRECIPITATION

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	4.20 <sup>1</sup> 1904 <sup>2</sup>	1.64 743	4.97 2253	2.86 1297	7.37 3341
1966	1.75 793	3.10 1405	1.06 481	7.19 3259	1.34 607
1967	0.33 150	1.49 675	1.77 802	2.64 1197	0.65 295
1968	3.12 1414	3.68 1668	5.81 2634	3.97 1800	1.58 716
1969	1.80 <sup>3</sup> 814	1.94 <sup>4</sup> 878	9.56 <sup>5</sup> 4333	1.99 902	3.89 1763
1970	1.62 734	3.93 1782	4.20 1904	1.86 843	3.83 1736
1971	0.20 91	10.36 4697	3.62 1641	1.16 526	3.00 1360

TABLE 5  
STREAMFLOW

1965	2.78 <sup>1</sup> 1262 <sup>2</sup>	1.20 556	0.31 146	0.20 93	2.20 998
1966	2.46 1120	0.48 223	0.18 83	0.88 402	0.07 36
1967	4.25 1930	0.66 300	0.11 51	0.04 21	0.01 3
1968	1.18 534	0.65 299	0.89 403	0.76 348	0.46 209
1969	0.87 <sup>3</sup> 395	0.95 <sup>4</sup> 431	5.45 <sup>5</sup> 2472	0.37 172	0.34 156
1970	7.17 3250	2.11 959	0.65 297	0.10 44	0.28 128
1971	0.88 399	5.09 2310	0.95 429	0.28 127	0.12 54

1. Inches of water over the watershed  
2. Acre-feet  
3. May 1-28

4. May 29-June 24  
5. June 25-July 31

STREAMFLOW

Streamflow was calculated on a daily basis by means of the yearly rating curves and daily mean stage recordings. Monthly total discharges were then calculated using the daily values. Monthly values of streamflow in inches and acre-feet may be found in Table 5.

Although rating curves are updated yearly, considerable scattering of the discharge measurement data points occurs about the plotted rating curve. This could be a source of considerable error and in the near future, each rating curve should be evaluated by means of confidence limits.

For example, during the months of May 1965 and May 1970, preliminary water budget calculations indicated that streamflow greatly exceeded precipitation plus any change in storage. This produced a large negative value of evapotranspiration. Although this may be accounted for by errors in estimating change in soil moisture storage for the two months, it was assumed that the error was in the measurement of streamflow. Therefore, an averaged rating curve of the years 1959, 1964, 1965, 1966, 1967 and 1968 was used for the two months rather than their respective rating curves. This procedure reduced the values of streamflow for the aforementioned two months and resulted in more reasonable estimates of evapotranspiration.

### CHANGE IN SNOW STORAGE

Calculation of the amount of snow storage change during the period of study was facilitated by the snow surveys undertaken at mid-March of every year. The estimates of water content along the eleven snow courses were averaged to obtain a value of water content for the whole watershed at mid-March of every year. Values of precipitation for the period mid-March to April 30 were obtained from readings taken at Dauphin Airport, which is about thirty miles north of the watershed. These values were combined with the snow survey results to obtain the maximum amount of snow cover available for snowmelt on May 1.

In order to estimate when snowmelt occurred and the quantity of snowmelt after May 1, the degree-day method was used.

The degree-day method uses temperature as an index for all the factors affecting snowmelt. Snowmelt is calculated from:

$$\text{Melt} = \text{DDF} (T_a - T_b) \quad (3)$$

where

$T_a$  = average daily air temperature ( $^{\circ}\text{F}$ );

$T_b$  = base temperature (assumed to be  $32^{\circ}\text{F}$ );

$DD$  =  $(T_a - T_b)$  = degree days;

$DDF$  = degree-day factor (inches/DD);

Melt in inches/day.

The degree-day method is applicable at the beginning of the general warming trend which occurs in the early spring. Periods of melting temperatures alternating with periods of freezing are not within the limits of this method. These periods are assumed to cause ripening of the snowpack. Evaporation was neglected during April.

According to Cass (1970), the degree-day factor for the watershed is 0.076.

Daily mean temperatures used in the calculations were taken from Dauphin Airport for April of each year.

For the years 1965, 1968, 1969 and 1971 the snow in storage had disappeared by mid-April. Although April 1966 was interspaced with periods of freezing and thawing, streamflow increased for the period April 22-24 and this was assumed to constitute snowmelt. This left a water equivalent of 3.62 inches on May 1, 1966. A similar situation occurred during April 1967. Although periods of freezing and thawing occurred during this month, increased streamflow indicated

snowmelt in the order of 2.04 inches which agreed favourably with the degree-day method. This left a water equivalent of 7.07 inches on the watershed at the beginning of May 1967. April 1970 was characterized by freezing temperatures until the last week in the month. The degree-day method indicated a melt of 2.12 inches while streamflow records indicated a melt of 0.17 inches. This small number was neglected and it was assumed the total 7.04 inches of water was available on May 1, 1970.

The water equivalent of the snowpack on May 1 of 1966, 1967 and 1970 was 3.62 inches (1641 acre-feet), 7.07 inches (3205 acre-feet), and 7.04 inches (3192 acre-feet) respectively.

#### CHANGE IN SOIL MOISTURE STORAGE

The soil moisture storage zone was considered to extend to a depth of three feet only. According to Lebedin (1972), soil moisture content below this depth remains relatively constant. As indicated previously, soil moisture content was estimated by feel during the study periods of 1965 - 1970 and with a neutron probe during the 1971 study period. The 1965-1970 data was calculated in terms of the soil moisture deficit, that is, the quantity of moisture

required to bring the soil to field capacity. This is primarily the result of the method that was used to calculate soil moisture content in the field during that period. The moisture content of the soil as determined by the neutron probe was initially expressed as a volume per cent, that is, a percentage of the volume of bulk soil occupied by water. The volume per cent expressed as a fraction is equal to the inches of water per inch depth of soil. This volume per cent was converted to inches of water simply by multiplying the volume per cent, expressed as a fraction, by the change in depth for each reading. In all cases with the neutron probe, this depth was 12 inches.

An average value for soil moisture at each site, whether expressed as a deficit or actual moisture content, was obtained simply by averaging the readings taken at the various depths. In the case of the "feel" method, this consisted of six readings at each site, and three readings at the neutron probe sites.

Rather than combining the average moisture value at each site to arrive at an average value for the whole watershed, an attempt was made to divide the drainage basin into areas having some common characteristics and that would be represented by at least one soil moisture sampling site.

Because there were only five sample sites for the period 1965-1970, the watershed was divided into two areas, each area having similar runoff characteristics. Zone 1 had slow runoff and Zone 2 had medium to rapid runoff. A table containing the soil types in each zone and their respective areas may be found in Appendix 1. The areas of the different soil types were taken from Figure 6. The soil moisture in each zone was taken as the average of the sites in that particular zone.

During the 1971 season, the number of soil sample sites was increased to nine (Figure 6). This enabled the watershed to be divided into five zones. Soil types which were not represented by a soil moisture sample site were grouped with represented soils on the basis of water-holding capacity. A list of these may be found in Appendix 1 also.

Soil moisture was estimated for periods during which no records were available. The months of May, during which melting of the snowpack occurred, were assumed to be saturated for the remainder of the month. Otherwise, the watershed was assumed saturated on May 1. Soil moisture was estimated either by a straight line approximation, or based on precipitation and soil moisture decline during the season.

The records of soil moisture deficit or soil moisture content for the period of study are located in Appendix 1. Table 6 contains the monthly net changes in soil moisture storage.

#### GROUNDWATER OUTFLOW

The movement of groundwater is governed by the distribution of hydraulic head and permeability of the porous media. For shallow, steady state, and transient flow systems, the expression for hydraulic head can be written:

$$h = Z + \frac{P}{\rho g} \quad (5)$$

where

- h = hydraulic head;
- Z = elevation above some datum;
- P = pressure;
- $\rho$  = fluid density;
- g = gravitational constant.

The pressure may be taken as zero, which leaves the hydraulic head equal to the water level in a watertable observation well, expressed in feet above sea level.

TABLE 6  
CHANGE IN SOIL MOISTURE STORAGE

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	-0.30 <sup>1</sup> - 140 <sup>2</sup>	-0.32 - 264	+0.20 + 89	-0.47 - 213	+0.42 + 191
1966	Nil Nil	-0.39 - 176	-1.46 - 668	+0.89 + 403	-1.57 - 712
1967	Nil Nil	-0.86 - 388	-1.56 - 708	-0.99 - 450	-0.61 - 276
1968	-0.16 - 75	+0.07 + 33	-0.18 - 80	-0.03 - 14	-0.61 - 276
1969	-0.23 <sup>3</sup> - 104	-0.18 <sup>4</sup> - 80	-0.08 <sup>5</sup> - 38	-0.67 - 305	+0.16 + 72
1970	Nil Nil	-0.82 - 370	+0.82 + 370	-2.42 -1097	+1.91 + 866
1971	-1.70 - 774	+1.70 + 774	-0.94 - 425	-0.06 - 32	+0.46 + 208

- 
1. Inches of water over the watershed
  2. Acre-feet
  3. May 1-28
  4. May 29-June 24
  5. June 25-July 31

In determining the flow of water through the ground, application of Darcy's law is used, that is:

$$q = K i A \quad (6)$$

where

$q$  = flow in unit time;

$K$  = coefficient of permeability (hydraulic conductivity)

$i$  = hydraulic gradient;

$A$  = cross-sectional area of ground.

Some of the watertable wells and piezometers installed in 1969 were subjected to drawdown response tests by Schwartz. Because the duration of any response test is generally short, estimated values of hydraulic conductivity represent only the water-bearing material close to the piezometer (Schwartz, 1970). Three measurements in the alluvium were made and a median horizontal hydraulic conductivity of  $1.6 \times 10^{-4}$  ft/sec., was obtained. Twelve measurements in the lacustrine sediments produced a median horizontal hydraulic conductivity of  $1 \times 10^{-5}$  ft/sec.

The groundwater outflow through the shale bedrock was neglected as it was thought to be part of the regional groundwater flow system.

A contour map of the watertable was constructed for September 1, 1971 (Figure 11). From this map, an average hydraulic gradient of .021 ft. per ft., was obtained. This agrees with .02 ft. per ft., found by Schwartz.

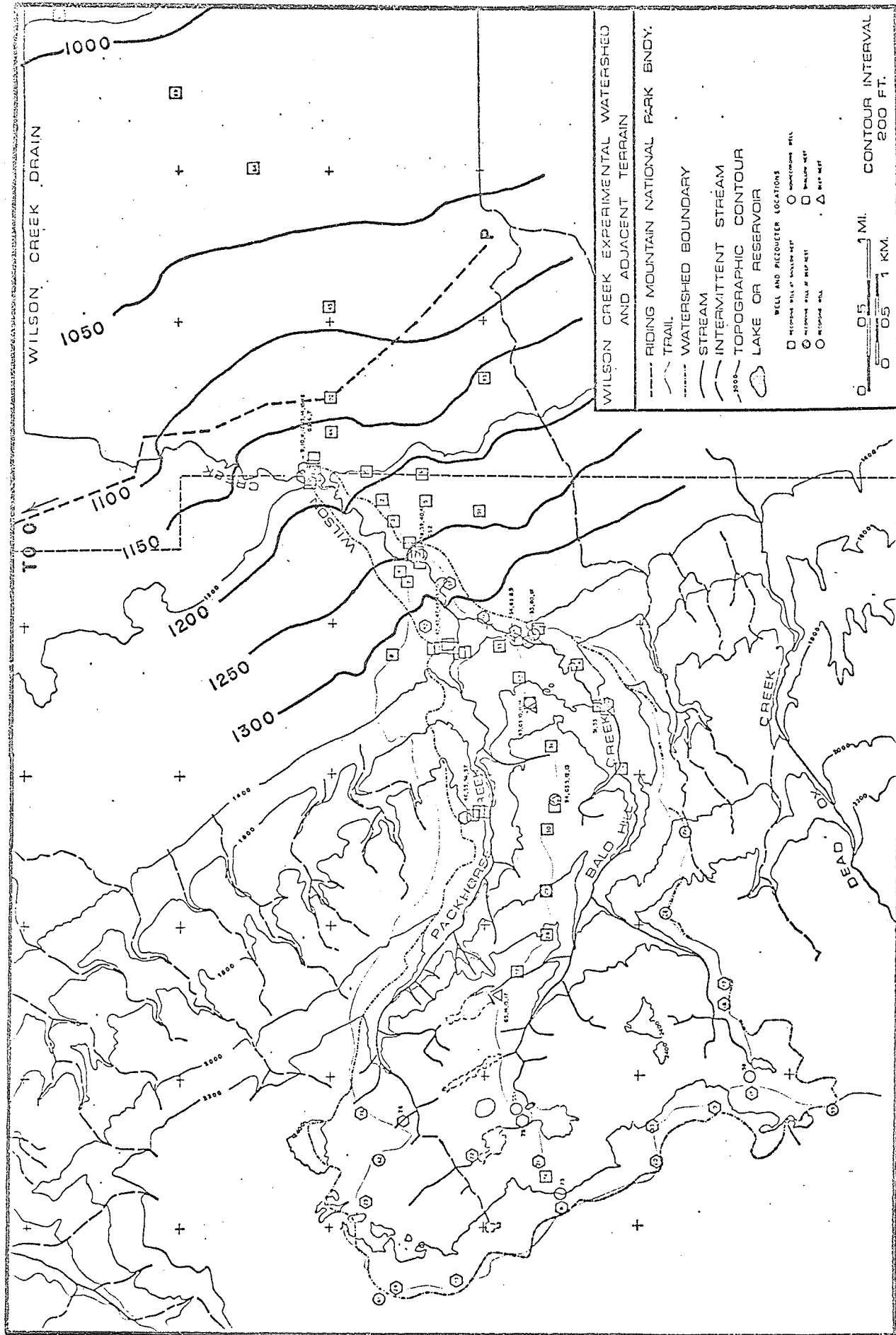


FIGURE 11. WATERTABLE CONTOUR MAP AND LOCATION OF GEOLOGIC CROSS-SECTION 0 - P

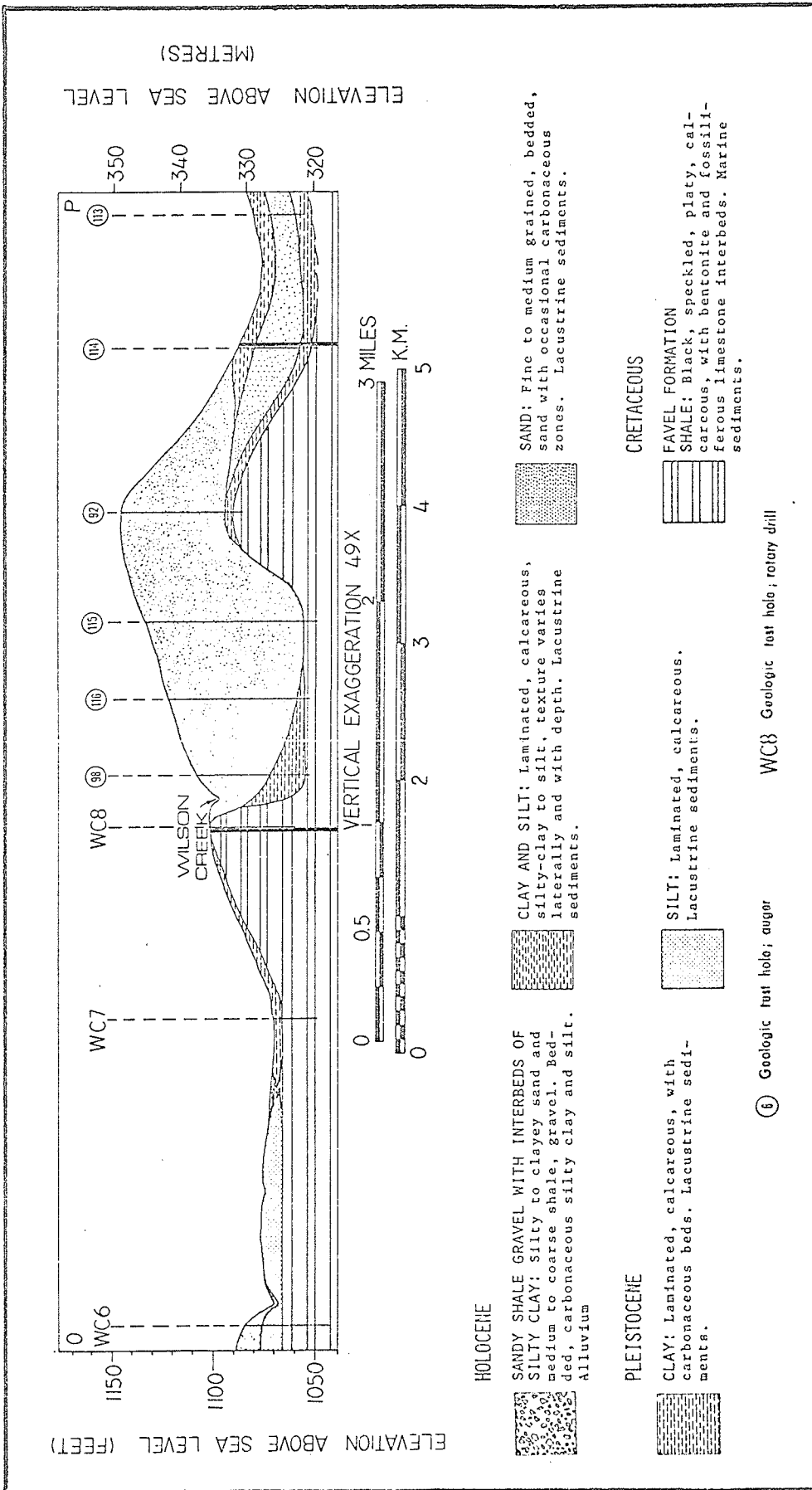


FIGURE 12  
GEOLOGIC CROSS-SECTION 9-P  
(SOURCE: McCULLOUGH, 1972)

A cross-section of the area of groundwater outflow is shown in Figure 12. From this cross-section, areas of 151,000 sq. ft., for the alluvium and 15,000 sq. ft., for the lacustrine sediments were found by planimetering.

Using Darcy's equation, an outflow of 0.5124 cfs for the alluvium and 0.00316 cfs for the lacustrine sediments was calculated. The total outflow then, was approximately 0.52 cfs or 1.03 acre-feet/day.

#### CHANGE IN GROUNDWATER STORAGE

The change in volume of groundwater storage is determined from the fluctuation of water level in the groundwater observation wells.

The storage coefficient of an aquifer is the volume of water it releases from or takes into storage per unit surface area of aquifer per unit change in watertable level. The specific yield,  $S_y$ , is the ratio of the volume of water which, after the rock having been saturated, will be yielded by gravity to the volume of the rock. For an unconfined aquifer, as at the Wilson Creek watershed, the storage coefficient equals the specific yield.

The product of change in watertable level multiplied by specific yield of the material surrounding the well multiplied by area equals change in groundwater storage.

This relationship may be expressed as follows:

$$\Delta G_{ws} = \Delta H_s \times S_y \times A \quad (4)$$

where

$\Delta G_{ws}$  = change in groundwater storage  
(acre-feet);

$\Delta H_s$  = change in watertable elevation (feet);

$S_y$  = specific yield;

A = area (acres).

The watershed was divided into three areas on the basis of surficial geology (Figure 5). It was assumed that the specific yield remained constant throughout each particular area. Area 1 consists of 4,320 acres, area 2 has 670 acres, and area 3 covers 451 acres of the watershed. Each area contained at least one recording watertable well throughout the study period.

Values of specific yield for the watershed were not available from any previous sources. Specific yield was estimated by two similar approaches. The first method consisted of comparing the rise in watertable level of all the wells in the area to the storm that occurred during June 5-7, 1971. The rise in watertable level was compared to precipitation collected in the nearest rain gauge to each well. As this approach was used to determine a maximum

upper limit of specific yield, it was assumed that all of the precipitation entered directly into groundwater storage. This method led to specific yields of 0.14 for area 1, 0.40 for area 2, and 0.42 for area 3, these being the maximum possible.

The second approach was to examine the snowmelt period during April 1969. During this period, wells GS-1, GS-5, and GS-2 were the only recording wells operating. They are located in areas 1, 2 and 3, respectively. This snowmelt period was chosen because no precipitation fell during this time, and good watertable level records were available.

From precipitation records of the previous fall, the soil moisture zone was assumed to be saturated prior to snowmelt. All the snowmelt would then have either entered the groundwater zone, or would have entered the stream channels, evaporation being neglected. According to Cass (1970), on March 26, 1969 there was 5.78 inches of water in the form of snow on the ground, by April 9 this had been reduced to 4.84 inches with the remainder disappearing in the next few days. Analysis of streamflow records indicated that direct runoff from snowmelt occurred from April 1 to April 24, the streamflow after this time being assumed to

consist mostly of baseflow. This streamflow resulting from snowmelt was equivalent to 2.45 inches of water over the entire watershed. This left 3.33 inches of water available for recharge. Comparison of the hydrographs of wells GS-1, GS-5 and GS-2 with the 3.33 inches resulted in specific yields of 0.04 for area 1, 0.014 for area 2, and 0.17 for area 3. The specific yields for areas 1 and 3 compare favourably with the maximum values obtained in that they are 30% and 40% of the upper limit. Area 2 has a much lower specific yield than the maximum. This may be explained by the fact that the upper limit was an average of wells located in the colluvium while GS-5 is located in shale which should have a lower specific yield. According to Davis and DeWiest (1966) the water yielding properties of till may vary from those of clay to those of the coarsest gravel (less than 0.10 to 0.25). Shale, being composed of clay, would have a specific yield comparable to clay, unless fractured. The specific yield of a silty sand and gravel (alluvium) would be approximately 0.20. The values of specific yield determined by the snowmelt approach agree favourably with specific yields given for similar materials and are assumed to be representative of their respective areas.

GS-1, GS-5 and GS-2 were the only recording wells in operation since 1965 so they were used to calculate the change in groundwater storage. Examination of the hydrographs of GS-1 revealed that it was unusual in comparison to the other recording wells in area 1 during 1971. It appeared to have an unusually slow response. A hydrograph of the other recording wells in area 1 was prepared, excluding wells located near the watershed boundary, which showed the average change in watertable level for these wells from May - September, 1971. This hydrograph showed little agreement with that of GS-1. However, it agreed closely with GS-5 in the time to peak after a rainstorm. Consequently, the hydrographs of GS-1 were adjusted to peak at the same time as those of GS-5. The magnitudes of the rises in GS-1 were retained and the recession limb of the adjusted hydrographs were constructed parallel to those of the original hydrographs. This was done for 1965-1970, the averaged hydrograph being used in 1971 for area 1. Appendix 2 contains the hydrographs of wells GS-1, GS-5 and GS-2, along with the averaged hydrograph. Table 7 is a summary of the net changes in groundwater storage expressed in inches of water over the watershed and acre-feet.

## CHANGE IN GROUNDWATER STORAGE

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	+0.28 <sup>1</sup> + 128 <sup>2</sup>	-1.36 - 615	+0.14 + 65	-2.42 -1096	+1.66 + 751
1966	+0.24 + 110	-0.83 - 376	-0.73 - 333	+0.12 + 53	-0.46 - 209
1967	+0.85 + 385	-0.79 - 363	-0.74 - 335	-0.78 - 355	-0.91 - 413
1968	-0.19 - 88	-0.64 - 291	+0.03 + 12	-0.44 - 199	-1.03 - 468
1969	-0.67 <sup>3</sup> - 306	+0.25 <sup>4</sup> + 114	+0.65 <sup>5</sup> + 293	-0.82 - 372	-0.16 - 71
1970	-0.58 - 265	-0.35 - 159	-0.60 - 271	-0.87 - 396	-0.22 - 99
1971	-0.50 - 228	+1.57 + 710	-1.32 - 598	-1.91 - 865	+0.22 + 99

TABLE 8

## CHANGE IN BALD HILL RESERVOIR STORAGE

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	-0.15 <sup>1</sup> - 69 <sup>2</sup>	-0.24 - 108	Nil Nil	Nil Nil	Nil Nil
1966	Nil Nil	Nil Nil	Nil Nil	Nil Nil	Nil Nil
1967	+0.19 + 85	-0.19 - 85	Nil Nil	Nil Nil	Nil Nil
1968	Nil Nil	+0.02 + 9	Nil Nil	-0.02 - 9	Nil Nil
1969	-0.03 <sup>3</sup> - 14	Nil Nil	Nil Nil	Nil Nil	Nil Nil
1970	+0.70 + 319	-0.67 - 305	-0.04 - 20	Nil Nil	Nil Nil
1971	-0.04 - 20	+0.06 + 27	-0.06 - 27	Nil Nil	Nil Nil

1. Inches of water over the watershed
2. Acre-feet
3. May 1-28

4. May 29-June 24
5. June 25-July 31

### SURFACE WATER STORAGE

Surface water storage was considered only for Bald Hill Reservoir. Ridge Dam Reservoir storage was considered negligible as was all other surface ponding. Table 8 contains the net changes in storage for Bald Hill Reservoir during the period of study.

### EVAPOTRANSPIRATION

Evapotranspiration ( $E_T$ ) was calculated by rearranging Equation 2 to the form

$$E_T = P - S \pm \Delta S_{ns} \pm \Delta S_{ms} \pm \Delta G_{ws} \pm \Delta S_s - G_{wo} \quad (2b)$$

The monthly estimates of evapotranspiration, along with the other components of the monthly water budgets, are found in Tables 9 - 15, expressed in inches of water over the watershed and acre-feet.

The values of  $E_T$  were calculated on a monthly basis except initially for May-July, 1969. As indicated previously, these months were divided into shorter or longer periods of time, for which evapotranspiration was calculated. An attempt was made to bring these values back to a period of time of one month by assuming evapotranspiration to be constant during each period. Ratios of the preceding or following periods were applied to increase or decrease each period.  $E_T$  for May 1-28 was increased by 3/27 of the  $E_T$  for May 29 - June 24.  $E_T$  for May 29 - June 24 was decreased by 3/27 of its  $E_T$  and increased by 6/37 of the  $E_T$  for June 25 -

July 31. Evapotranspiration for June 25 - July 31 was decreased by 6/37 of its  $E_T$ .

#### CHECKING THE WATER BUDGET

In order to check the water budget for accuracy, in light of all the assumptions made, a period of time was chosen in which as many storage components as possible had a zero net change in storage.

The period chosen extended from June 1, 1971 to August 5, 1971. During this time, there was no net change in snow cover, groundwater storage, or surface water storage.

Precipitation during the period was 13.98 inches (6338 acre-feet). Streamflow was 6.13 inches (2779 acre-feet). The change in soil moisture storage was calculated to be + 0.82 inches (+ 371 acre-feet). Substitution of these values and the zero values for the other storage components into Equation 2b yields a value of  $E_T$  equal to 7.03 inches (3187 acre-feet). This compares with a value of 7.37 inches (3341 acre-feet) for  $E_T$  as calculated from the monthly water budgets. The difference of 0.34 inches is less than 5% of the evapotranspiration as calculated by the zero net change in storage method.

TABLE 9  
1965 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	4.20 <sup>1</sup> 1904 <sup>2</sup>	2.78 1262	Nil Nil	-0.30 - 140	+0.28 + 128	-0.15 - 69	0.07 32	1.52 691
JUNE	1.64 743	1.20 556	Nil Nil	-0.32 - 264	-1.36 - 615	-0.24 - 108	0.07 31	2.52 1143
JULY	4.97 2253	0.31 146	Nil Nil	+0.20 + 89	+0.14 + 65	Nil Nil	0.07 32	4.24 1921
AUGUST	2.86 1297	0.20 93	Nil Nil	-0.47 - 213	-2.42 -1096	Nil Nil	0.07 32	5.47 2482
SEPT.	7.37 3341	2.20 998	Nil Nil	+0.42 + 191	+1.66 + 751	Nil Nil	0.07 31	3.02 1370

1. Inches of water over the watershed.
2. Acre-feet.

TABLE 10  
1966 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	1.75 <sup>1</sup> 793 <sup>2</sup>	2.46 1120	-3.62 -1641	Nil Nil	+0.24 + 110	Nil Nil	0.07 32	2.58 1172
JUNE	3.10 1405	0.48 223	Nil Nil	-0.39 - 176	-0.83 - 376	Nil Nil	0.07 31	3.76 1703
JULY	1.06 481	0.18 83	Nil Nil	-1.46 - 668	-0.73 - 333	Nil Nil	0.07 32	3.00 1367
AUGUST	7.19 3259	0.88 402	Nil Nil	+0.89 + 403	+0.12 + 53	Nil Nil	0.07 32	5.22 2369
SEPT.	1.34 607	0.07 36	Nil Nil	-1.57 - 712	-0.46 - 209	Nil Nil	0.07 31	3.22 1460

1. Inches of water over the watershed.
2. Acre-feet.

TABLE 11  
1967 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	0.33 <sup>1</sup> 150 <sup>2</sup>	4.25 1930	-7.07 -3205	Nil Nil	+0.85 + 385	+0.19 + 85	0.07 32	2.04 923
JUNE	1.49 675	0.66 300	Nil Nil	-0.86 - 388	-0.79 - 363	-0.19 - 85	-0.07 31	2.60 1180
JULY	1.77 802	0.11 51	Nil Nil	-1.56 - 708	-0.74 - 335	Nil Nil	0.07 32	3.89 1762
AUGUST	2.64 1197	0.04 21	Nil Nil	-0.99 - 450	-0.78 - 355	Nil Nil	0.07 32	4.30 1949
SEPT.	0.65 295	0.01 3	Nil Nil	-0.61 - 276	-0.91 - 413	Nil Nil	0.07 31	2.10 950

1. Inches of water over the watershed.
2. Acre-feet.

TABLE 12

## 1968 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	3.12 <sup>1</sup> 1414 <sup>2</sup>	1.18 534	Nil Nil	-0.16 - 75	-0.19 - 88	Nil Nil	0.07 32	2.23 1011
JUNE	3.68 1668	0.65 299	Nil Nil	+0.07 + 33	-0.64 - 291	+0.02 + 9	0.07 31	3.49 1587
JULY	5.81 2634	0.89 403	Nil Nil	-0.18 - 80	+0.03 + 12	Nil Nil	0.07 32	5.00 2268
AUGUST	3.97 1800	0.76 348	Nil Nil	-0.03 - 14	-0.44 - 198	-0.02 - 11	0.07 32	3.63 1644
SEPT.	1.58 716	0.46 209	Nil Nil	-0.61 - 276	-1.03 - 468	Nil Nil	0.07 31	2.69 1220

1. Inches of water over the watershed.

2. Acre-feet.

TABLE 13  
1969 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY 1-	1.80 <sup>1</sup>	0.87	Nil	-0.23	-0.67	-0.03	0.07	1.88 <sup>3</sup>
MAY 28	814 <sup>2</sup>	395	Nil	- .104	- 306	- 14	31	852
MAY 29-	1.94	0.95	Nil	-0.18	+0.25	Nil	0.06	1.32 <sup>4</sup>
JUNE 24	878	431	Nil	- 80	+ 114	Nil	27	598
JUNE 25-	9.56	5.45	Nil	-0.08	+0.65	Nil	0.09	2.90 <sup>5</sup>
JULY 31	4333	2472	Nil	- 38	+ 293	Nil	39	1315
AUGUST	1.99	0.37	Nil	-0.67	-0.82	Nil	0.07	3.03
	902	172	Nil	- 305	- 372	Nil	32	1375
SEPT.	3.89	0.34	Nil	+0.16	-0.16	Nil	0.07	3.47
	1763	156	Nil	+ 72	- 71	Nil	32	1574

1. Inches of water over the watershed.
2. Acre-feet.
3. May 1-31.
4. June 1-30.
5. July 1-31.

TABLE 14  
1970 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	1.62 <sup>1</sup> 734 <sup>2</sup>	7.17 3250	-7.04 -3192	Nil Nil	-0.58 - 265	+0.70 + 319	0.07 32	1.30 590
JUNE	3.93 1782	2.11 959	Nil Nil	-0.82 - 370	-0.35 - 159	-0.67 - 305	0.07 31	3.59 1626
JULY	4.20 1904	0.65 297	Nil Nil	+0.82 + 370	-0.60 - 271	-0.04 - 20	0.07 32	3.30 1496
AUGUST	1.86 843	0.10 44	Nil Nil	-2.42 -1097	-0.87 - 396	Nil Nil	0.07 32	4.98 2260
SEPT.	3.83 1736	0.28 128	Nil Nil	+1.91 + 866	-0.22 - 99	Nil Nil	0.07 31	1.79 810

1. Inches of water over the watershed.
2. Acre-feet.

TABLE 15  
1971 WATER BUDGET

<u>MONTH</u>	<u>P</u>	<u>S</u>	<u><math>\Delta S_{ns}</math></u>	<u><math>\Delta S_{ms}</math></u>	<u><math>\Delta G_{ws}</math></u>	<u><math>\Delta S_s</math></u>	<u><math>G_{wo}</math></u>	<u><math>E_T</math></u>
MAY	0.20 <sup>1</sup> 91 <sup>2</sup>	0.88 399	Nil Nil	-1.70 -.774	-0.50 - 228	-0.04 - 20	0.07 32	1.49 682
JUNE	10.36 4697	5.09 2310	Nil Nil	+1.70 + 774	+1.57 + 710	+0.06 + 27	0.07 31	1.86 845
JULY	3.62 1641	0.95 429	Nil Nil	-0.94 - 425	-1.32 - 598	-0.06 - 27	0.07 32	5.06 2230
AUGUST	1.16 526	0.28 127	Nil Nil	-0.06 - 32	-1.91 - 865	Nil Nil	0.07 32	2.78 1264
SEPT.	3.00 1360	0.12 54	Nil Nil	+0.46 + 208	+0.22 + 99	Nil Nil	0.07 31	2.13 968

1. Inches of water over the watershed.

2. Acre-feet.

## CHAPTER VI

### ALTERNATE METHODS OF ESTIMATING EVAPOTRANSPIRATION

There are several methods which may be used to estimate the amount of evapotranspiration from a watershed.

Some of them are:

1. Class "A" evaporation pan measurement.
2. Blaney-Criddle formula.
3. Meyer formula.
4. Thornthwaite formula.
5. Penman formula.
6. Energy budget.

The above mentioned methods produce estimates of potential evapotranspiration, consumptive use when soil moisture is non-limiting. Constants must be applied to arrive at actual evapotranspiration. These constants are taken equal to the ratio of the actual evapotranspiration to the potential evapotranspiration. The consumptive use as calculated by the water budget method is actual evapotranspiration.

The correlation coefficient is a measure of the strength of correlation between the actual evapotranspiration and the potential evapotranspiration as calculated by the various methods.

The correlation coefficient, as calculated by the slope of the regression line method, has a possible range of 0.0 to 1.0; where 1.0 represents perfect correlation and 0.0 signifies absolutely no correlation.

The equation for the correlation coefficient,  $P$ , is:

$$P = \frac{\Sigma (X-\bar{X})(Y-\bar{Y})}{\sqrt{\Sigma (X-\bar{X})^2 \Sigma (Y-\bar{Y})^2}} \quad (7)$$

where

X = potential evapotranspiration;

Y = actual evapotranspiration.

### 1. PAN EVAPORATION

Measurements taken on evaporation pans have been used to provide estimates of the amounts of evaporation from lakes and reservoirs. Pan evaporation is considered equivalent to potential evapotranspiration in this study.

The most common type of evaporation pan is the surface pan. Evaporation is determined from records of the water level changes in the pan corrected for the amounts of water added by rainfall and by artificial filling.

Pan evaporation has been measured at rain gauge #32 since 1965 for the period of study. Measurements were also taken during 1971 at a pan installed near rain gauge #35. Comparison of the records for the two pans in 1971 showed the ratio of the average evaporation of pan stations #32 and #35 to pan station #32 as having a range of 1.153 to 1.320 with a mean of 1.208. The records at pan station #32 were subsequently corrected by a factor of 1.208. The evaporation records are summarized in Table 16. The coefficients necessary to convert pan evaporation to actual evapotranspiration for the months May - September and their correlation coefficients are shown in Table 17.

## 2. BLANEY-CRIDDLE FORMULA

Blaney and Criddle (1950) developed a simplified formula for estimating consumptive use. Briefly, the Blaney-Criddle method estimates monthly consumptive use by multiplying together the mean monthly temperature,  $T_m$  ( $^{\circ}\text{F}$ ), the monthly per cent of annual daytime hours,  $p$ , and a monthly crop coefficient,  $k$ . Expressed mathematically:

$$cu = \frac{k T_m p}{100} = kf \quad (8)$$

where

$$\frac{T_m p}{100} = \text{monthly consumptive use factor, } f;$$

$$cu = \text{consumptive use of water by crops in inches for a one month period.}$$

TABLE 16

## CLASS "A" PAN EVAPORATION

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	3.85 <sup>1</sup> 1741 <sup>2</sup>	5.87 2660	4.89 2214	4.16 1883	1.70 767
1966	5.00 2263	5.54 2508	5.46 2476	3.83 1736	2.98 1349
1967	4.14 1877	5.88 2666	6.28 3117	5.65 2557	4.03 1823
1968	3.89 1763	5.00 2263	5.01 2269	3.12 1437	2.46 1115
1969	4.79 2171	4.43 2008	5.12 2340	5.47 2476	2.17 979
1970	4.03 1823	6.15 2786	5.22 2367	5.38 2438	2.50 1132
1971	6.56 2971	4.25 1926	5.20 2356	5.26 2383	2.46 1115

1. Inches of water over the watershed
2. Acre-feet

TABLE 17

## CLASS "A" PAN COEFFICIENTS

<u>PERIOD</u>	<u>PAN COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	0.40	0.08
JUNE	0.52	0.64
JULY	0.74	0.12
AUGUST	0.90	0.26
SEPT.	0.99	0.30
SEASON	0.68	0.43

Mean monthly temperatures have been recorded by a pair of maximum and minimum thermometers at rain gauge #32 since 1965 and at rain gauge #35 since 1971. The ratio of the average values of the two sites to that of site #32 for 1971 was seen to have a range of 1.031 to 1.050 with a mean of 1.037. The mean monthly temperatures of site #32 were corrected by the above factor.

The monthly per cent of annual daytime hours was extrapolated for a latitude of  $50^{\circ}40'20''$  north from Appendix Table 3.1. The monthly consumptive use factors are recorded in Table 18. The crop coefficients,  $k$ , and their respective correlation coefficients are listed in Table 19. The temperature and monthly per cent of daytime hours are found in Appendix Table 3.2.

### 3. MEYER FORMULA

The Meyer formula is one of the many mass-transfer methods used to estimate evaporation from lakes. As was the case with pan evaporation, the Meyer formula is assumed to represent potential evapotranspiration.

Mass-transfer methods are based on the fact that the rate at which water molecules leave the water surface is dependent on the temperature of the water surface and the atmospheric pressure. As the evaporation process takes

TABLE 18

## BLANEY-CRIDDLE CONSUMPTIVE-USE FACTORS

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	5.02	6.62	6.89	6.04	3.60
1966	5.13	6.62	7.47	6.15	4.66
1967	5.69	6.51	7.12	6.25	5.01
1968	5.02	6.28	6.89	5.73	4.66
1969	5.02	5.71	6.89	6.77	4.48
1970	5.38	7.05	7.36	6.36	4.48
1971	5.46	6.72	6.65	6.53	4.45

TABLE 19

## BLANEY-CRIDDLE CROP COEFFICIENTS

<u>PERIOD</u>	<u>CROP COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	0.36	0.20
JUNE	0.43	0.78
JULY	0.56	0.70
AUGUST	0.67	0.45
SEPT.	0.59	0.30
SEASON	0.52	0.17

place, the lowest layer of the atmosphere gradually becomes saturated and an increasing number of molecules move from air to water, decreasing the rate of evaporation. An agent which tends to carry away the water molecules as they leave the water surface is necessary for continuous evaporation. The wind is such an agent.

The Meyer equation may be stated as:

$$E = c (e_s - e_a) (1 + 0.10 u) \quad (9)$$

where

$c$  = constant;

$e_s$  = saturation vapour pressure corresponding to the mean air temperature (in. Hg);

$e_a$  = actual vapour pressure of air;

$u$  = monthly mean wind speed at 8 meters (miles per hour);

$E$  = evaporation in inches per month.

Saturation vapour pressure was calculated using Appendix Table 4.1. Actual vapour pressure was calculated from the relationship:

$$\text{R.H.} = \frac{e_a}{e_s} \quad (10)$$

where

R.H. = relative humidity;

$e_a$  = actual vapour pressure;

$e_s$  = saturation vapour pressure.

Mean monthly values of relative humidity were obtained from the hygrothermograph charts. Comparison of the averaged 1971 values of wind speed taken at rain gauge #13 and rain gauge #35 with those of the anemometer at rain gauge #13 indicated that the records at station #13 should be corrected by 0.9. Although the Meyer equation calls for wind speed at a height of 8 meters, the 10 meter height of the anemometers was considered sufficiently accurate for this study. The data used in the Meyer equation may be found in Appendix Table 4.2.

The monthly results of the mass-transfer method are given in Table 20. The monthly and seasonal constants with their correlation coefficients are located in Table 21.

#### 4. THORNTHWAITE FORMULA

Thornthwaite developed a method by which evapo-transpiration could be determined from temperature and length of day. The Thornthwaite equation may be written as:

$$E = c T_m^a \quad (11)$$

where

E = evaporation (cm. per month);

c = coefficient;

$T_m$  = mean monthly temperature ( $^{\circ}$ C);

a = exponent.

TABLE 20

MEYER FORMULA  $(e_s - e_a)(1 + 0.10u)$ 

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	0.23	0.33	0.22	0.18	0.11
1966	0.24	0.29	0.37	0.25	0.25
1967	0.17	0.36	0.43	0.43	0.38
1968	0.22	0.27	0.29	0.17	0.21
1969	0.19	0.20	0.29	0.37	0.17
1970	0.22	0.33	0.33	0.27	0.17
1971	0.30	0.24	0.23	0.30	0.22

TABLE 21

MEYER FORMULA COEFFICIENTS

<u>PERIOD</u>	<u>COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	8.31	0.22
JUNE	9.48	0.55
JULY	12.68	0.48
AUGUST	14.93	0.27
SEPT.	12.20	0.34
SEASON	11.65	0.06

Both constants, a and c, depend on location. The exponent "a" may be evaluated in terms of the annual Heat Index, I, as:

$$a = 67.5 \times 10^{-8} I^3 - 77.1 \times 10^{-6} I^2 + 0.0179 I + 0.492 \quad (12)$$

$$\text{in which } I = \text{Heat Index} = \sum_{m=1}^{12} \left[ \frac{T_m}{5} \right]^{1.51} \quad (13)$$

According to Thornthwaite, the basic equation reduces to

$$E = c \left[ \frac{10 T_m}{I} \right]^a \quad (14)$$

The results using the Thornthwaite method are given in Table 22. The monthly and seasonal coefficients with their correlation coefficients are given in Table 23.

##### 5. PENMAN FORMULA

A simple heat or energy budget, written in terms of gains and losses in energy, may be stated as:

$$H = RN = S + E_T + K + N + \text{Storage Terms} \quad (15)$$

where

H = heat budget;

RN = net radiation;

S = energy to heat soil;

$E_T$  = energy used for evapotranspiration;

K = sensible heat transferred to the air;

N = energy used by plants in photosynthesis (Gray, 1970).

TABLE 22

## THORNTHWAITE POTENTIAL EVAPOTRANSPIRATION

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	2.41 <sup>1</sup> 1093 <sup>2</sup>	4.19 1900	4.47 2027	4.19 1900	1.79 811
1966	2.93 1328	5.04 2285	6.26 2838	5.20 2357	4.21 1909
1967	4.06 1841	5.20 2357	6.14 2783	5.75 2607	5.20 2357
1968	2.48 1124	3.94 1786	4.65 2108	3.94 1786	3.66 1659
1969	2.57 1165	3.38 1532	4.88 2212	5.63 2552	3.50 1587
1970	3.51 1591	6.10 2765	6.50 2947	5.94 2693	4.06 1841
1971	3.46 1569	5.53 2507	5.00 2267	5.81 2634	3.74 1695

1. Inches of water over the watershed
2. Acre-feet

TABLE 23

## THORNTHWAITE COEFFICIENTS

<u>PERIOD</u>	<u>COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	0.61	0.45
JUNE	0.57	0.40
JULY	0.72	0.55
AUGUST	0.81	0.25
SEPT.	0.70	0.30
SEASON	0.69	0.22

The components of the net energy exchange for a land surface are illustrated in Figure 13.

If the smaller terms of the budget are neglected, the heat balance for short periods may be written as:

$$H = K + E_T \quad (16)$$

Penman solved Equation 16 by considering evaporation from a free water surface in place of evapotranspiration and by using aerodynamic equations to determine the proportion of net energy utilized by each of the components, E and K.

The following three formulas are used by Penman in estimating evapotranspiration:

$$H = R_A (1-r)(0.18 + 0.55 n/N) - \sigma T_a^4 (0.56 - 0.092 \sqrt{e_d}) \\ (0.10 + 0.90 n/N) \quad (17)$$

$$E_a = 0.35 (e_a - e_d) (1 + 0.0098 u_2) \quad (18)$$

$$E_T = \frac{\Delta H - 0.27 E_a}{\Delta - 0.27} \quad (19)$$

where

H = daily heat budget at surface (mm. H<sub>2</sub>O/day);

R<sub>A</sub> = mean monthly extraterrestrial radiation  
(mm. H<sub>2</sub>O/day);

r = reflection coefficient of surface;

n = actual duration of bright sunshine;

N = maximum possible duration of bright sunshine;

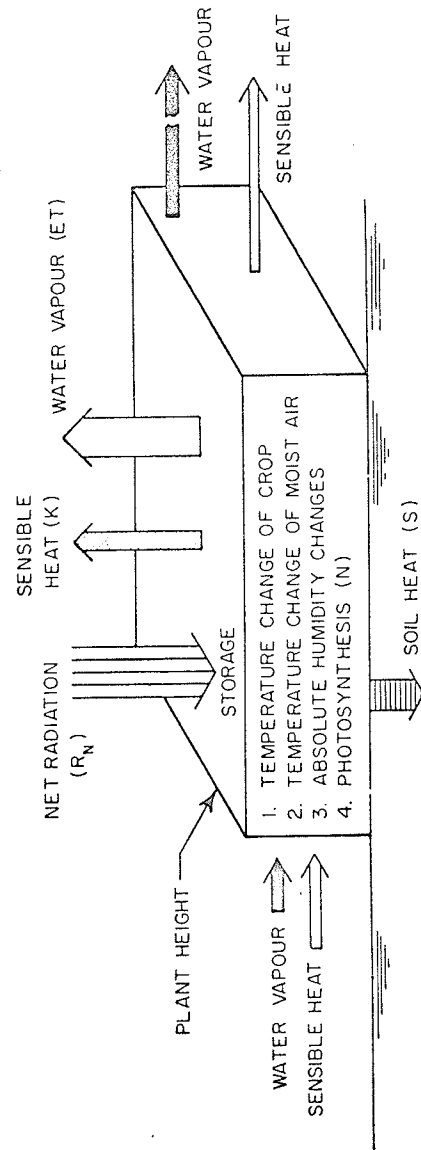


FIGURE 13 ENERGY BALANCE OVER A VEGETATIONAL SURFACE

(SOURCE: GRAY, 1970)

$$\sigma T_a^4 = \text{mm. H}_2\text{O/day};$$

$$e_d = \text{actual vapour pressure in the air (mm. Hg.)};$$

$$E_a = \text{evaporation in mm. H}_2\text{O/day};$$

$$e_a = \text{saturation vapour pressure at mean air temperature (mm. Hg.)};$$

$$u_2 = \text{mean wind speed at 2 meters above the ground (miles/day)};$$

$$\Delta = \text{slope of the saturation vapour pressure-temperature curve at } T_a;$$

$$T_a = \text{mean monthly temperature (}^\circ\text{F)};$$

$$E_T = \text{evapotranspiration (potential) in mm. H}_2\text{O/day.}$$

The reflection coefficient of the surface was assumed to remain constant throughout the season and was assumed to equal 0.15 (Gray, 1970; Munn and Truhlar, 1963; Eagleson, 1970). The actual duration of bright sunshine was taken from records at Dauphin Airport. The wind measurements at the 10 meter height were corrected to the 2 meter elevation by use of the formula:

$$u_2 = u_1 \times \frac{\log 6.6}{\log h} \quad (20)$$

where

$$u_1 = \text{measured windspeed in miles per day at } h \text{ feet.}$$

All of the data required in the use of the Penman equation are given in Appendix 5. The Penman estimates of potential evapotranspiration are summarized in Table 24 and the monthly constants and correlation coefficients are given in Table 25.

## 6. ENERGY BUDGET

As indicated previously, the heat balance for short periods may be written as:

$$H = RN = K + E_T \quad (16)$$

where

H = heat budget;

RN = net radiation;

K = QH = sensible heat transfer to  
the atmosphere;

$E_T$  = QE = energy utilized for evaporation.

As RN is directly measurable by use of net radiometers, all that is required is an estimate of QH in order to determine QE and  $E_T$ . The direct measurement of QH is very difficult. To evaluate this component, use is made of the ratio of energy utilized by evaporative processes and that energy conducted to or from the body by the air as sensible heat. In 1926, Bowen attempted to relate this ratio to easily measured quantities. He concluded this ratio could be expressed as:

TABLE 24

## PENMAN POTENTIAL EVAPOTRANSPIRATION

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1965	3.55 <sup>1</sup> 1609 <sup>2</sup>	4.90 2221	4.87 2208	3.58 1623	1.59 721
1966	3.94 1786	4.45 2017	5.39 2443	3.80 1723	2.19 993
1967	3.70 1677	4.87 2208	4.83 2190	4.81 2181	2.95 1337
1968	3.53 1600	4.32 1958	5.05 2289	3.23 1464	2.28 1034
1969	3.41 1544	3.96 1794	4.93 2233	4.71 2135	1.99 902
1970	3.70 1677	5.08 2302	5.22 2365	4.58 2076	2.04 925
1971	4.55 2064	4.46 2020	4.72 2138	4.52 2051	2.22 1006

1. Inches of water over the watershed

2. Acre-feet

TABLE 25

## PENMAN COEFFICIENTS

<u>PERIOD</u>	<u>COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	0.49	0.12
JUNE	0.60	0.45
JULY	0.78	0.57
AUGUST	1.01	0.36
SEPT.	1.21	0.44
SEASON	0.78	0.34

$$R_B = \frac{QH}{QE} \approx 0.64 \left[ \frac{T_o - T_a}{e_o - e_a} \right] \quad (21)$$

where

$R_B$  = Bowens ratio;

$T_o, T_a$  = temperature of the water surface and air ( $^{\circ}C$ ) respectively;

$e_o$  = saturation vapour (mbars) corresponding to temperature  $T_o$ ;

$e_a$  = vapour pressure of air (mbars).

Equation 16 then reduces to

$$RN - QH - QE = 0 \quad (22)$$

and

$$RN - (1 + R_B) QE = 0 \quad (23)$$

The temperature,  $T_o$ , was taken as being equal to the temperature of the water in the evaporation pans.

Appendix 6 contains the data used in Equation 23. Tables 26 and 27 contain the energy budget results and the monthly constants and correlation coefficients, respectively. The correlation coefficients for May, June, and the season were omitted because only two years of data were available. This produces a correlation coefficient of unity.

The heat of vaporization was assumed to be constant at 590 calories/gram of  $H_2O$ .

TABLE 26

## ENERGY BUDGET POTENTIAL EVAPOTRANSPIRATION

<u>YEAR</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>	<u>SEPTEMBER</u>
1969	3.67 <sup>1</sup> 1667 <sup>2</sup>	3.74 1694	4.73 2143	4.57 2072	2.33 1056
1970	4.27 1936	4.25 1928	4.51 2047	4.32 1958	2.37 1073
1971	N.A. N.A.	N.A. N.A.	4.41 1999	3.95 1790	1.91 866

1. Inches of water over the watershed

2. Acre-feet

N.A. Data not available

TABLE 27

## ENERGY BUDGET COEFFICIENTS

<u>PERIOD</u>	<u>COEFFICIENT</u>	<u>CORRELATION COEFFICIENT</u>
MAY	0.40	-
JUNE	0.68	-
JULY	0.82	0.85
AUGUST	0.84	0.21
SEPT.	1.12	0.21
SEASON	0.71	-

## CHAPTER VII

### DISCUSSION OF RESULTS

Table 28 contains a summary of the monthly and seasonal coefficients, as calculated for each of the alternate methods of estimating evapotranspiration. Figures 14 - 20 show a graphical comparison of actual evapotranspiration calculated by the water budget method and evapotranspiration calculated by the alternate methods with their computed coefficients.

The monthly coefficients for the Class "A" Pan increased steadily throughout the season and had a range of 0.40 to 0.99. Kohler (1954) states that the Lake Hefner Experiment produced pan-to-lake coefficients for the months May, June, July, August and September of 0.35, 0.60, 0.71, 0.82, and 0.93 respectively. These coefficients agree quite well with those given for the Class "A" Pan in Table 28. The seasonal constant of 0.68 also is in close agreement with those found by other researchers (Kohler, 1954).

TABLE 28

## SUMMARY OF COEFFICIENTS AND CORRELATION COEFFICIENTS "P"

PERIOD	CLASS "A" PAN		BLANEY-CRIDDLE FORMULA		MEYER FORMULA		THORNTHWAITE FORMULA		PENMAN FORMULA		ENERGY BUDGET	
	C	P	K	P	C	P	C	P	C	P	C	P
MAY	0.40	0.08	0.36	0.20	8.31	0.22	0.61	0.45	0.49	0.12	0.40	-
JUNE	0.52	0.64	0.43	0.78	9.48	0.55	0.57	0.40	0.60	0.45	0.68	-
JULY	0.74	0.12	0.56	0.70	12.68	0.48	0.72	0.55	0.78	0.57	0.82	0.85
AUGUST	0.90	0.26	0.67	0.45	14.93	0.27	0.81	0.25	1.01	0.36	0.84	0.21
SEPT.	0.99	0.30	0.59	0.30	12.20	0.34	0.70	0.30	1.21	0.44	1.12	0.21
SEASON	0.68	0.43	0.52	0.17	11.65	0.06	0.69	0.22	0.78	0.34	0.71	-

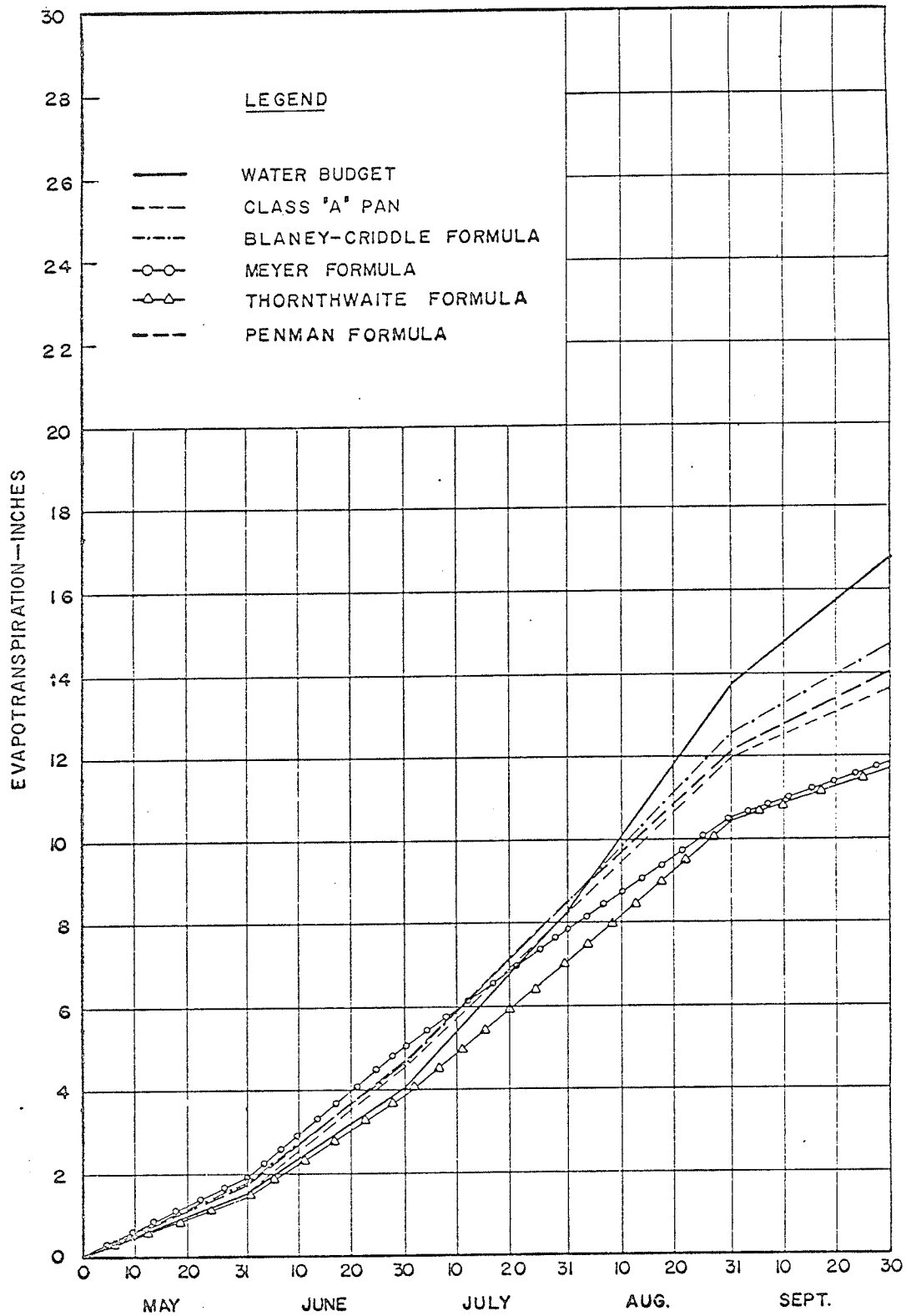


FIGURE 14 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1965

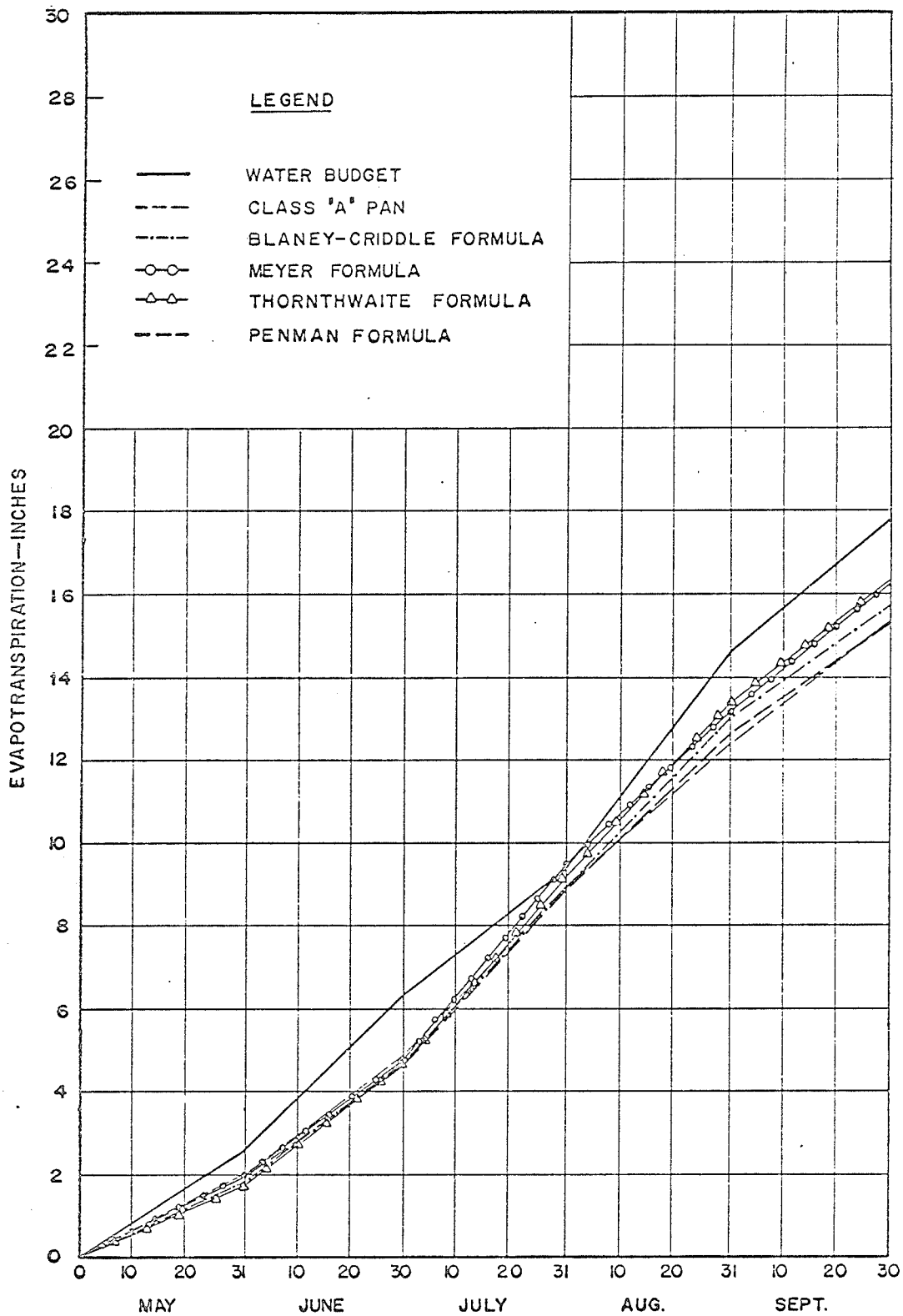


FIGURE 15 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1966

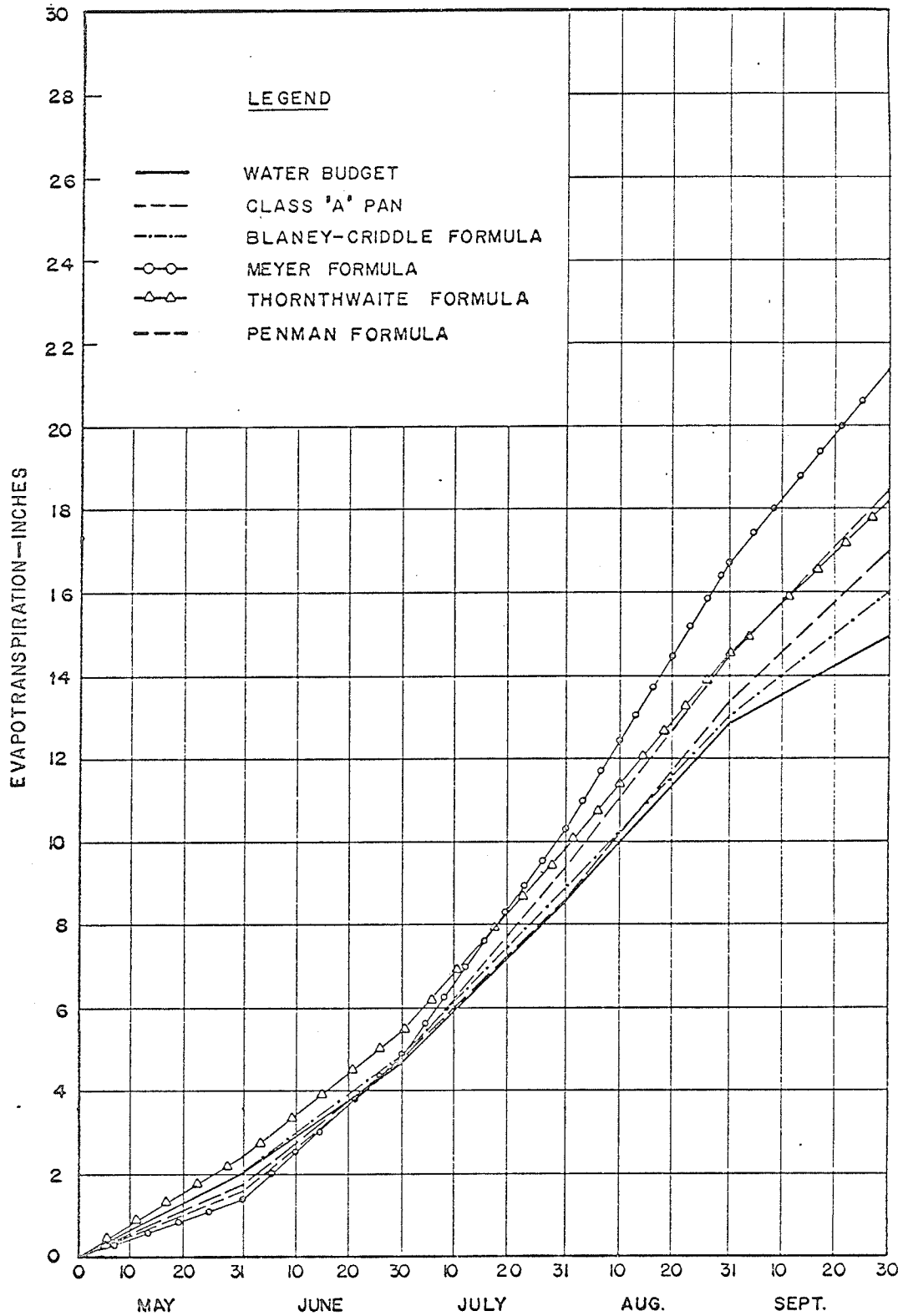


FIGURE 16 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1967

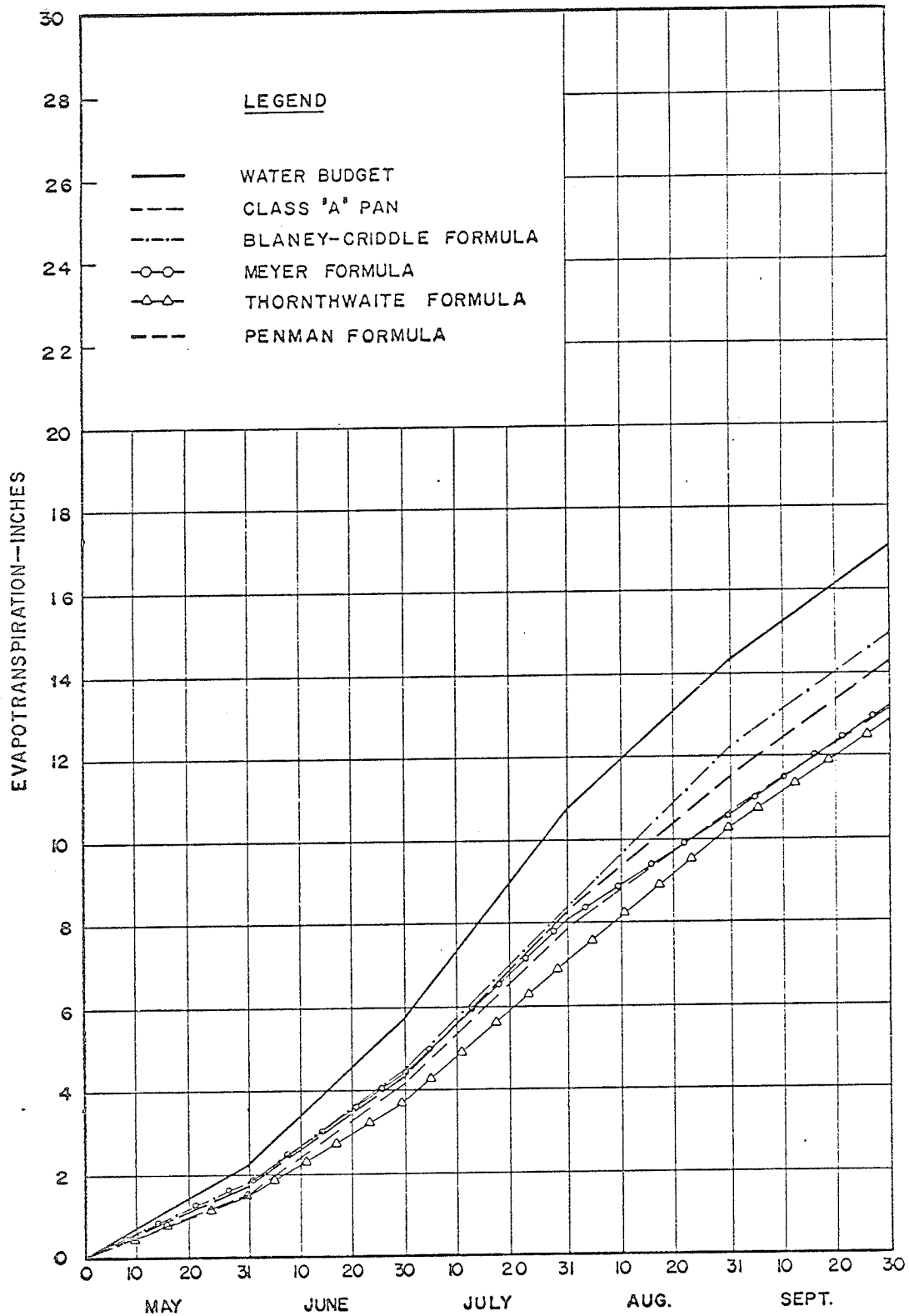


FIGURE 17 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1968

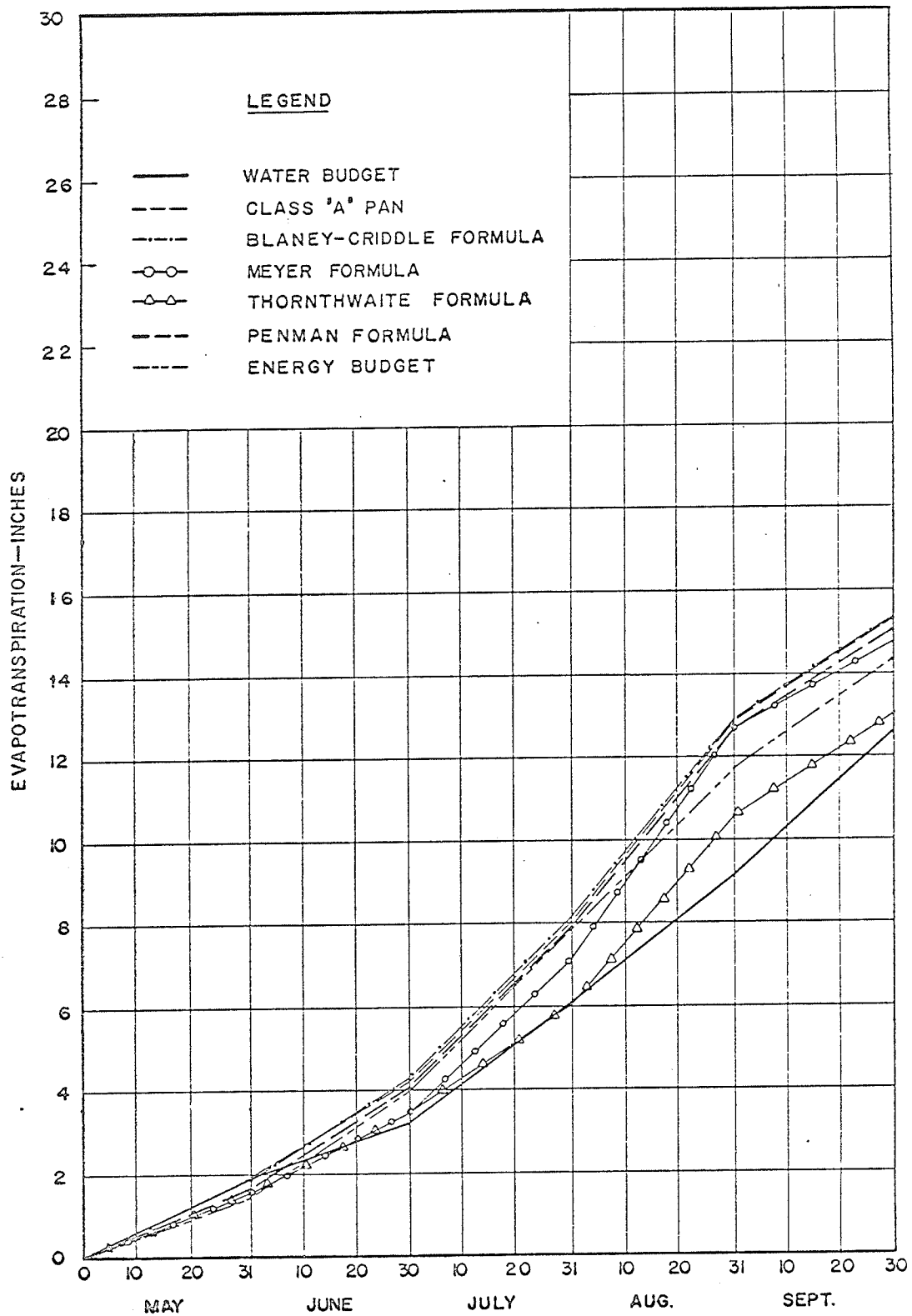


FIGURE 18 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1969

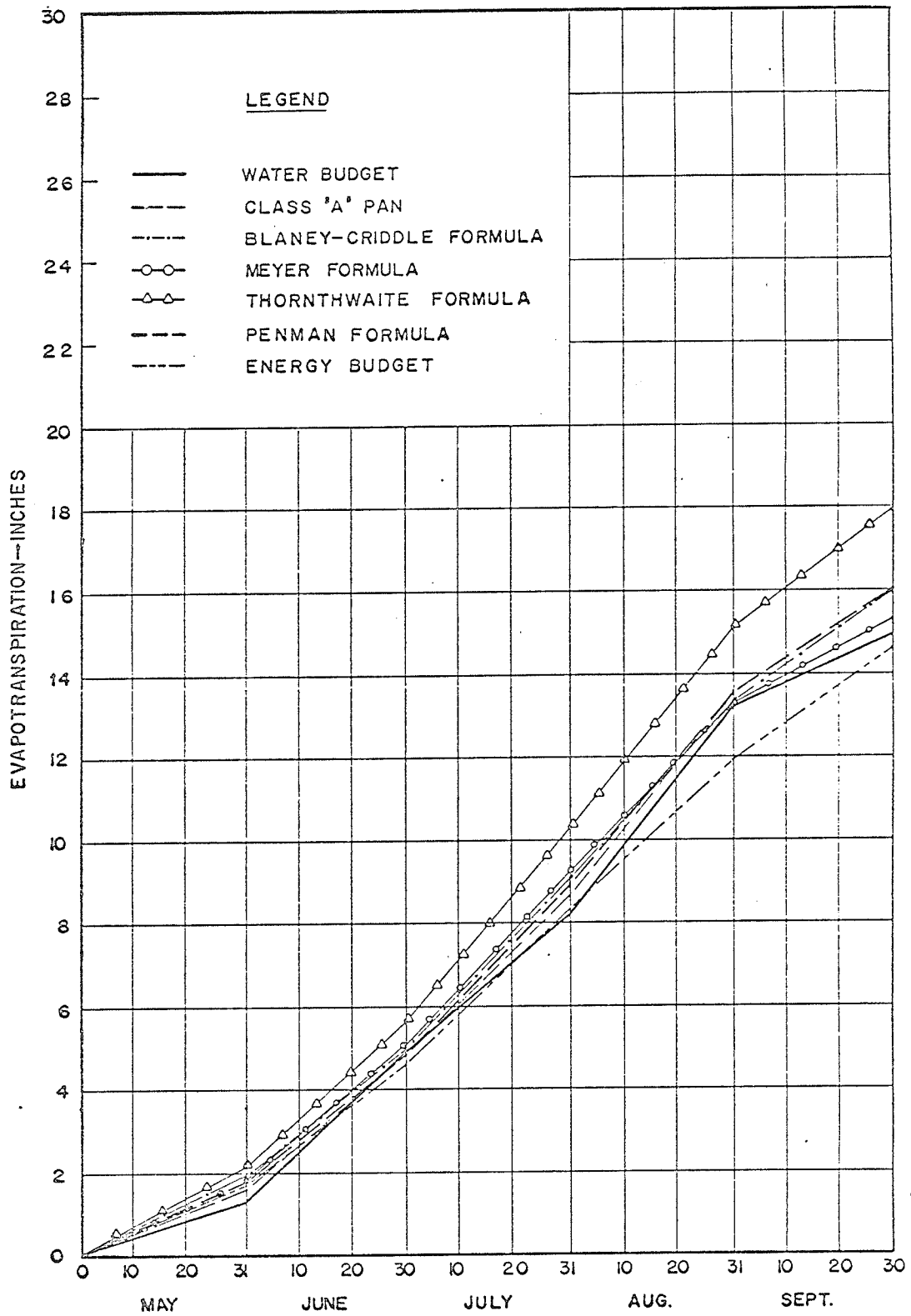


FIGURE 19 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1970

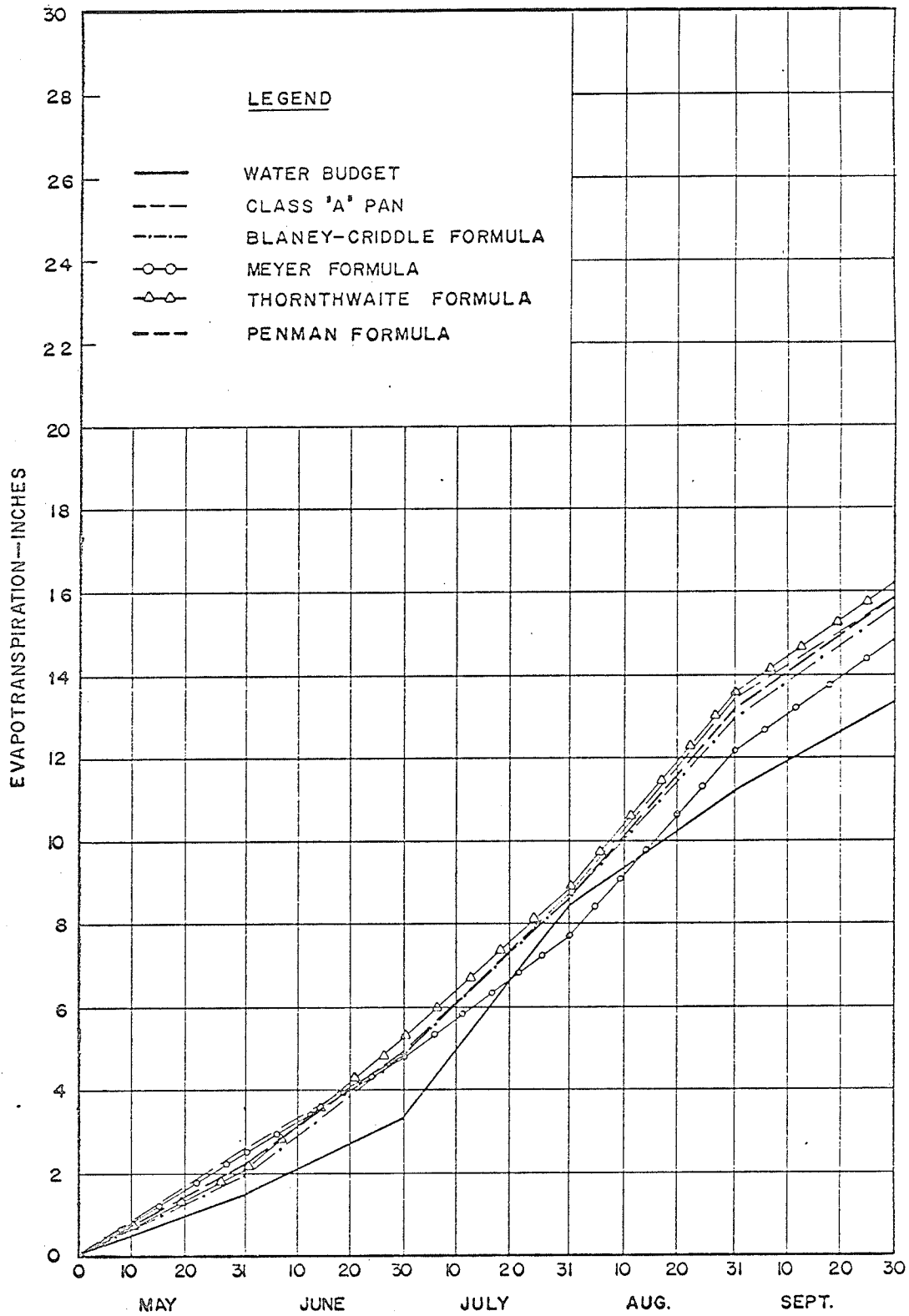


FIGURE 20 CUMULATIVE MEASURED AND COMPUTED  
EVAPOTRANSPIRATION FOR 1971

Blaney and Criddle (1950) list four localities which have a seasonal consumptive-use coefficient in the range of 0.51 to 0.75, for deciduous orchards. The seasonal coefficient of 0.52 calculated in this study falls within the range given by Blaney and Criddle. According to Criddle (1958) the range of the maximum monthly value is from 0.70 to 0.95. The maximum monthly value of 0.67 resulting from this study does not exceed the limits of 0.70 to 0.95. A comparison of the computed monthly values with those found by other researchers is difficult, as they usually deal with seasonal constants. The Blaney-Criddle formula was developed for irrigated crops, whereas this study deals with "natural" vegetation. In general, the Blaney-Criddle constants increase from May to August and decrease in September.

The Meyer equation or mass-transfer approach yielded constants ranging from 8.31 to 14.93, with a seasonal constant of 11.65. The coefficient normally applied to the Meyer equation for shallow lakes is 11.0 (Gray, 1970). The monthly constants for the Meyer formula have the same general trend as those of the Blaney-Criddle method. They increase from May to August and decrease in September.

Except for the month of June, the constants for the Thornthwaite formula have the same trend as the Blaney-Criddle and Meyer formulas. Comparison of the computed monthly values

with those found by other researchers is virtually impossible. The Thornthwaite formula was derived to provide an estimate of potential evaporation; no real provision was made to allow actual evapotranspiration to be estimated. The correlation coefficients given in Table 28 do indicate that the Thornthwaite method constants are as accurate as those of the other methods.

The Penman constants increase steadily throughout the season following the general pattern shown by the Class "A" Pan coefficients. Penman states that a coefficient of 0.80 should be applied for May - August and 0.70 for September. If these constants were averaged, the result would be 0.78 for the season, which is exactly the computed seasonal coefficient, although the May - August average value is .72 and September is 1.21.

The energy budget constants generally follow the trend of the Class "A" Pan and Penman coefficients. Other than by examining the correlation coefficients in Table 28, it is difficult to assess the accuracy of the energy budget constants. The energy budget has been used primarily to estimate lake evaporation and coefficients for use in estimating evapotranspiration are not available.

In general, the six alternate methods of estimating evapotranspiration may be divided into two groups. The first group, consisting of the Blaney-Criddle, mass-transfer, and Thornthwaite methods, is based largely on temperature or

indirectly on solar radiation in estimating evapotranspiration. These methods have constants which increase from May to August and decrease in September. A "natural" vegetation, which reaches maturity in August and subsequently requires less water in September, may produce this phenomenon of the constants peaking in August. The second group, consisting of the Class "A" Pan, Penman and energy budget methods, is characterized by coefficients which increase steadily throughout the season. This steady increase in the value of the monthly constants may be due to the lag of temperature behind radiation, which arises from the thermal storage of the soil. According to Pelton et. al. (1970), the least lag error in monthly estimates is in the period May to August. The fall estimates may be in serious error.

The underestimation of the September evapotranspiration by the Penman formula and energy budget may be explained by a changing albedo or reflectivity coefficient of the natural vegetation in September. The albedo was assumed constant throughout the period of study.

In summary, each of the six alternate methods should provide reasonable estimates of evapotranspiration in the Wilson Creek drainage basin when the coefficients listed in Table 28 are used with their respective formulas.

## CHAPTER VIII

### CONCLUSIONS

This study consisted of two parts. The first part was the calculation of the Wilson Creek water budget during the months of May to September for the years 1965 to 1971. The second part was an attempt to derive coefficients, applicable to the Wilson Creek drainage basin, which would allow actual evapotranspiration or consumptive use to be approximated when used with six methods of calculating potential evapotranspiration.

The calculation of the water budget required several assumptions to be made regarding such parameters as snowmelt, soil moisture, groundwater, etc. It is felt that these assumptions are valid and that the water budget and evapotranspiration (calculated as a residual) estimates are accurate.

Each of the six methods, Class "A" Pan, Blaney-Criddle formula, Meyer formula, Thornthwaite formula, Penman formula, and energy budget, when used with the appropriate coefficient, should provide reasonable monthly or seasonal estimates of actual evapotranspiration. Each of these methods, whether directly or indirectly, are controlled by the net solar radiation reaching the ground.

When the surface layer of a soil is wet, evaporation is indeed governed by atmospheric conditions which are primarily a result of solar radiation. However, as this layer dries out, the rate of evaporation decreases very rapidly. Evaporation then becomes dependent upon such things as the relative humidity of soil air, a diffusion coefficient, the capillary conductivity and the hydraulic conductivity of the surface layer (Gray, 1970).

From the above factors, it becomes apparent that evapotranspiration is dependent upon soil moisture properties as well as the evaporative capacity of the atmosphere. Formulas based essentially on atmospheric properties can never predicate exactly evapotranspiration if soil moisture is a limiting factor.

## SELECTED BIBLIOGRAPHY

- BLANEY, H.F., "Determining Evapotranspiration by Phreatophytes from Climatological Data". Transactions of the American Geophysical Union, Vol. 33-1, (1952), pp. 61-66.
- BLANEY, H.F. and CRIDDLE, W.D., "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data". United States Department of Agriculture, SCS TP96, Washington, D.C., 1950.
- BUTLER, S.S., Engineering Hydrology. New Jersey: Prentice-Hall, Inc., 1957.
- BYERS, H.R., General Meteorology. New York: McGraw-Hill Book Co., Inc., 1959.
- CASS, D.E., "Snowmelt as Predicted by a Surface Energy Balance". M.Sc. Thesis, Faculty of Graduate Studies, University of Manitoba, Winnipeg, 1970.
- CHOW, VEN TE, Handbook of Applied Hydrology. New York: McGraw-Hill Book Co., Inc., 1964.
- CRIDDLE, W.D., "Methods of Computing Consumptive Use of Water". J. of Irrig. and Drain. Div., ASCE Proc., Paper 1507-26, 1958.
- DAVIS, S.N. and DE WIEST, R.J.M., Hydrogeology. New York: John Wiley and Sons, Inc., 1966.
- DEACON, E.L., PRIESTLEY, C.H.B., and SWINBANK, W.C., "Evaporation and the Water Balance". Climatol. Revs. of Research, UNESCO Arid Zone Research Ser., 10 (1958) pp. 9-34.
- EAGLESON, P.S., Dynamic Hydrology. New York: McGraw-Hill Book Co., Inc., 1970.
- FARVOLDEN, R.N., "Methods of Study of the Groundwater Budget in North America". Groundwater, General Assem. of Bern, Sept-Oct. 1967, pp. 108-125.
- GRAY, D.M., Handbook on the Principles of Hydrology. National Research Council of Canada, Ottawa, 1970.

- KOHLER, M.A., "Lake and Pan Evaporation". U.S. Geol. Survey, Prof. Paper 269, 1954, pp. 127-148.
- LEBEDIN, J., Personal communication, 1972.
- LINSLEY, R.K. JR., KOHLER, M.A., and PAULHUS, J.L.H., Applied Hydrology. New York: McGraw-Hill Book Co., Inc., 1949.
- MackAY, G.H., "A Quantitative Study of the Geomorphology of the Wilson Creek Watershed, Manitoba". M.Sc. Thesis, Faculty of Graduate Studies, University of Manitoba, Winnipeg, 1970.
- MackAY, G.H. and STANTON, C.R., "Wilson Creek Study, Erosion and Sedimentation Control". Proceedings of Hydrology Symposium No. 4, NRC, Assoc. Committee on Geodesy and Geophysics, Subcommittee on Hydrology, Ottawa, 1965, pp. 41-77.
- MARCIANO, J.J., and HORBECK, C.E., "Mass Transfer Studies". U.S.G.S., Profess. Paper 269, 1954, pp. 46-70.
- McCULLOUGH, G.K., Unpublished Report, 1972.
- McKAY, G.A., "Evaporation from Weyburn Reservoir Progress Report 1960-61". Canada Dept. of Agric., P.F.R.A., March, 1962.
- MEINZER, O.E., Hydrology. New York: Dover Publications, Inc., 1942.
- MORTON, F.I., "Potential Evaporation and River Basin Evaporation". J. of Hyd. Div., ASCE., Nov. 1965, pp. 67-97.
- MUNN, R.E., and TRUHLAR, E.J., "The Energy Budget Approach to Heat Transfer at the Surface of the Earth". EIC Trans., Vol. 6, July, 1963,
- NEWBURY, R.W., CHERRY, J.A., and COX, R.A., "Groundwater-Streamflow Systems in Wilson Creek Experimental Watershed, Manitoba". Can. Jour. Earth Sciences, Vol. 6, No. 4 (1969), pp. 613-623.

- PELTON, W.L., KING, K.M., and TURNER, C.B., "An Evaluation of the Thornthwaite Method for Determining Potential Evapotranspiration". Agron. Jour., 52 (1960), pp. 387-395.
- PENMAN, H.L., "Estimating Evaporation". Trans. Am. Geophys. Union, 37 (1956b), pp. 43-50.
- POYSER, E.A. and PRATT, L., "Detailed Report on Reconnaissance Soil Survey of Wilson Creek Watershed". Unpublished report.
- RITCHIE, J.C., 1958, unpublished report.
- SCHWARTZ, F.W., "Geohydrology and Hydrogeochemistry of Groundwater: Streamflow Systems in the Wilson Creek Experimental Watershed". M.Sc. Thesis, Faculty of Graduate Studies, University of Manitoba, Winnipeg, 1970.
- SHJEFLO, J.B., "Evapotranspiration and the Water Budget of Prairie Potholes in North Dakota". Geol. Survey Prof. Paper 585B, 1968.
- SONMAR, L.G., "Seasonal Consumptive Use of Water by Crops Grown in Southern Alberta and Its Relationship to Evaporation". Can. J. Soil Sci., 43 (1963), pp. 287-297
- TANNER, C.B., and PELTON, W.L., "Potential Evapotranspiration Estimates by the Approximate Energy Balance Method of Penman". Journal of Geophys. Res., Vol. 65, No. 10, Oct. 1960, pp. 3391-3413.
- THORNTHWAITTE, C.W., and MATHER, J.R., "The Water Balance". Public in Climatol., 8 (1), 1955, pp. 5-86.
- WARD, R.C., "Measuring Potential Evapotranspiration". Geography, 48 (1963), pp. 49-55.
- WARD, R.C., "Checks on the Water Balance of a Small Catchment". Nordic Hydrology, 3 (1972), pp. 44-63.

A P P E N D I X 1

SOIL MOISTURE DATA

APPENDIX TABLE 1.1

SOIL MOISTURE ZONES FOR 1965-1970

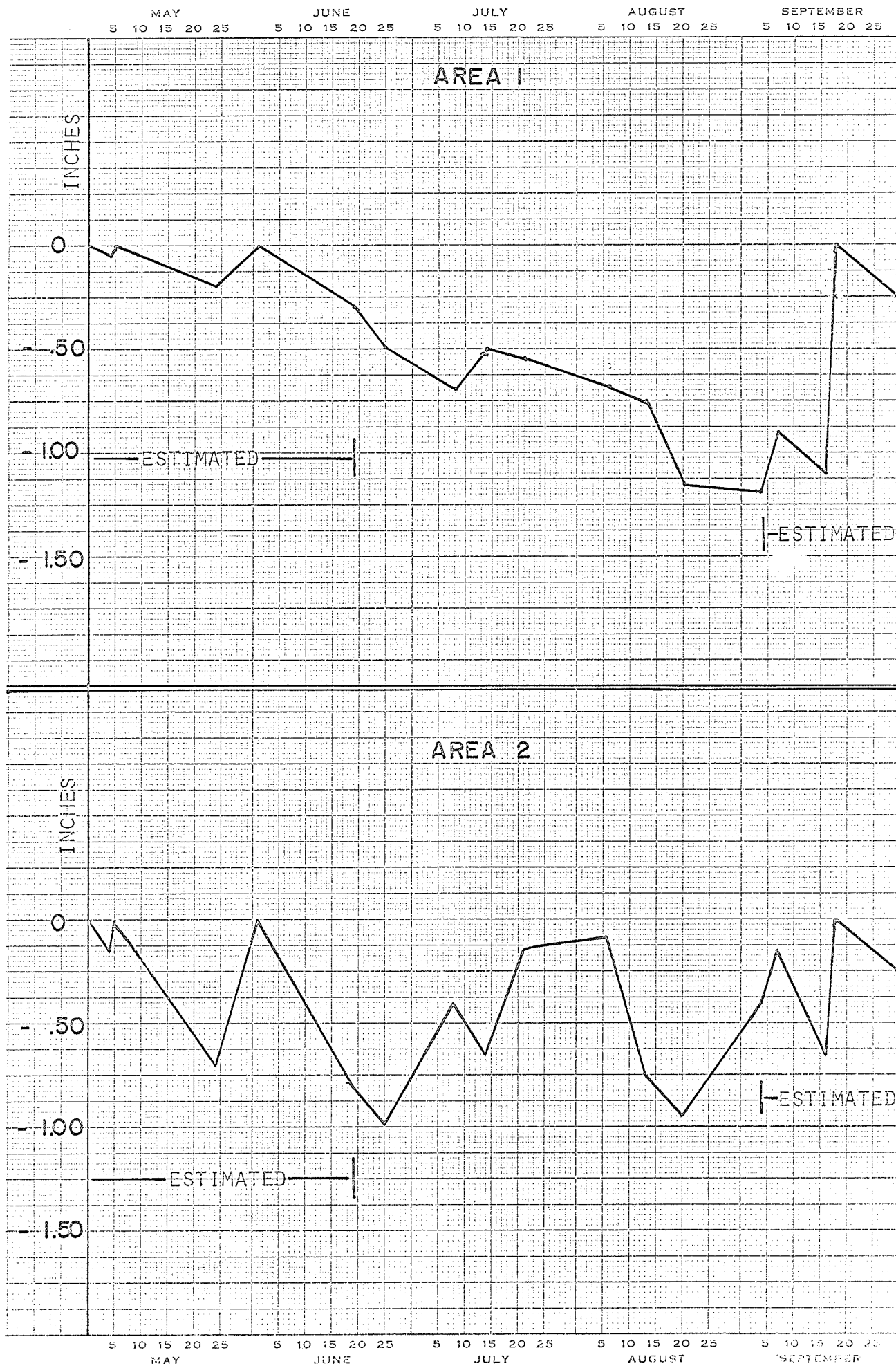
ZONE	SOIL MOISTURE SAMPLE LOCATIONS	SOIL TYPE	AREA ACRES
1	3, 4, 5	Alsh	217
		Wp	404
		Wp(s)	518
		Wp-Ts	128
		CK	1391
		B	434
		Wn-CK	434
		<u>3527</u>	
2	1, 2	B1	89
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		Gv	730
		Gv-B	99
		<u>1914</u>	

APPENDIX TABLE 1.2

SOIL MOISTURE ZONES FOR 1971

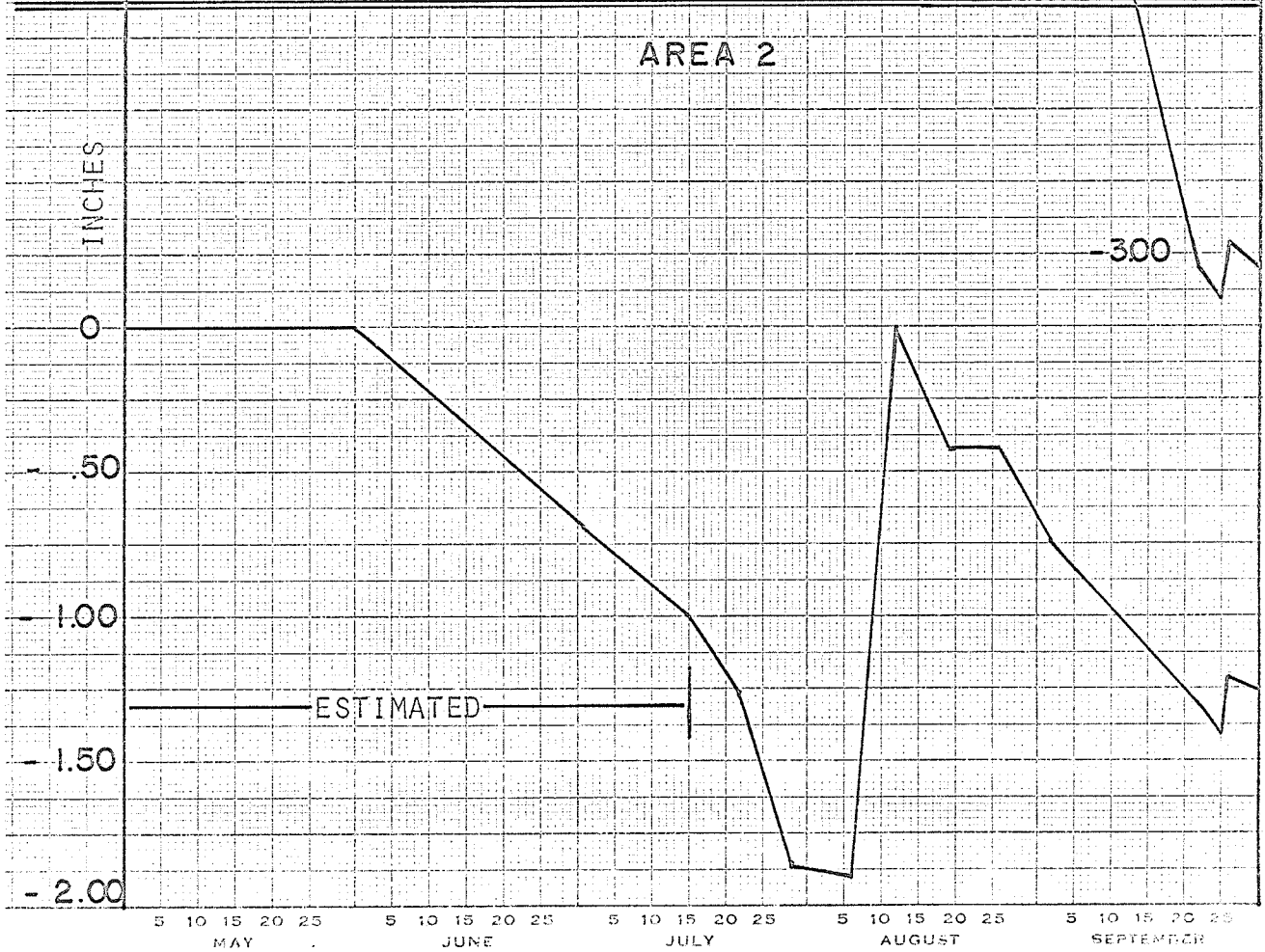
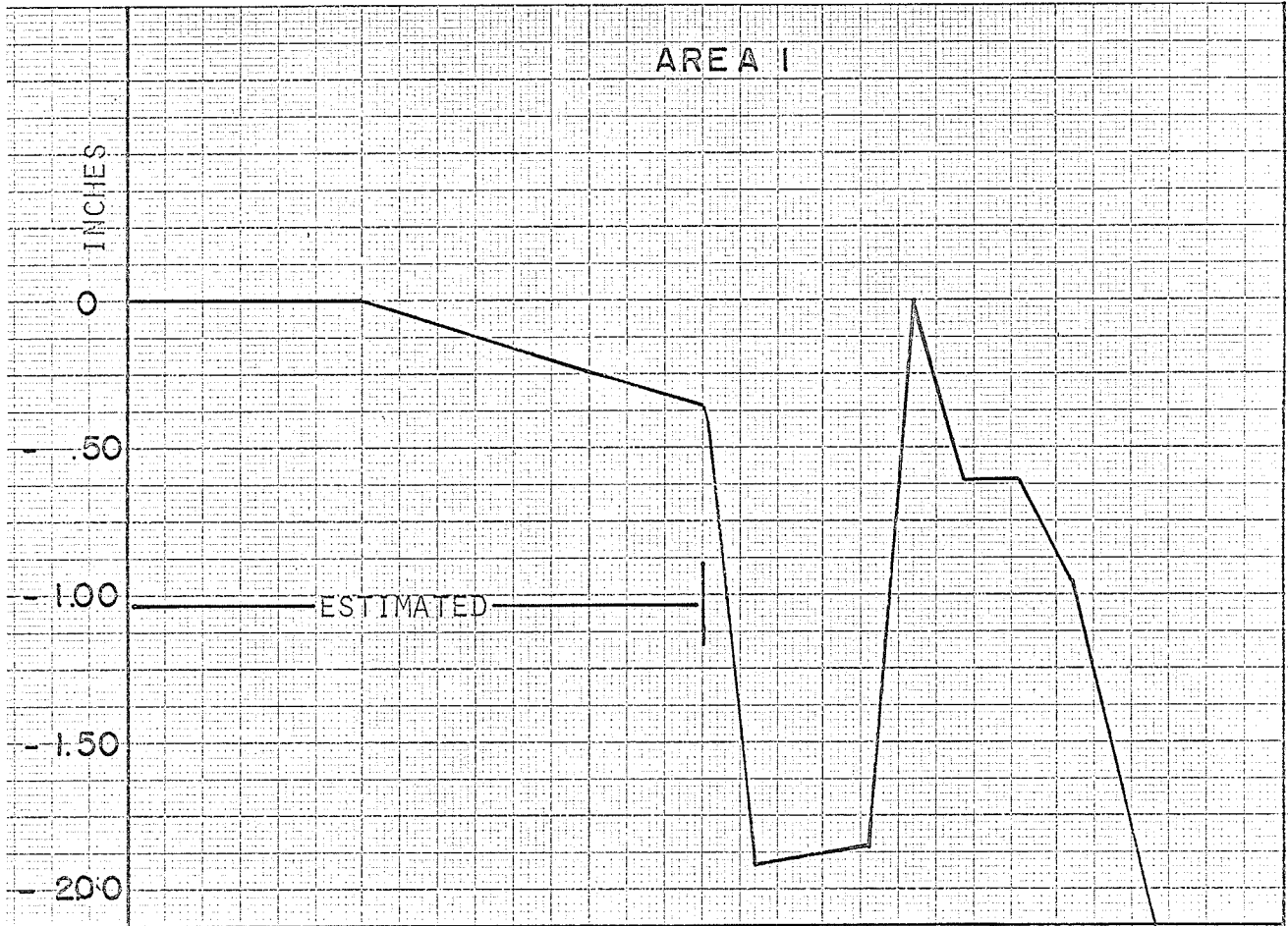
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		B	434
		Gv	730
		Gv-B	99
		<u>1352</u>	
2	2, 6, 7	CK	1391
		CK(s)	996
		<u>2387</u>	
3	5	Wn-CK	434
4	8	Wp	404
		Wp(s)	518
		Wp-Ts	128
		<u>1050</u>	
5	9	Alsh	217

# SOIL MOISTURE DEFICIT 1965



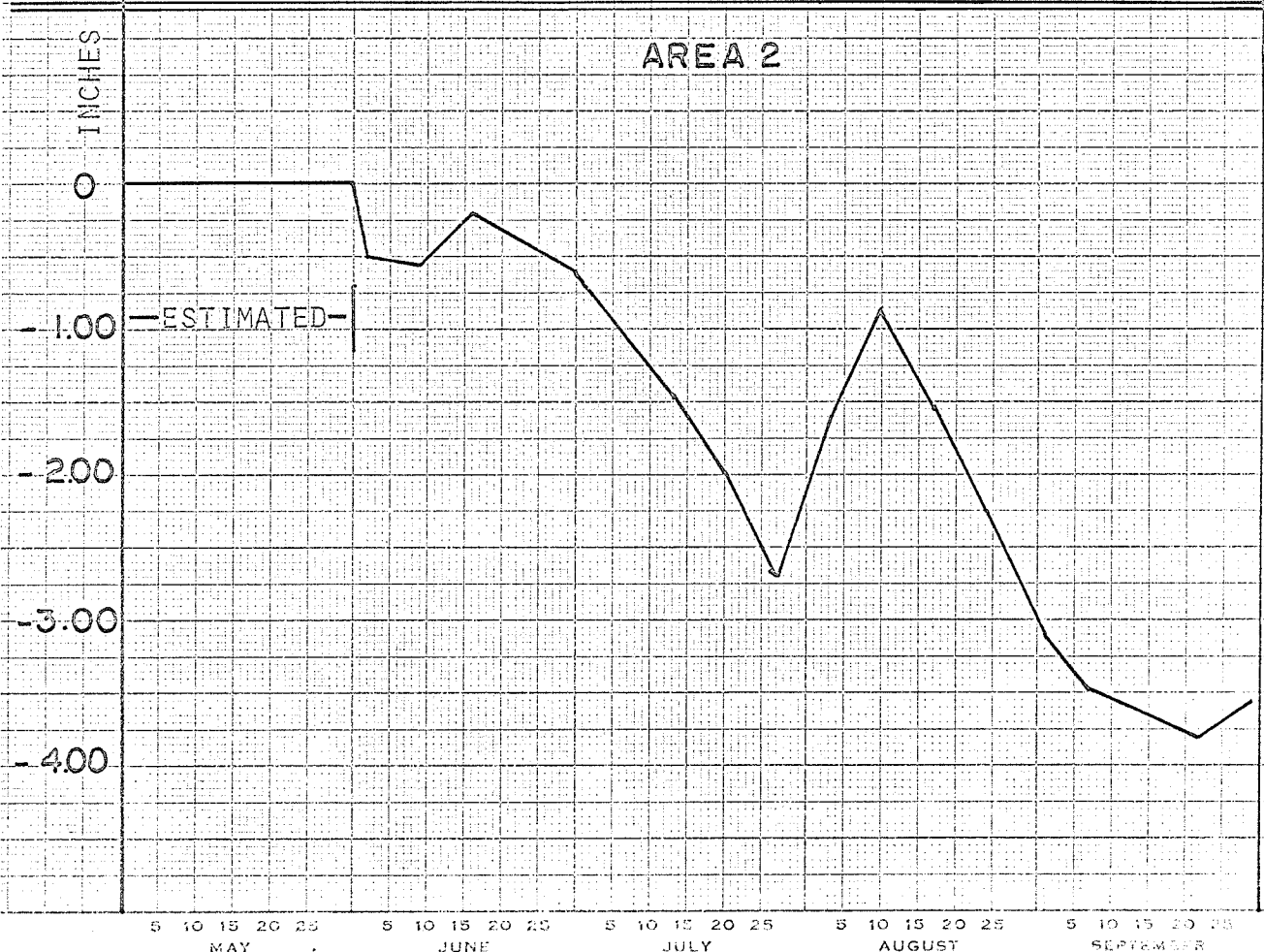
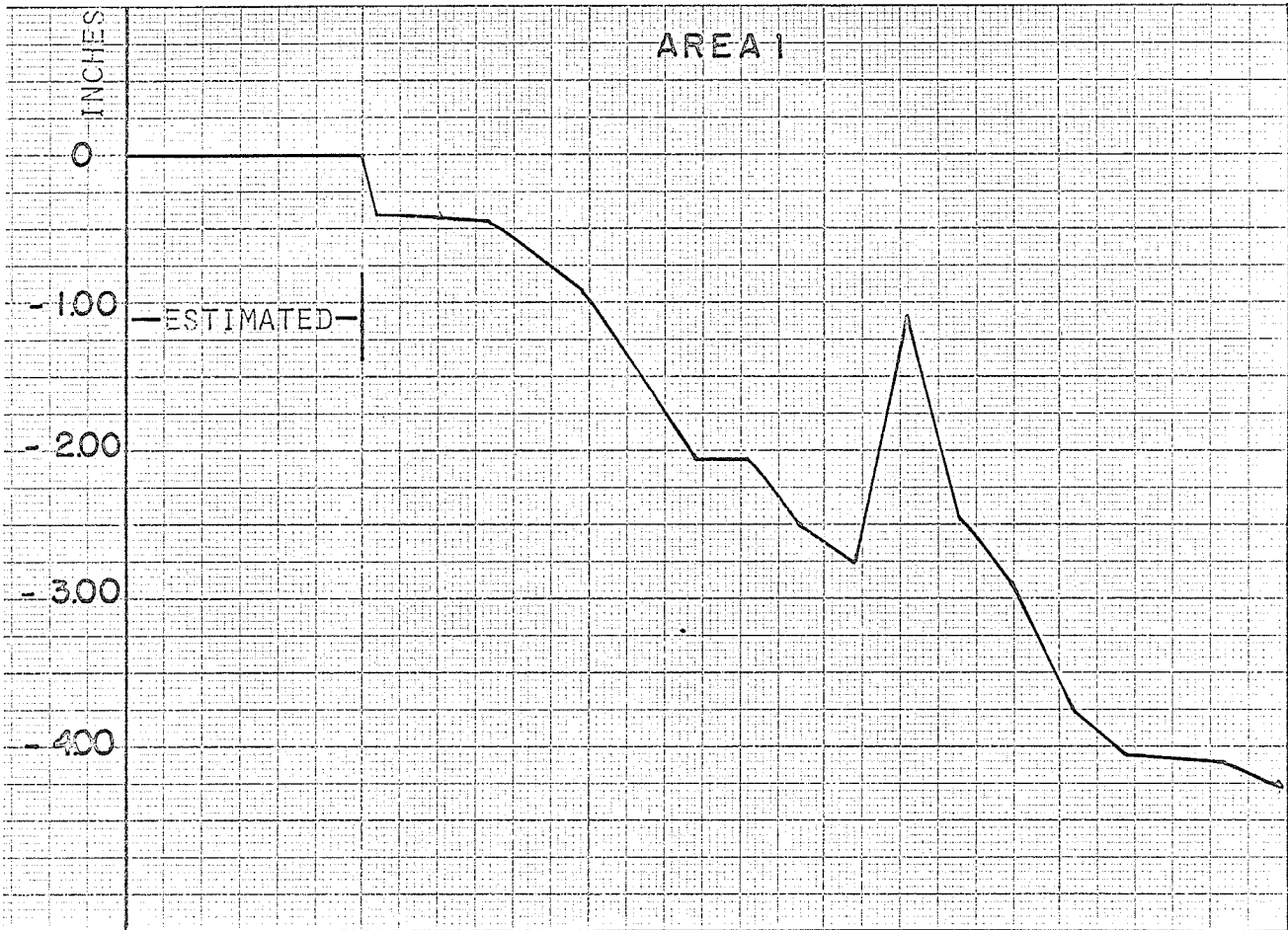
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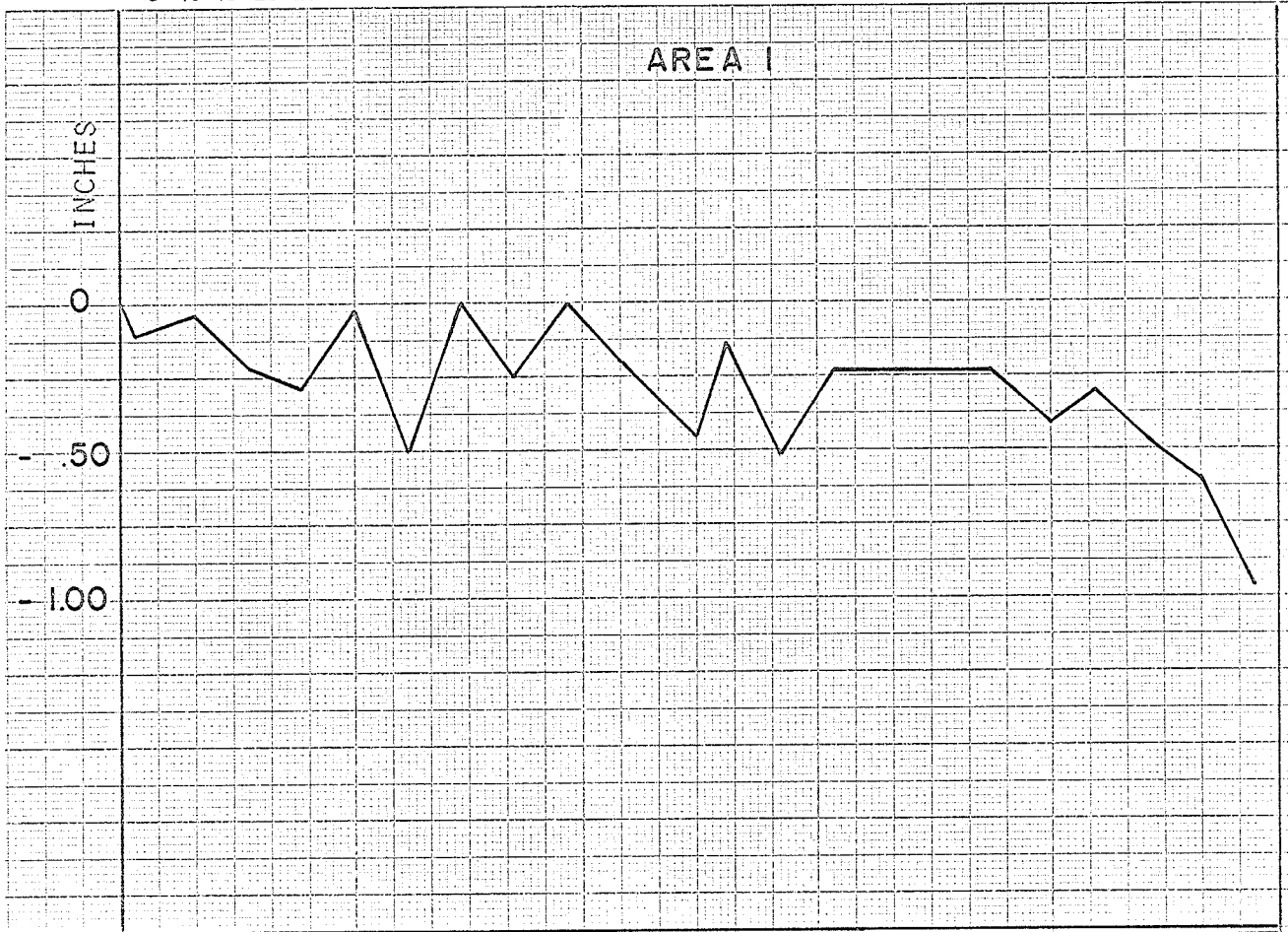
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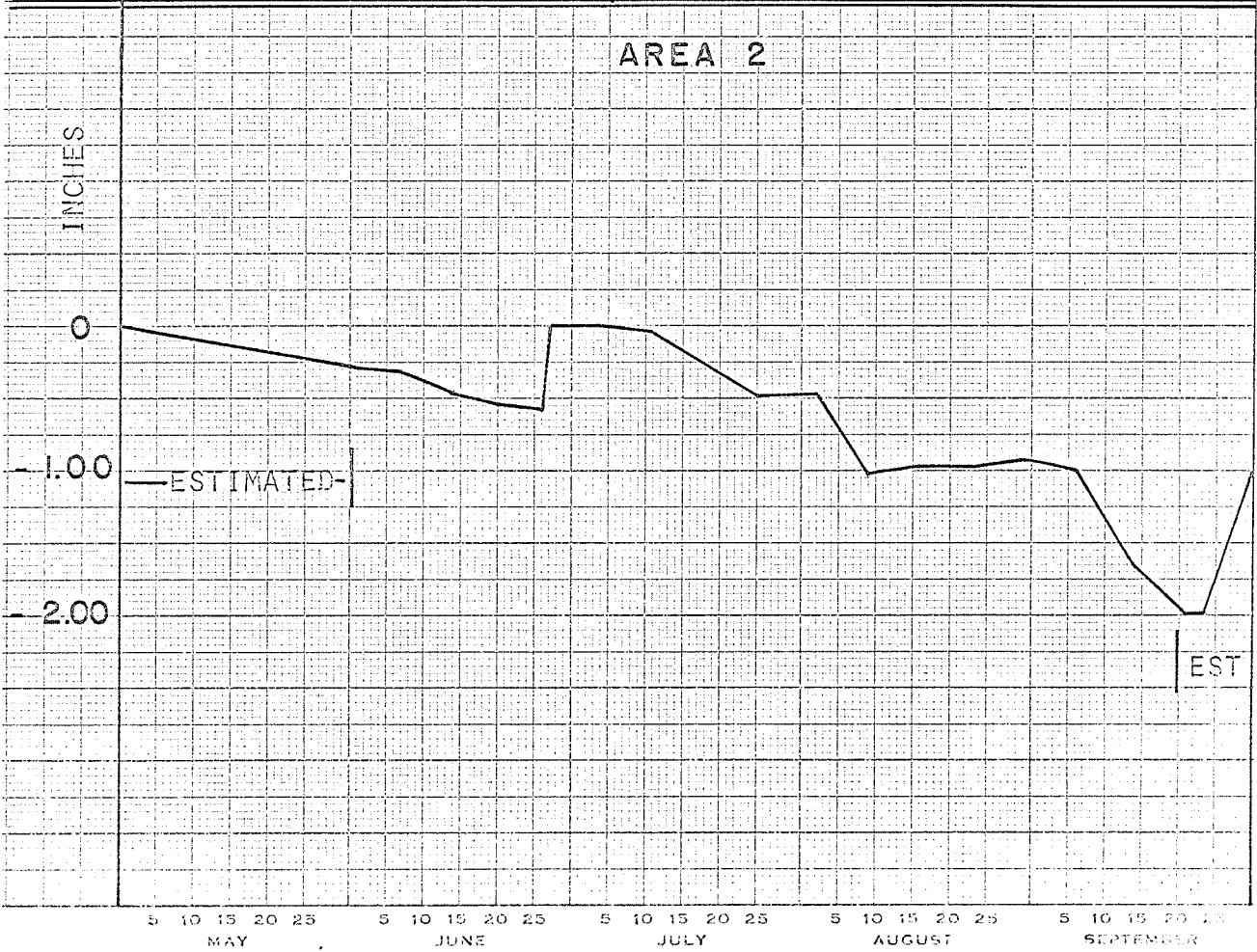
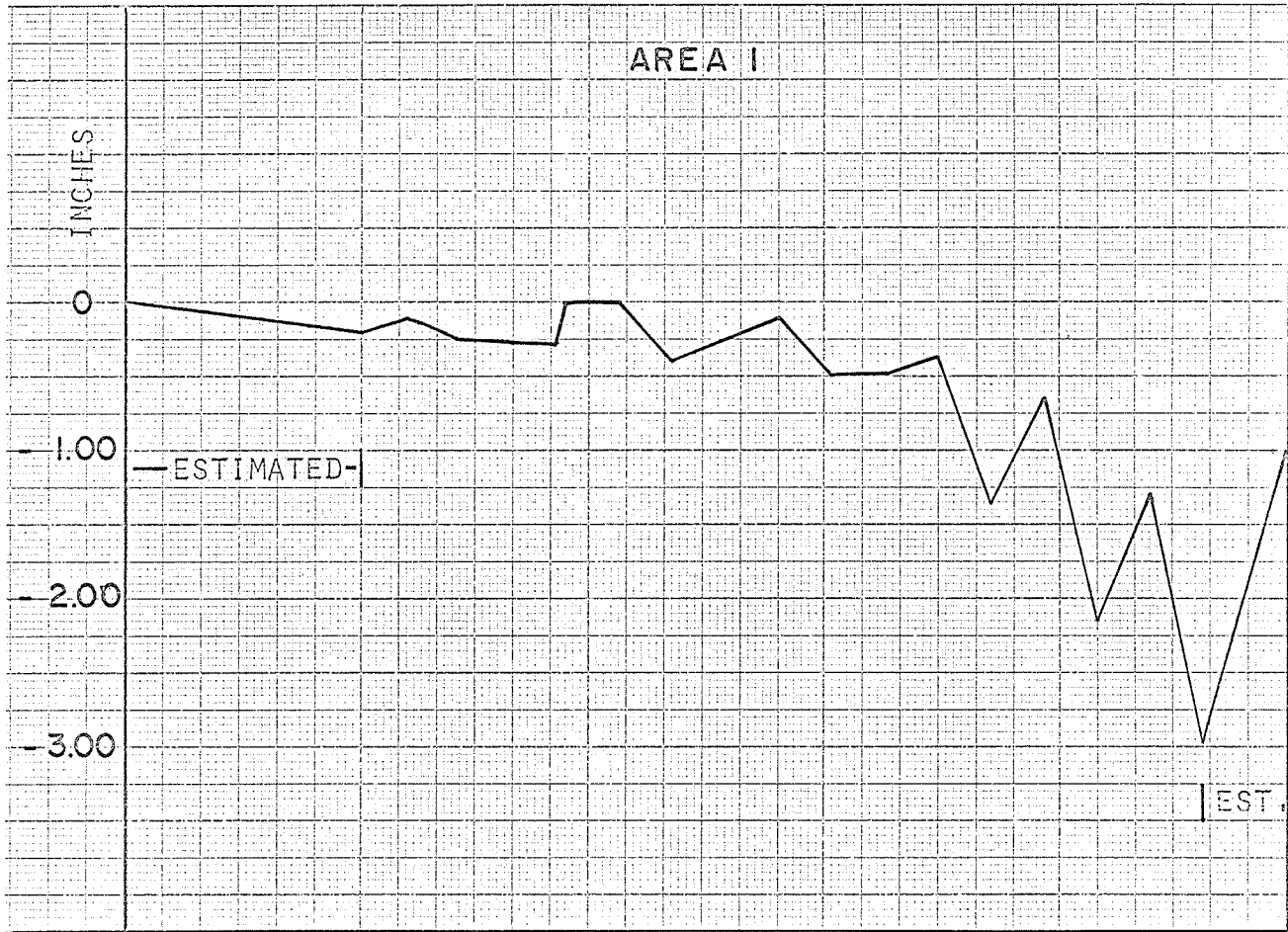
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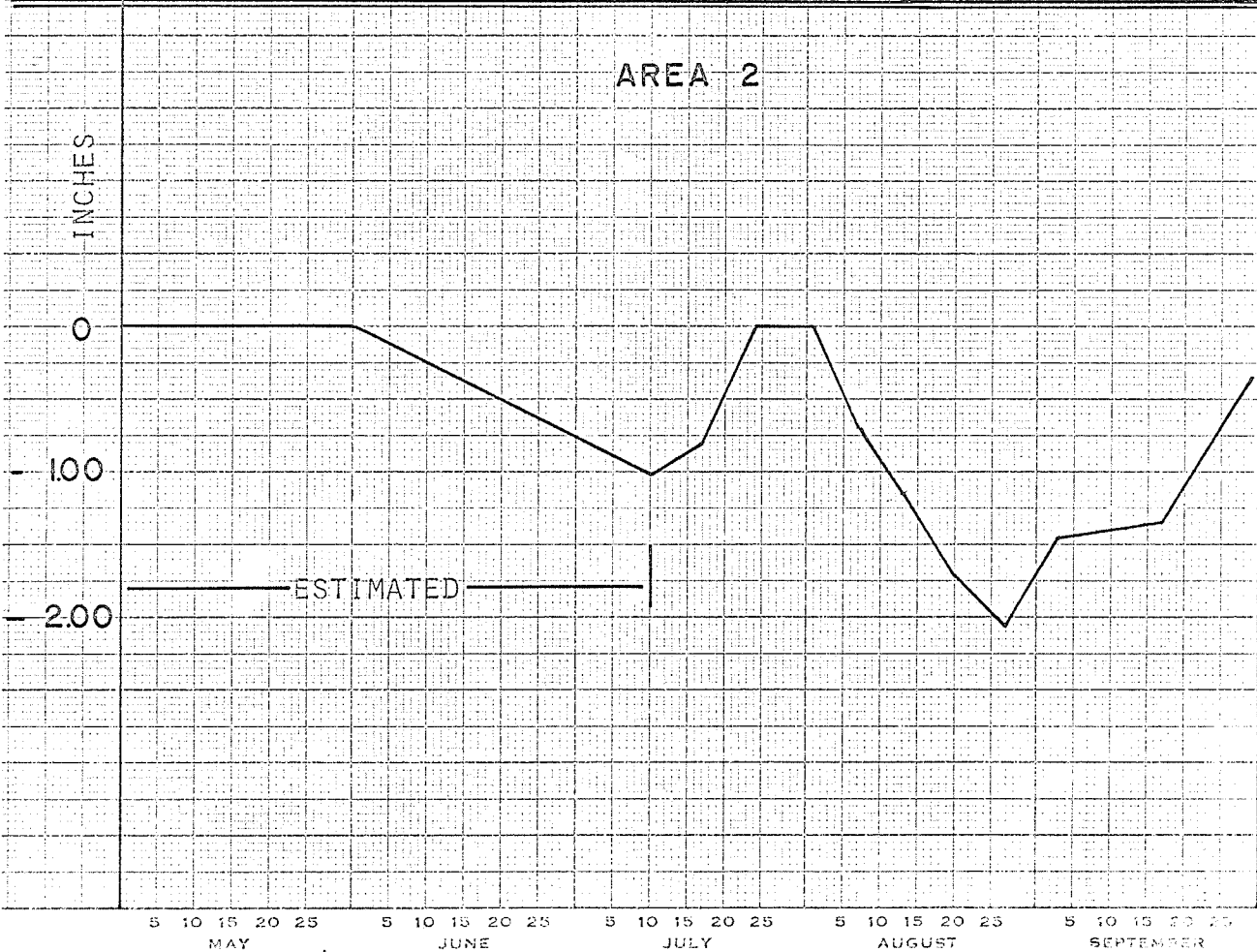
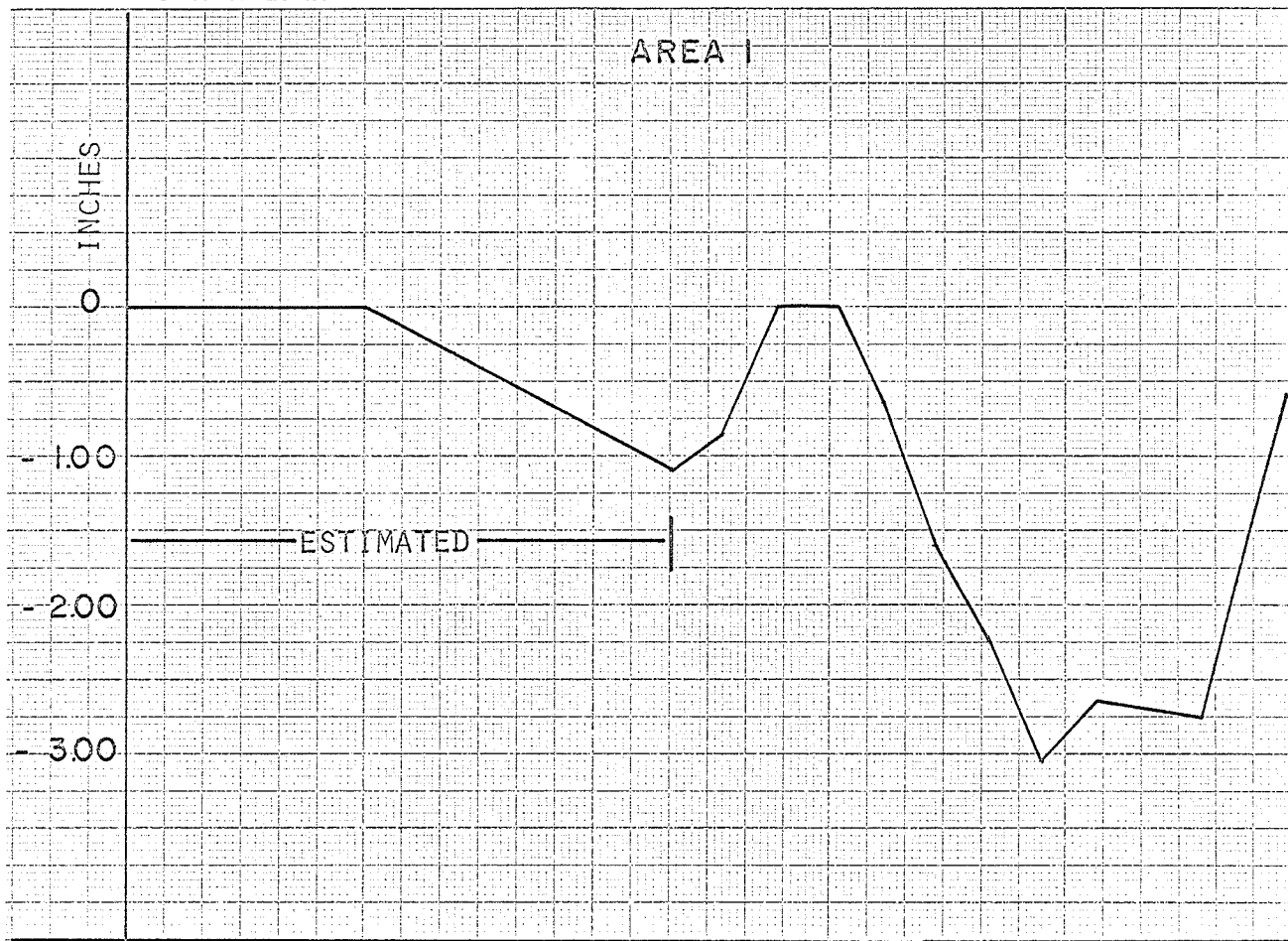
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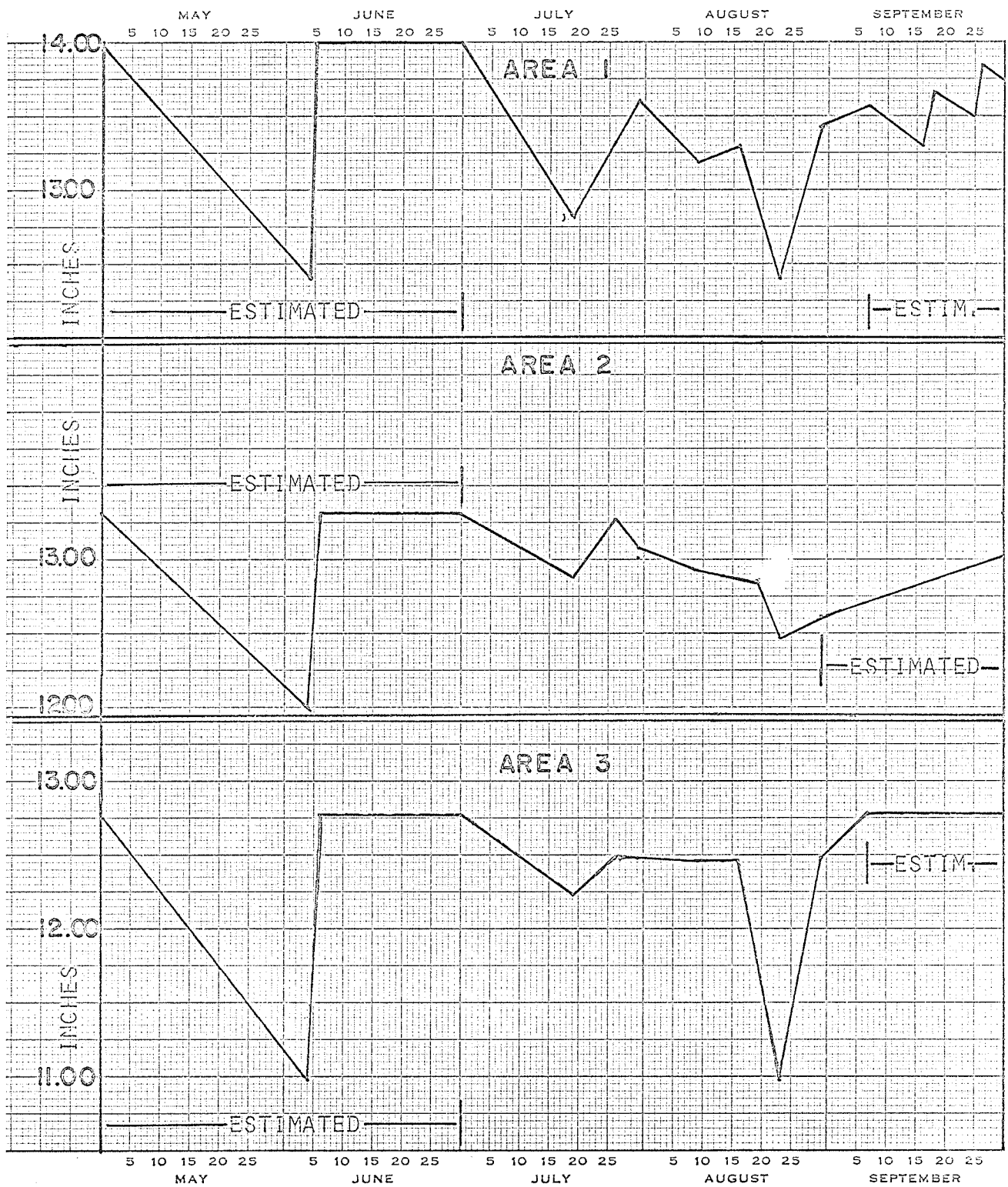


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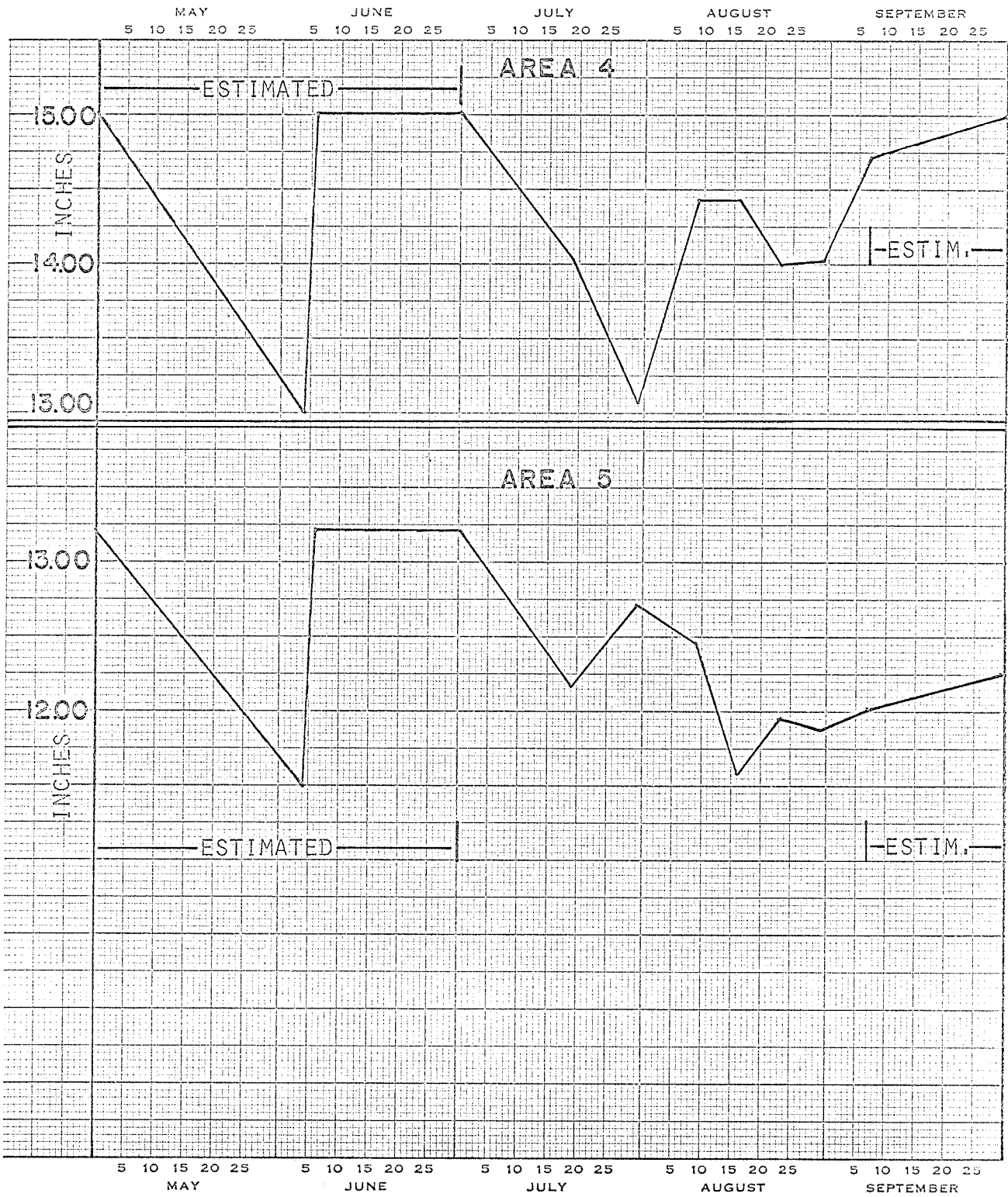
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### SOIL MOISTURE CONTENT 1971



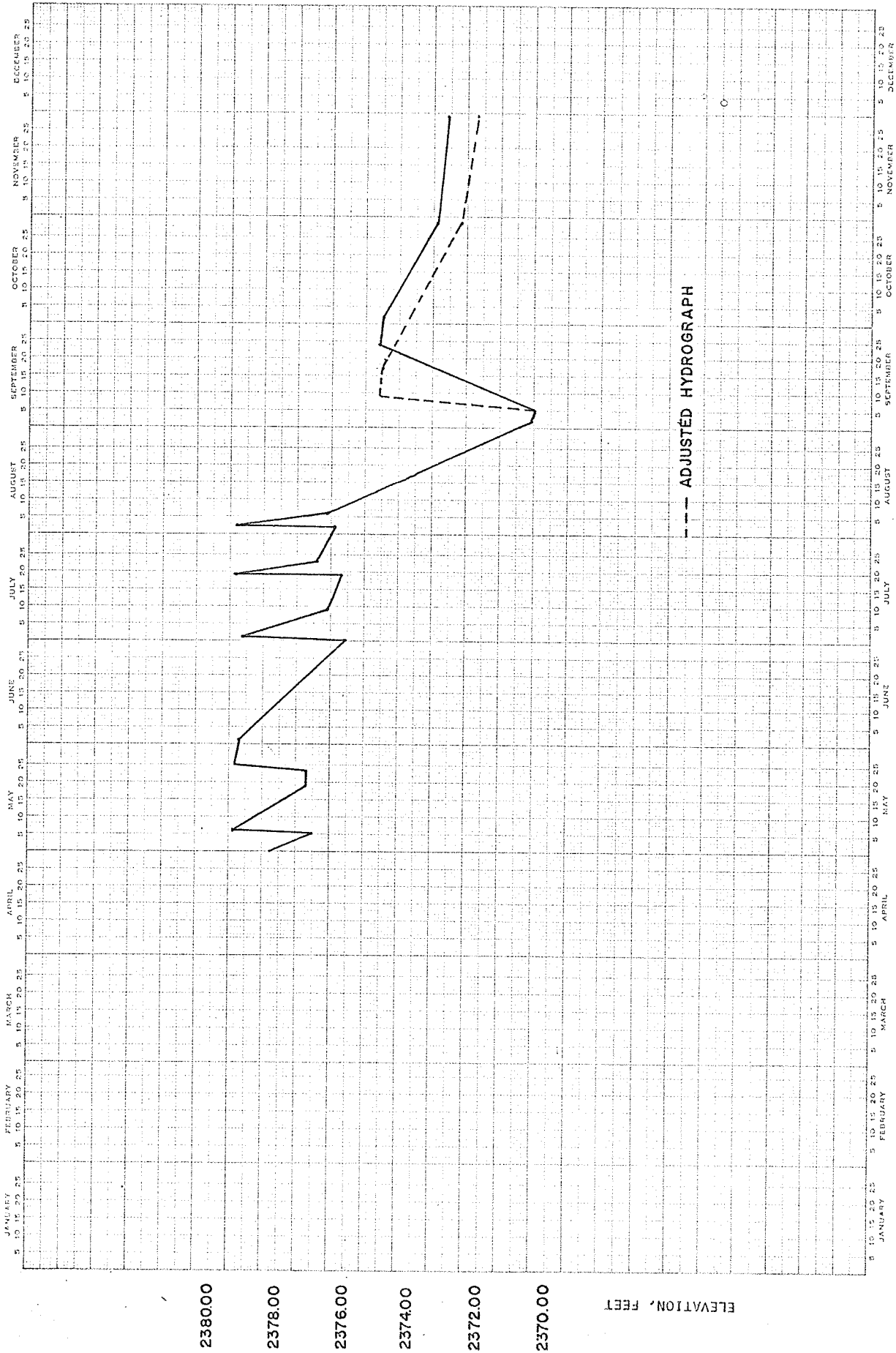
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A P P E N D I X 2

WATERTABLE WFLH HYDROGRAPHS 1965-1971

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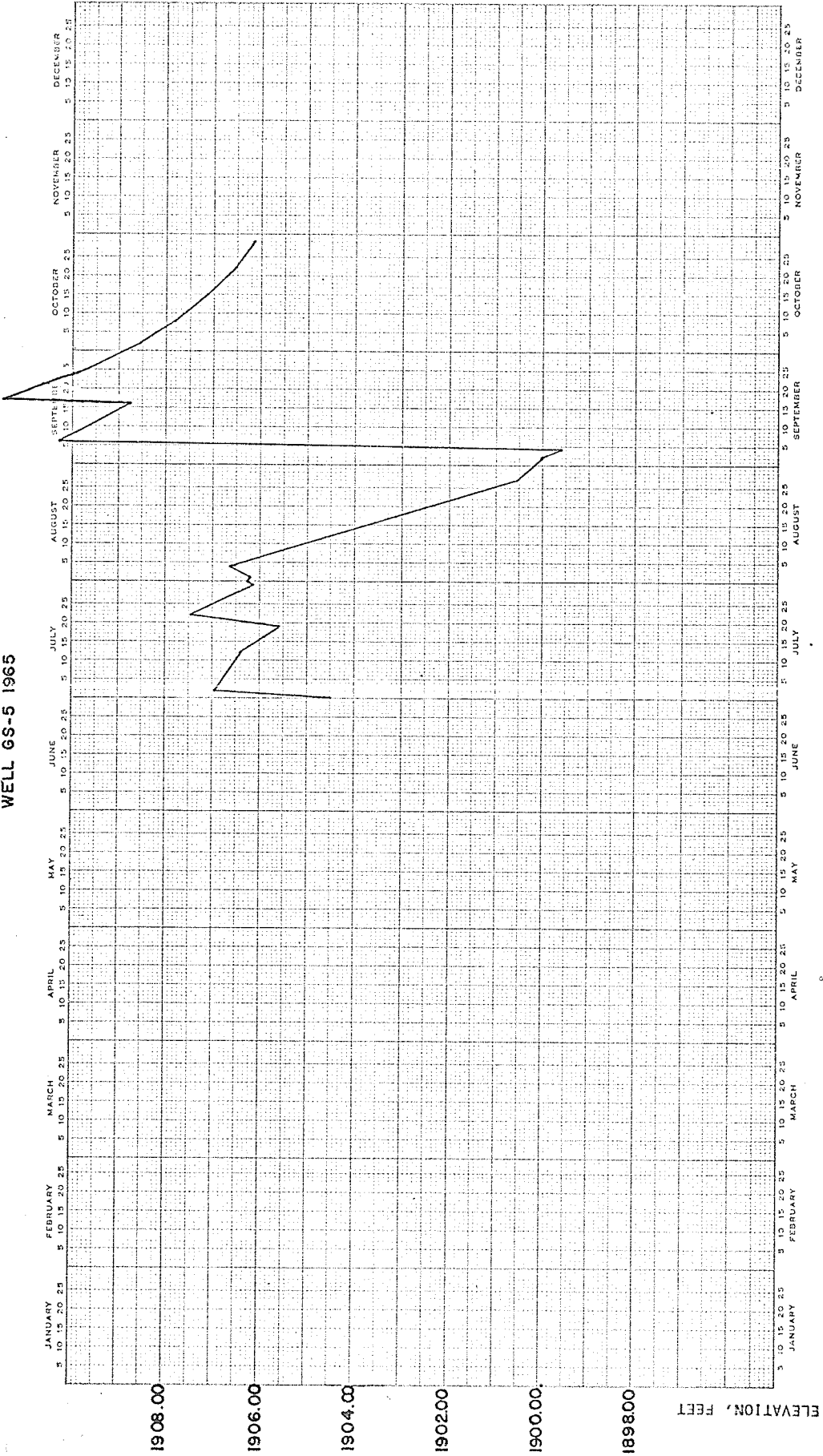


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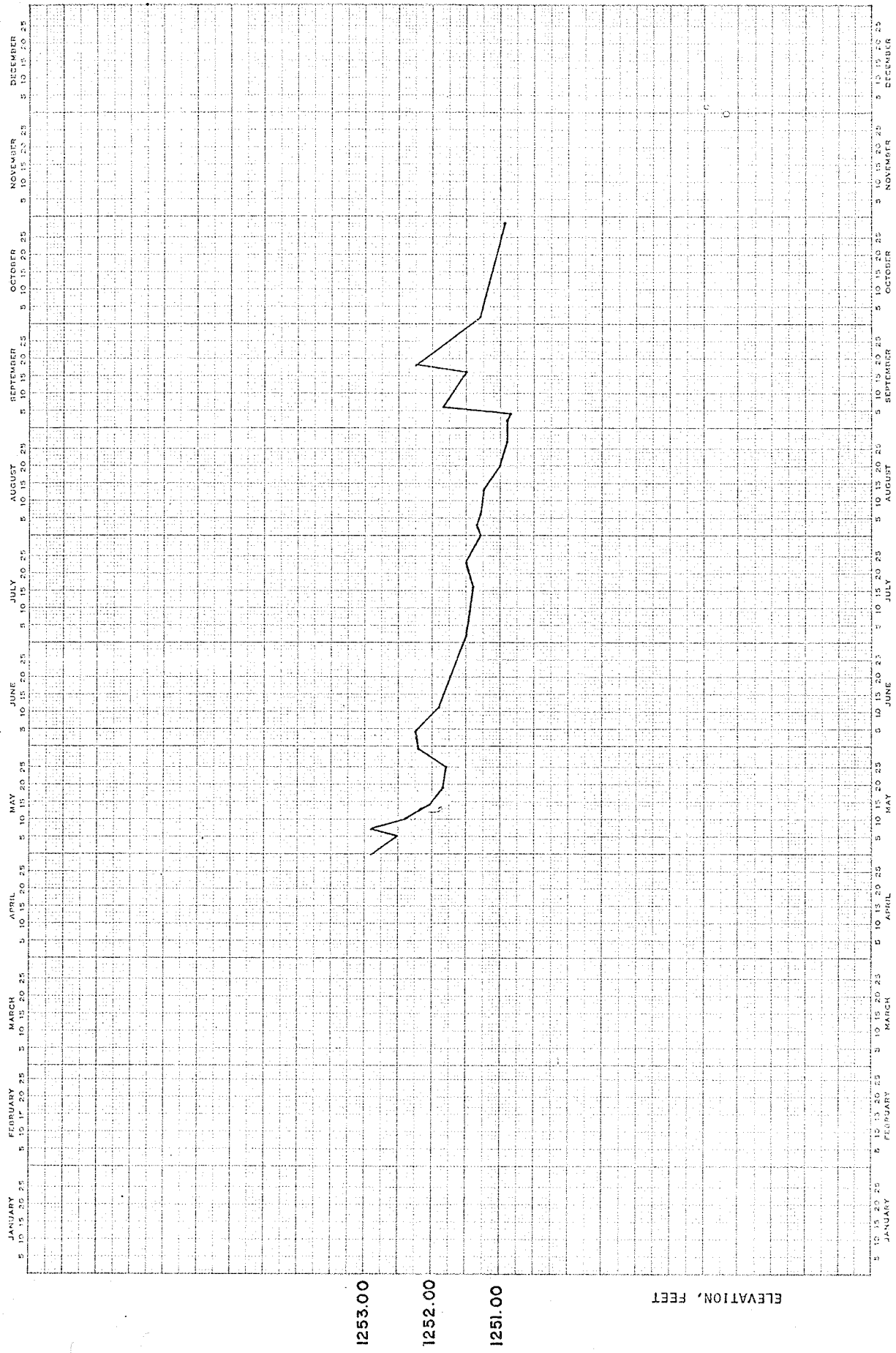
ELEVATION, FEET

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WELL GS-5 1965



WELL GS-2 1965



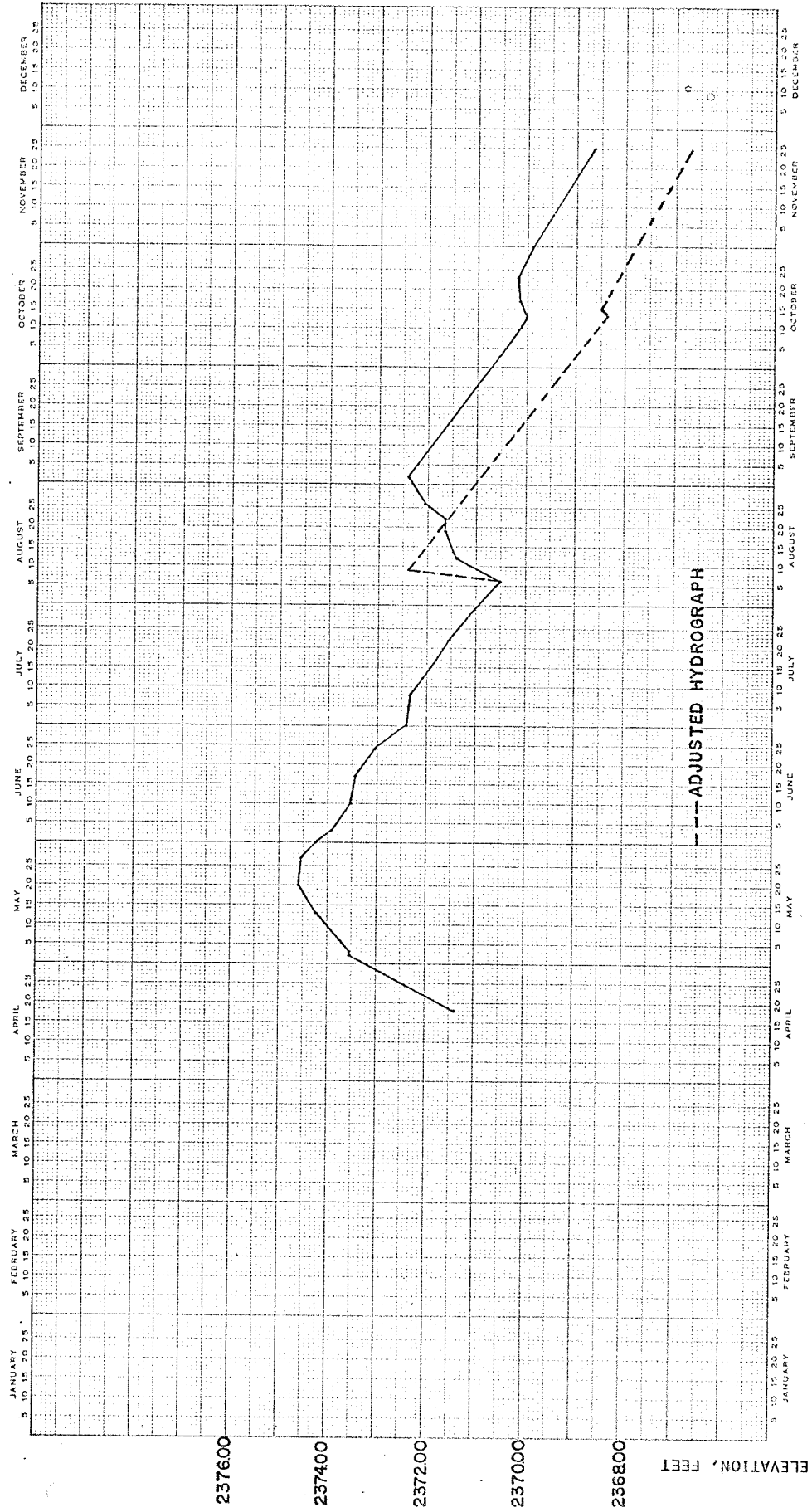
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1251.00

ELEVATION, FEET

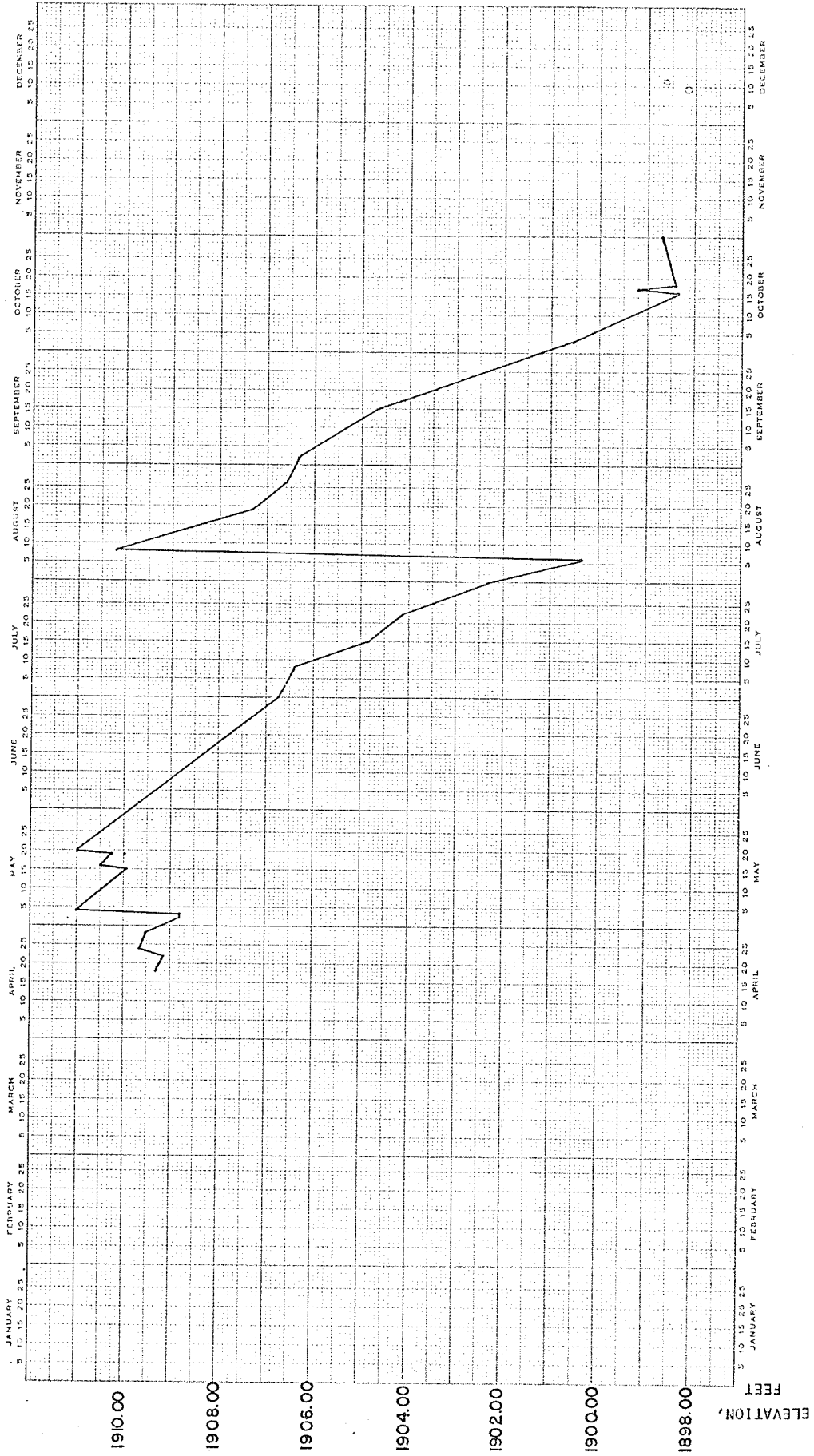
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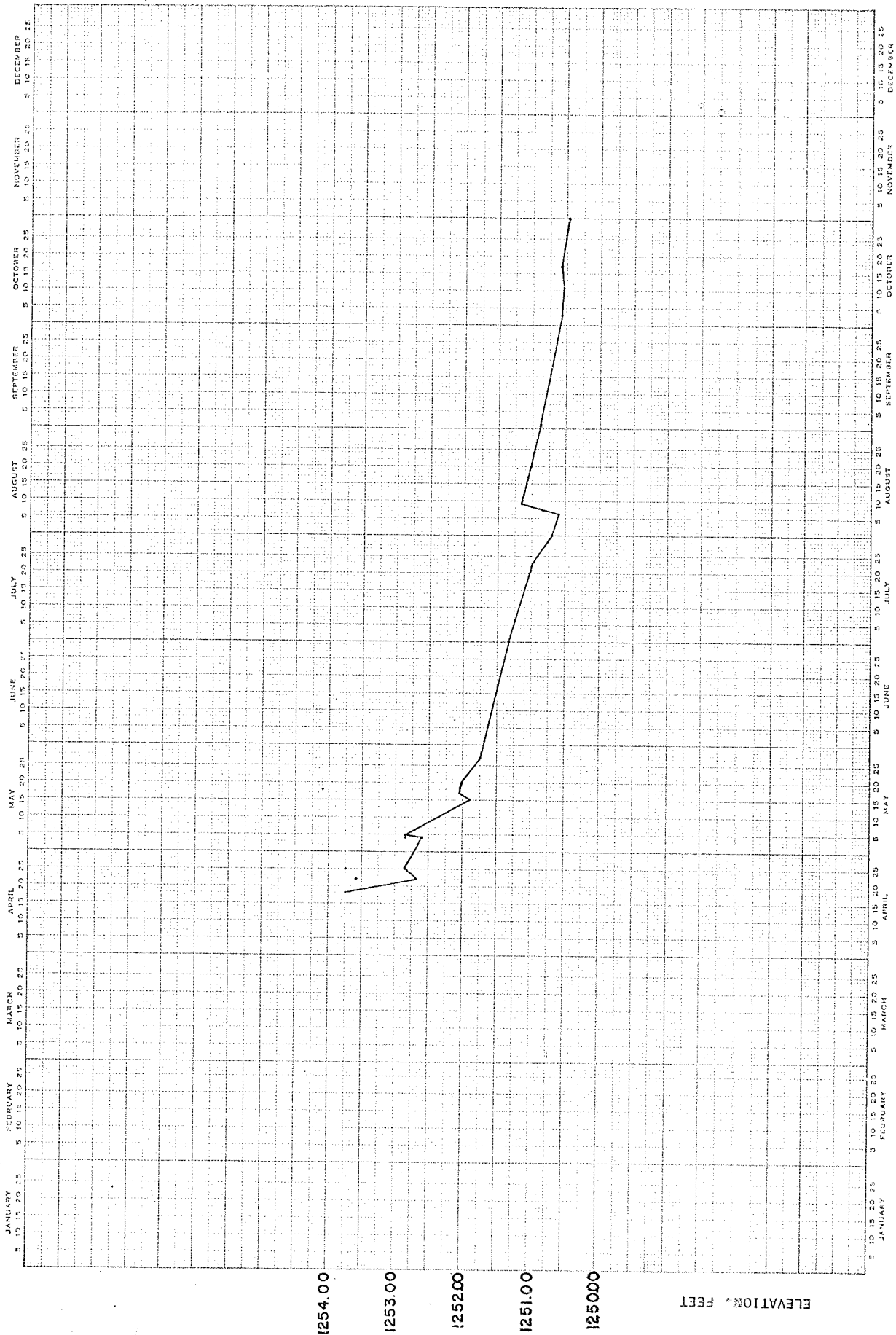
ELEVATION, FEET

---ADJUSTED HYDROGRAPH

WELL GS-5 1966

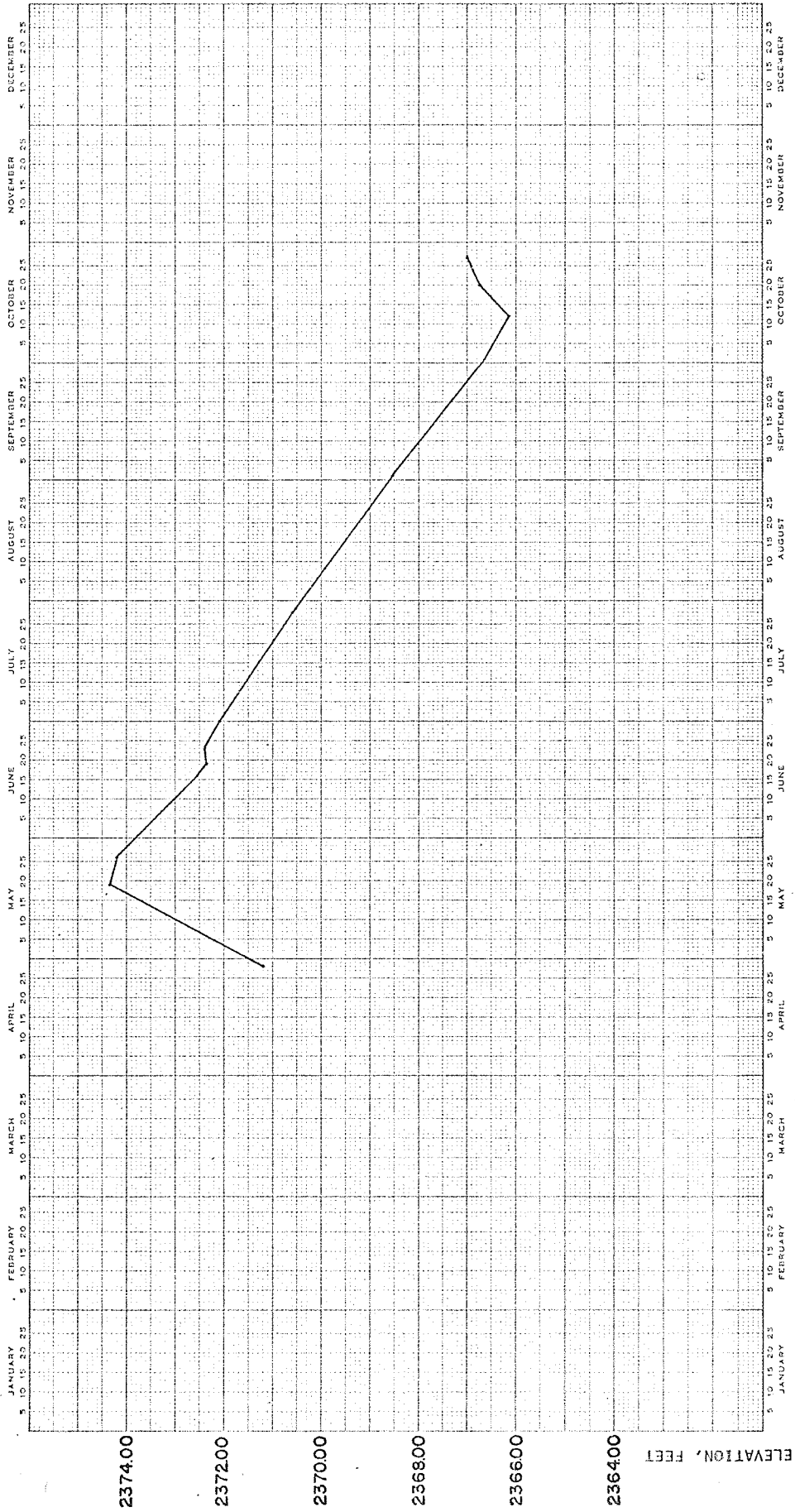


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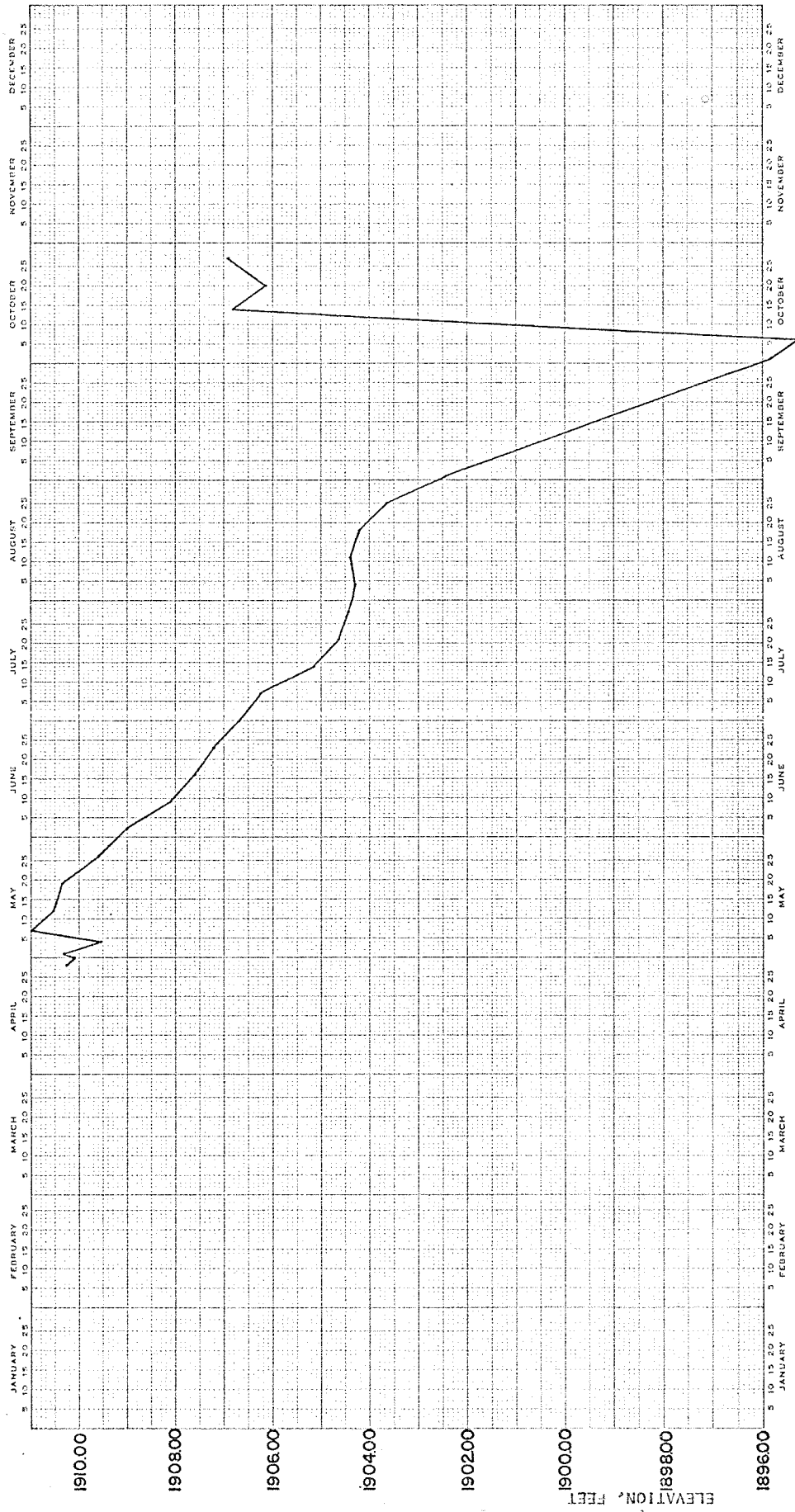


ELEVATION, FEET

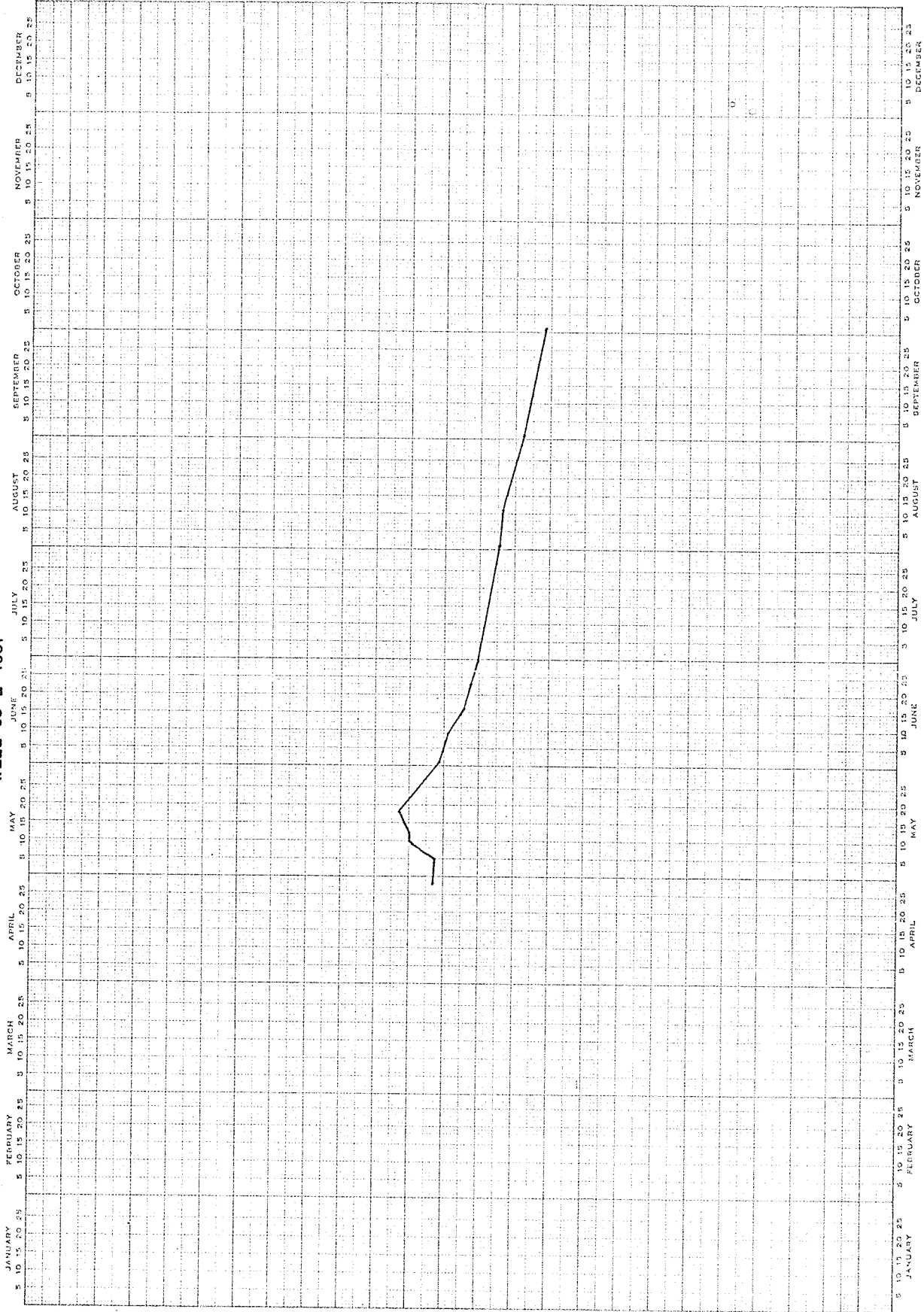
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WELL GS-5 1967

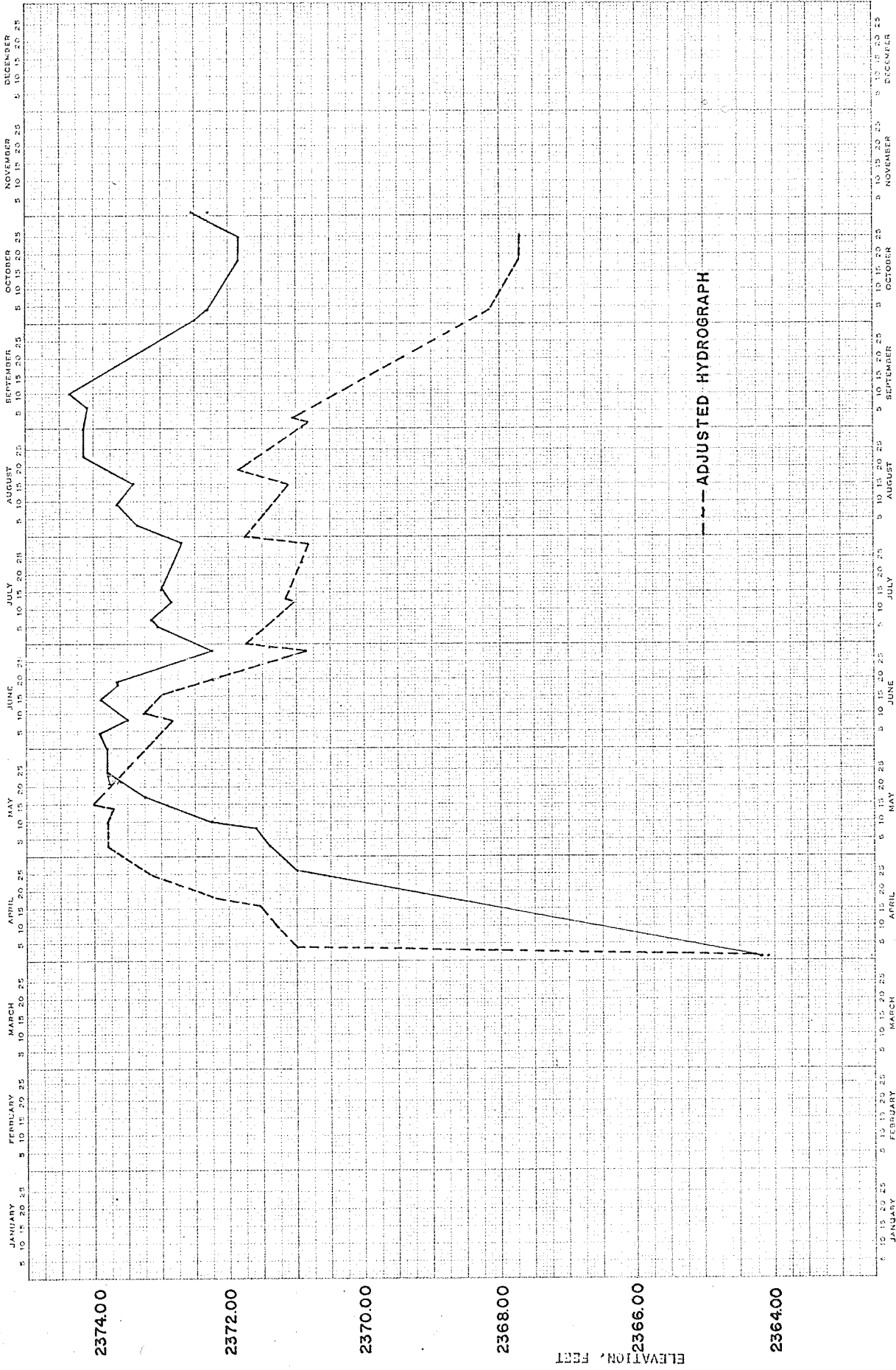


WELL GS-2 1967



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ELEVATION, FEET

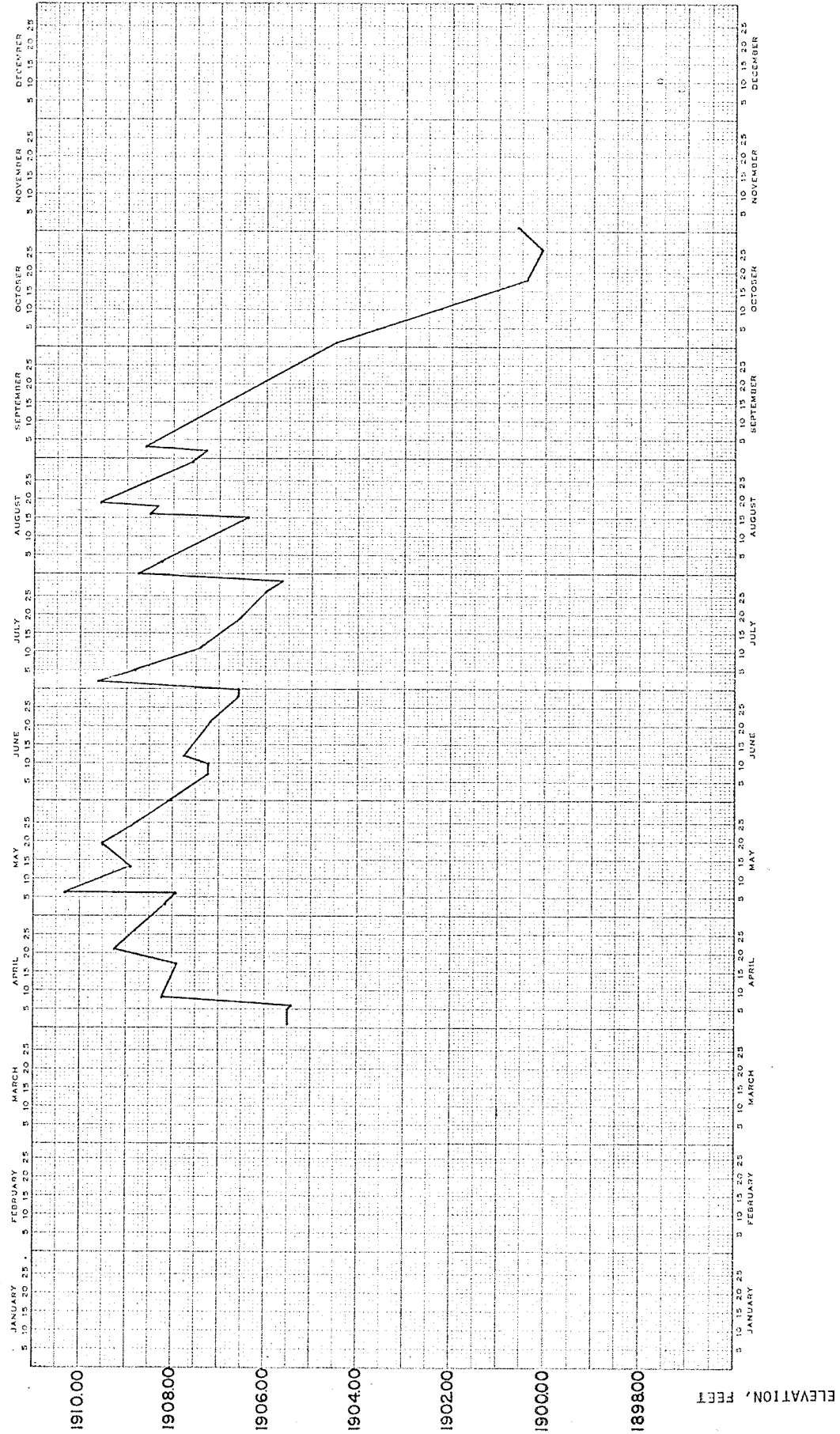
WELL GS-1 1968



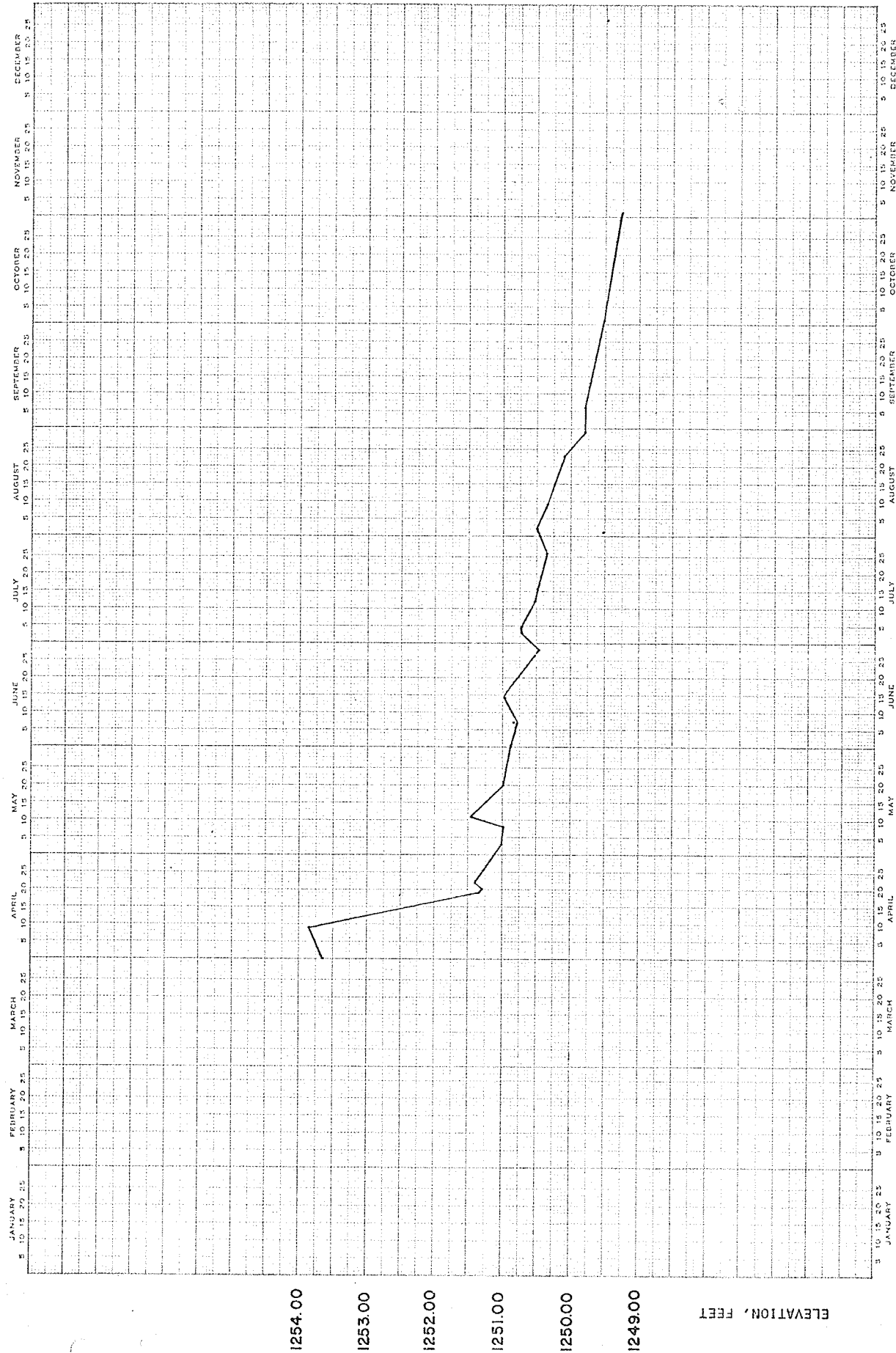
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ELEVATION, FEET

WELL GS-5 1968

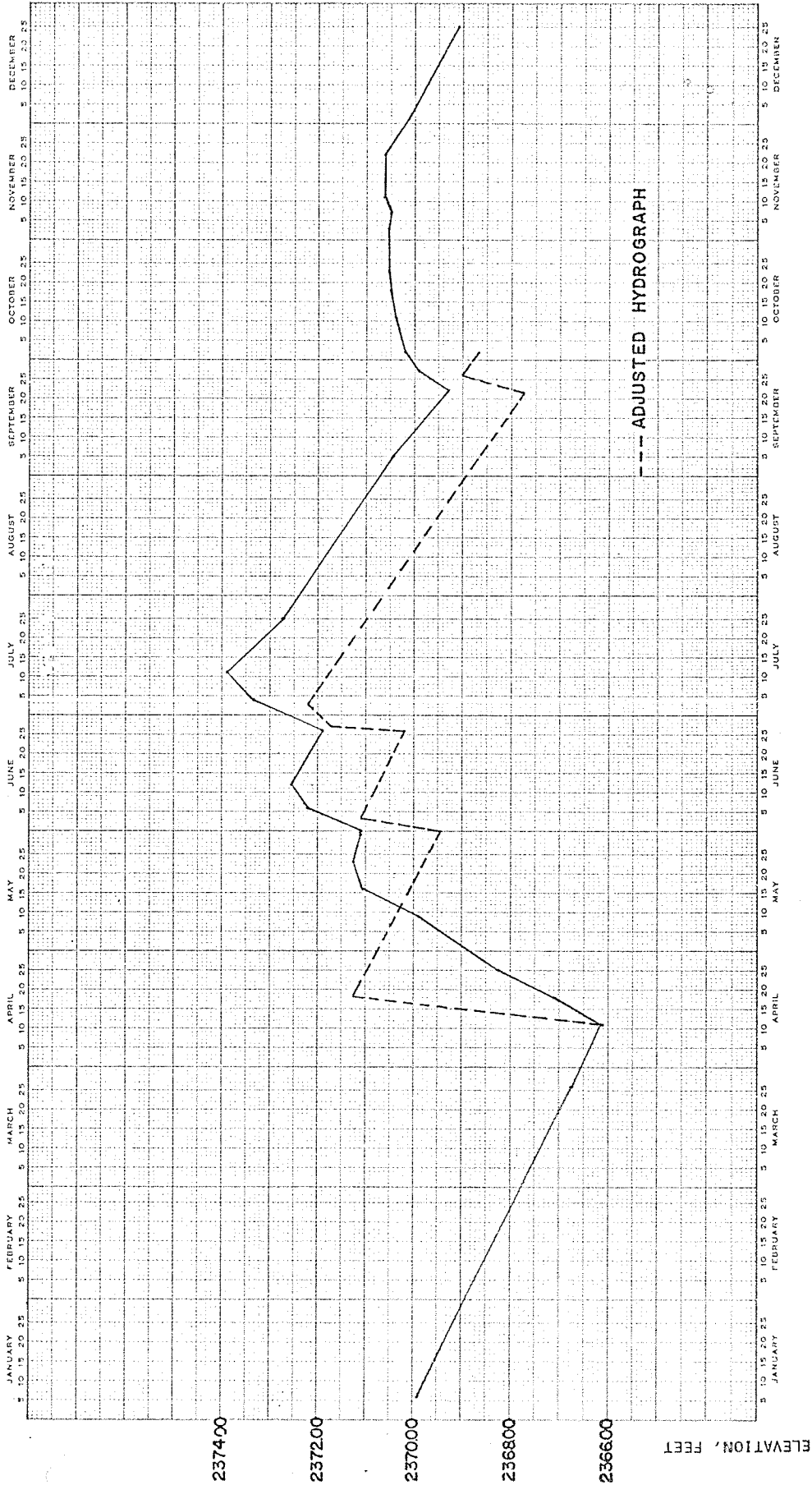


WELL GS-2 1968

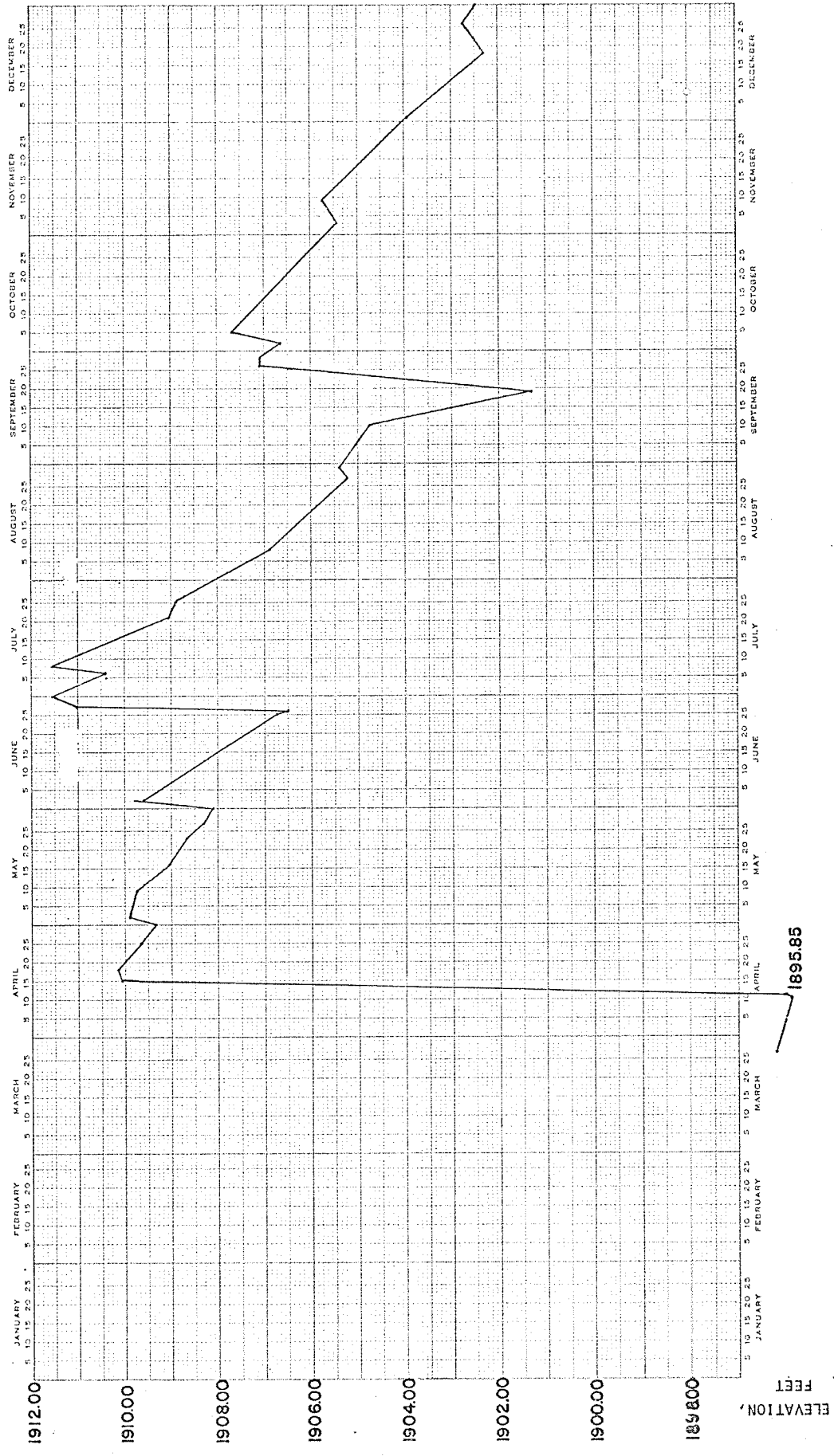


ELEVATION, FEET

WELL GS-1 1969



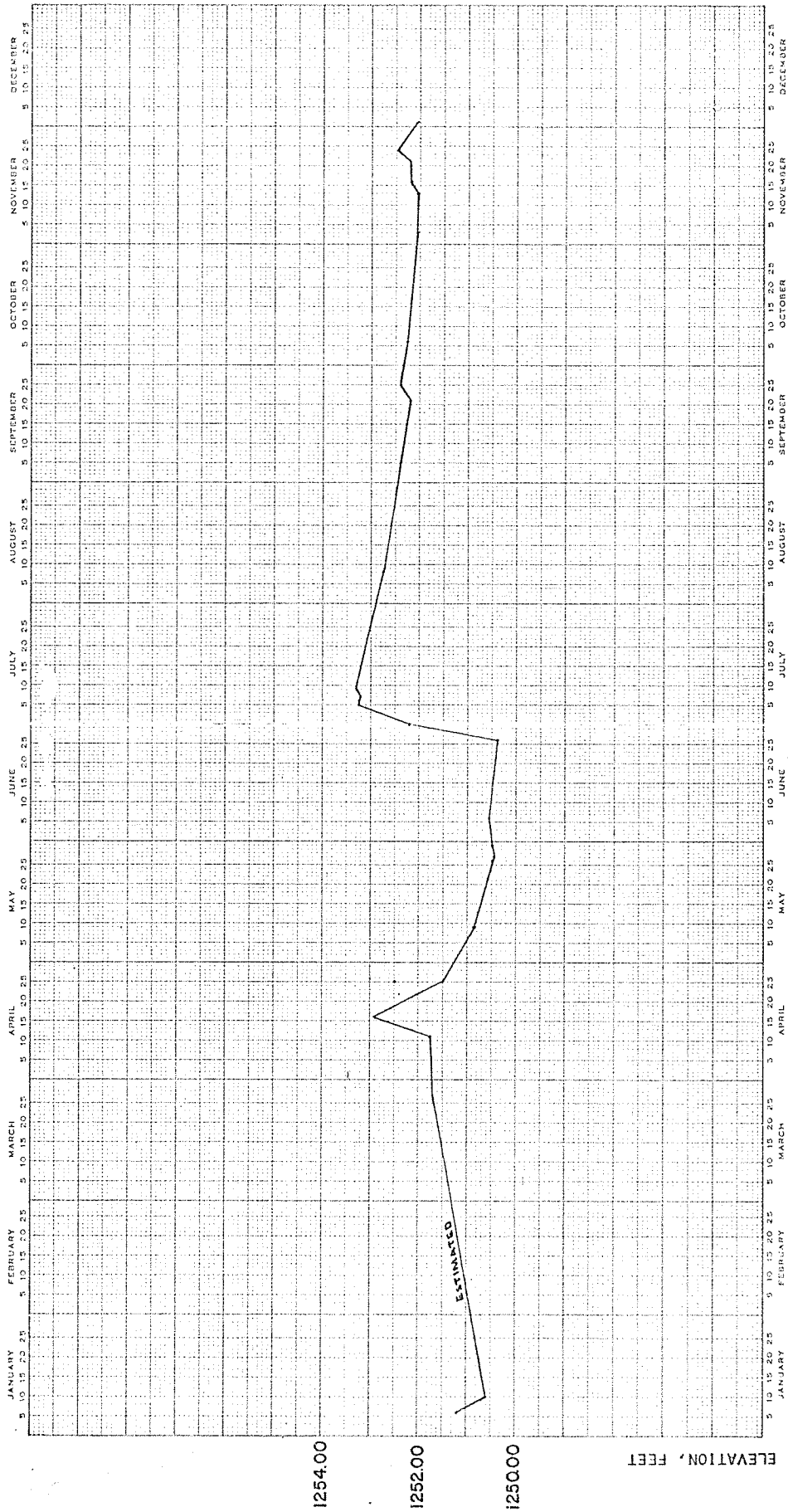
WELL GS-5 1969



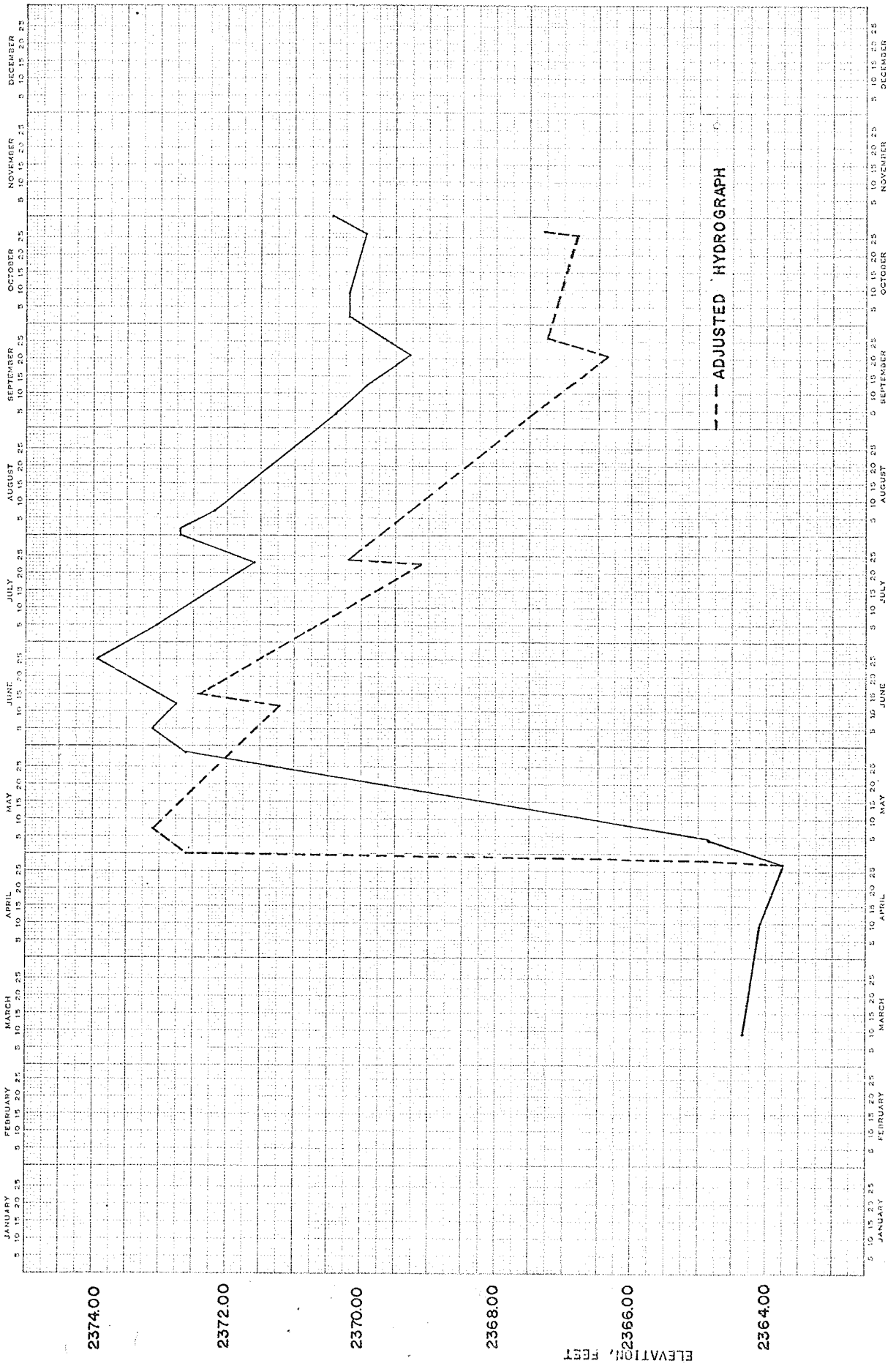
1895.85

ELEVATION, FEET

WELL GS-2 1969



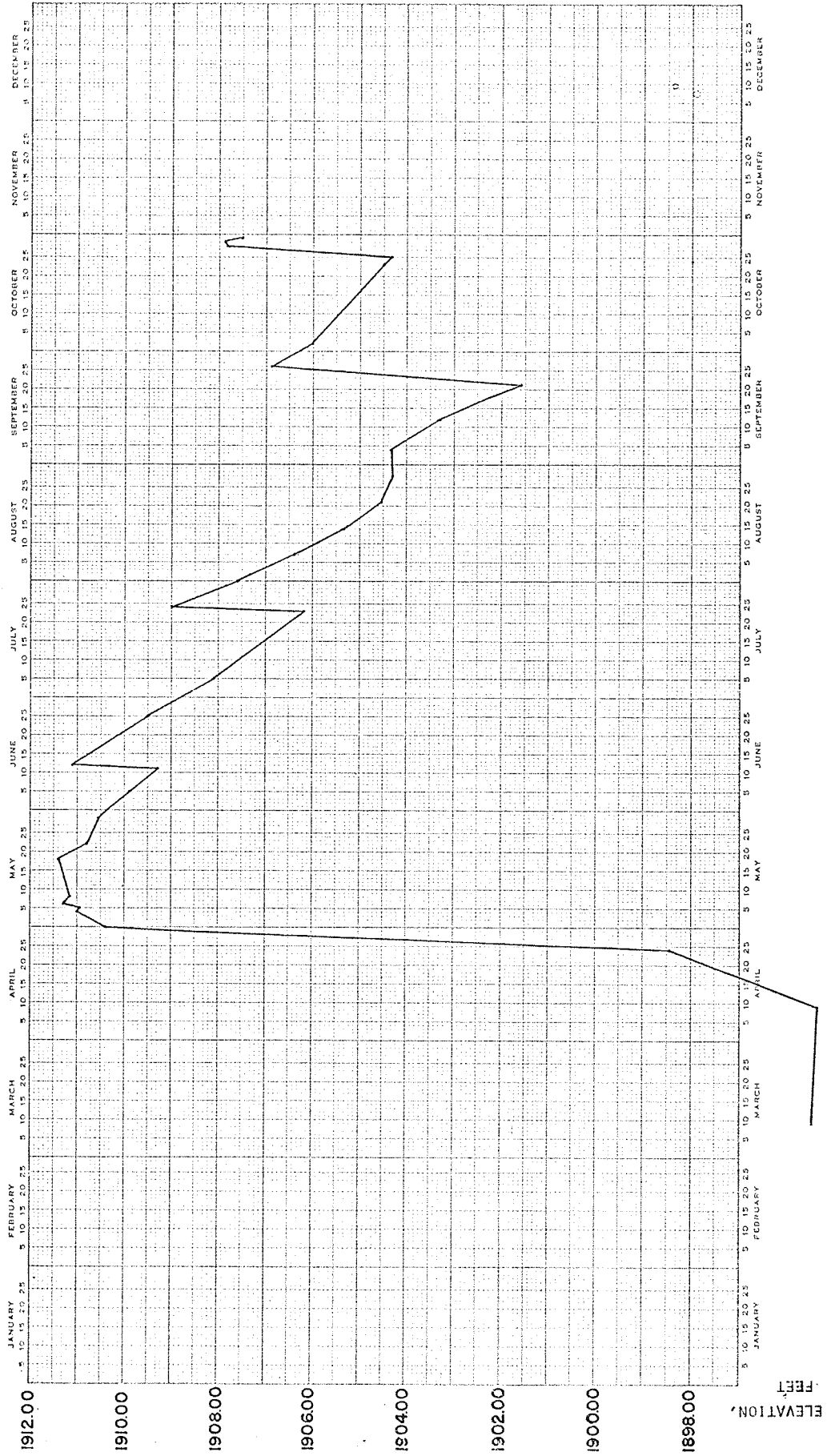
WELL GS-1 1970



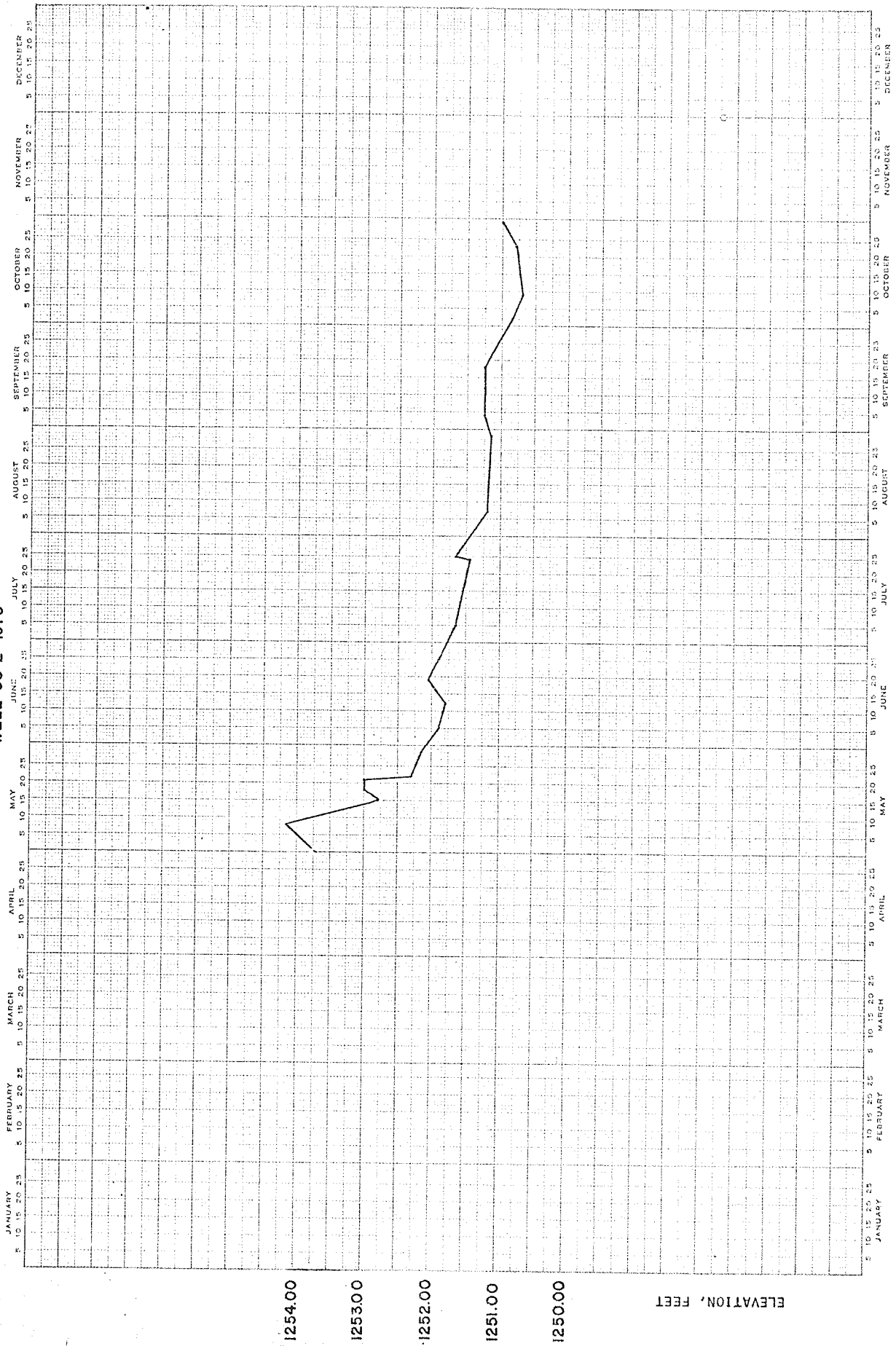
--- ADJUSTED HYDROGRAPH

ELEVATION, FEET

WELL GS-5 1970

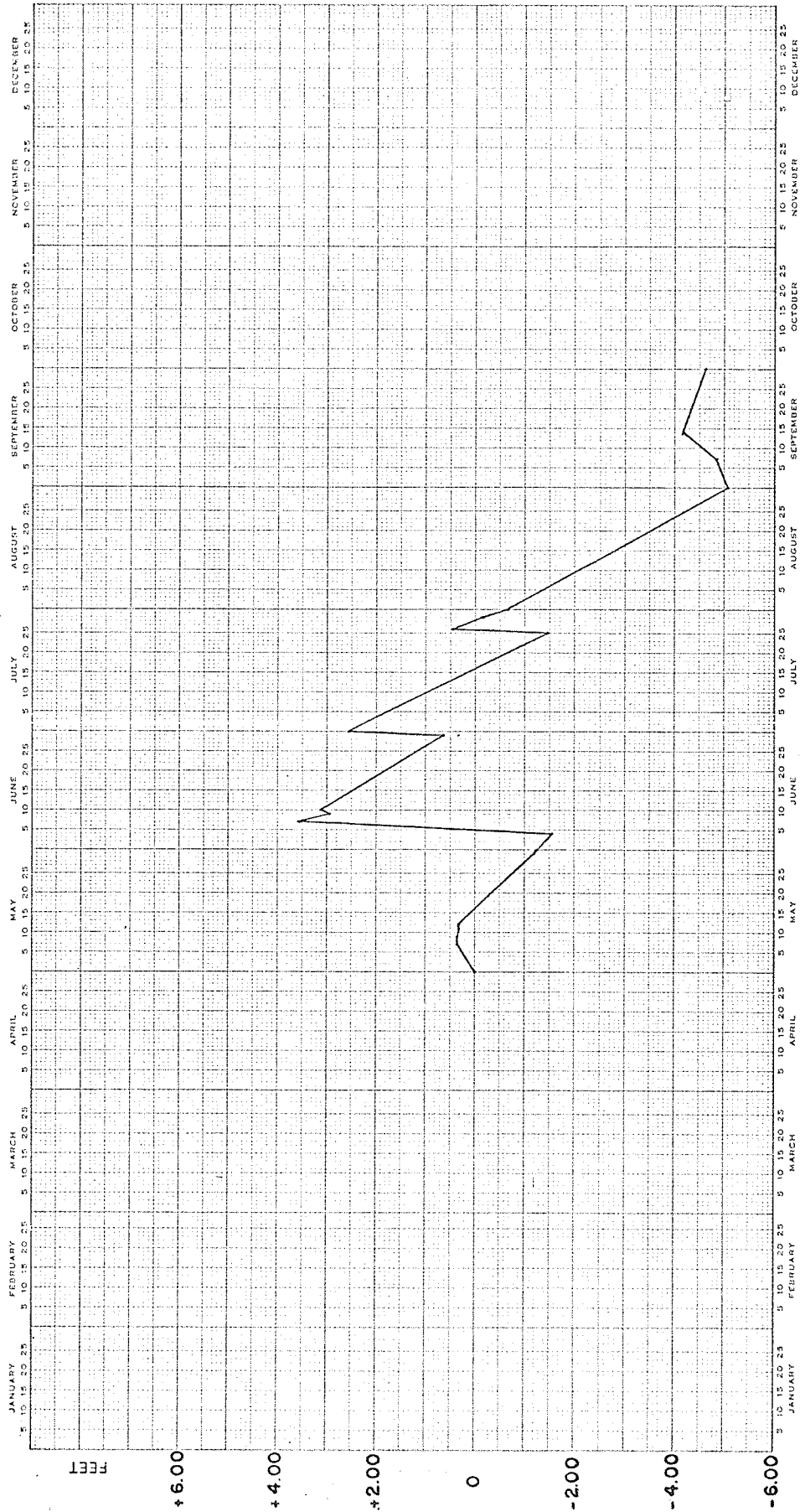


WELL GS-2 1970

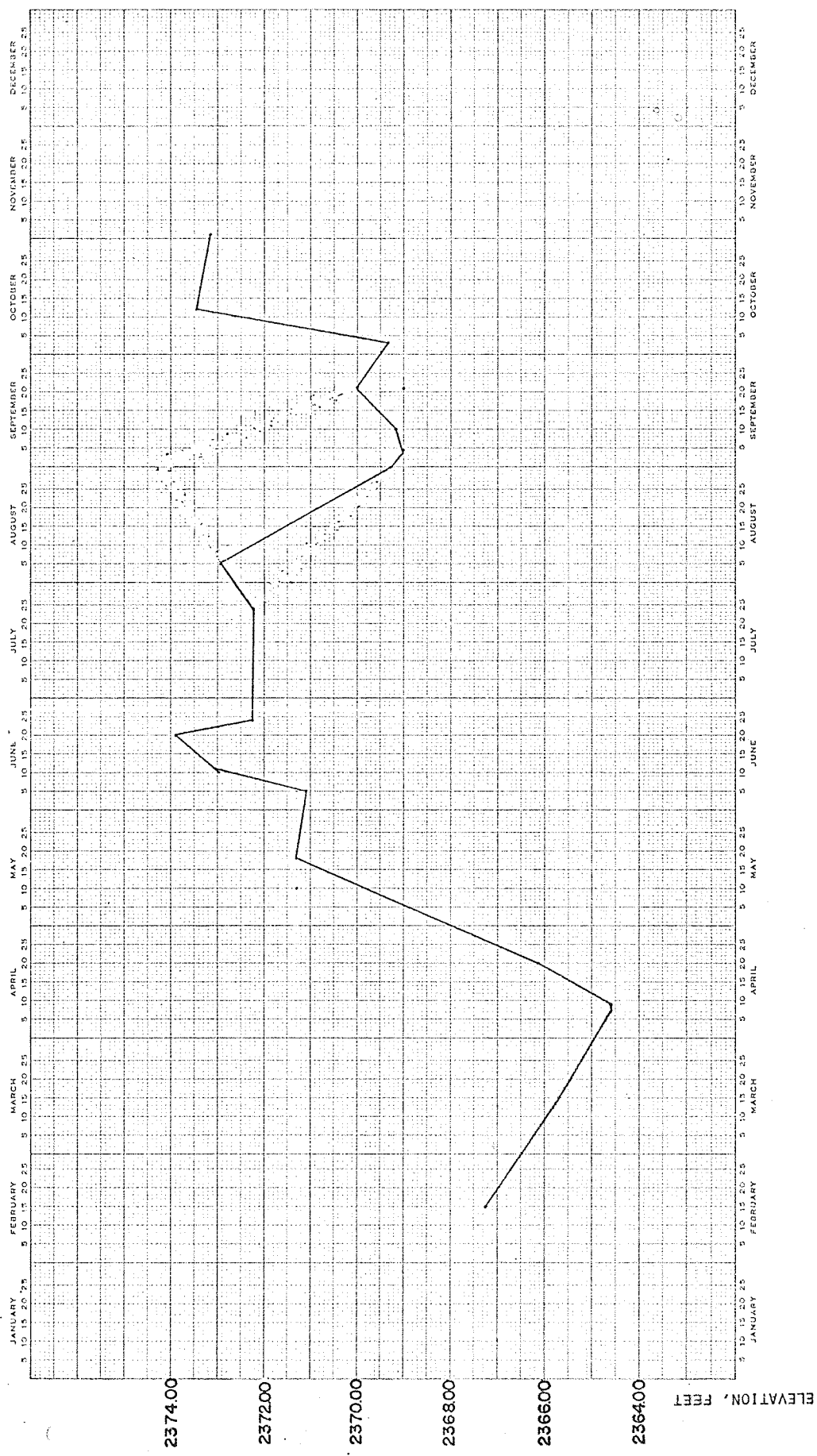


ELEVATION, FEET

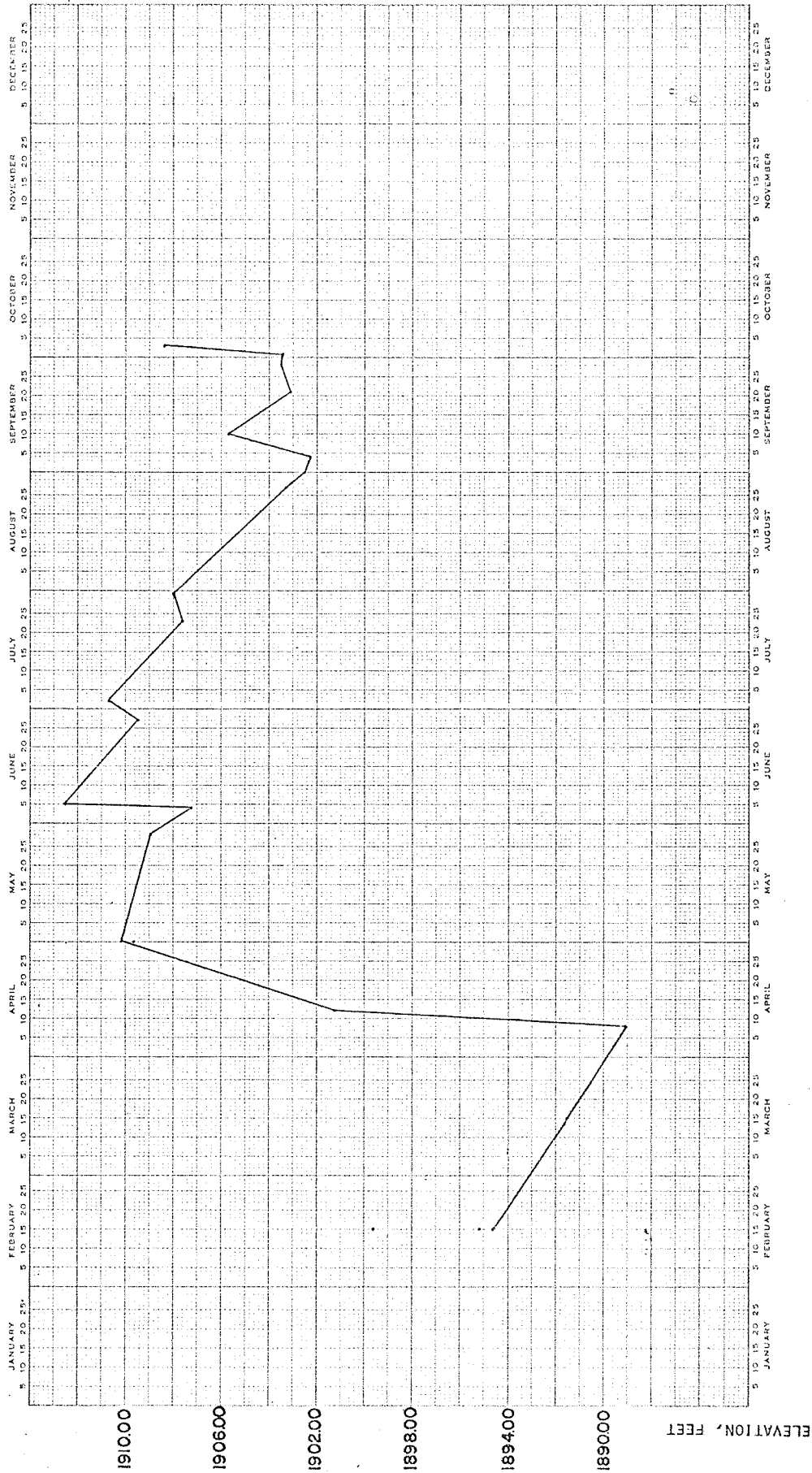
AVERAGE WATER TABLE CHANGE IN WELLS 29-4, 58, 59, 61, 62, and 73 1971



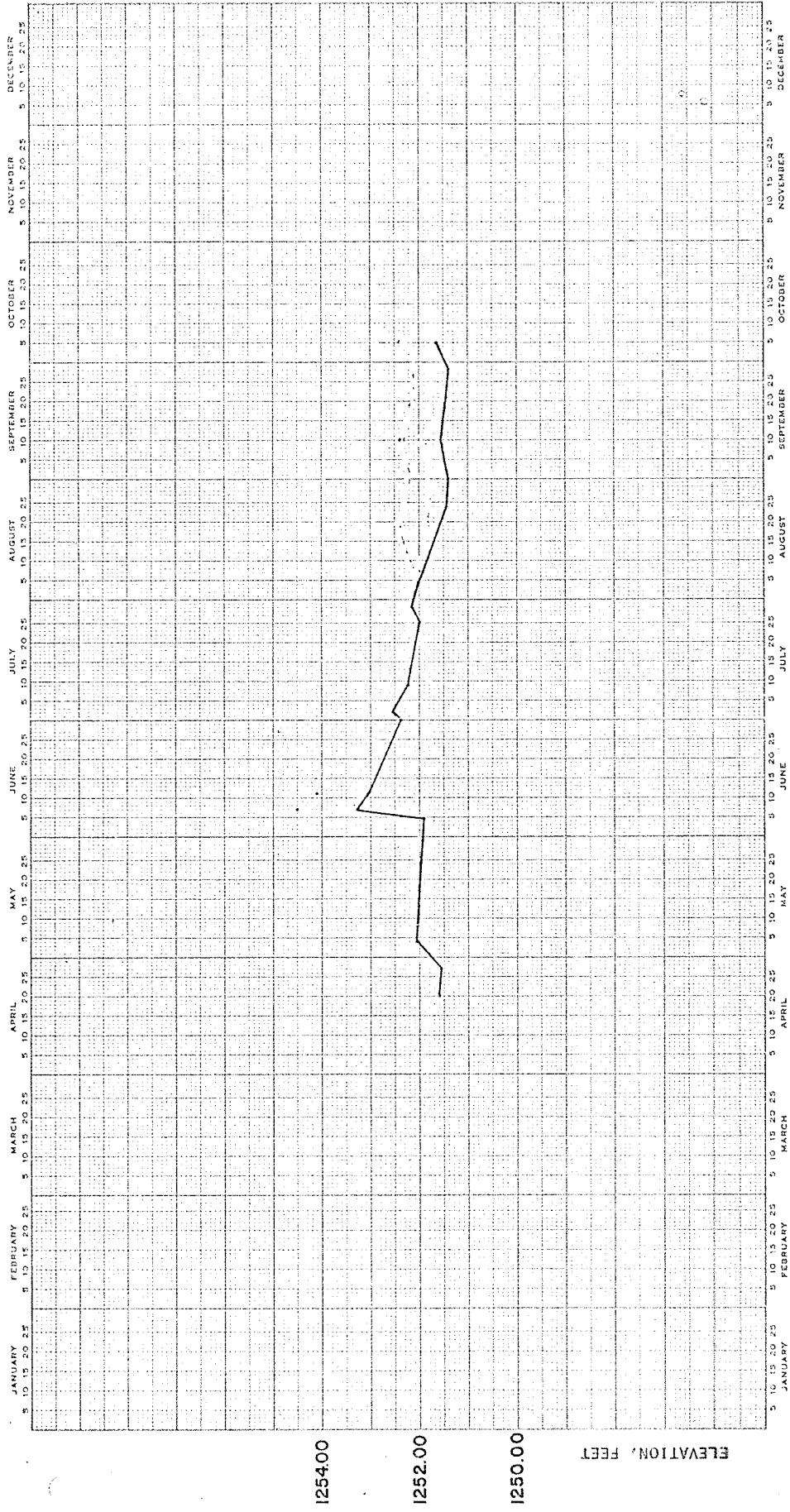
WELL GS-1 1971



WELL GS-5 1971



WELL GS-2 1971



ELEVATION, FEET

A P P E N D I X 3

DATA FOR THE BLANEY-CRIDDLE FORMULA

APPENDIX TABLE 3.1

## MONTHLY PERCENTAGE OF ANNUAL DAYTIME HOURS

Latitude °N	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
40	6.76	6.72	8.33	8.95	10.02	10.08	10.22	9.54	8.29	7.75	6.72	7.52
42	6.63	6.65	8.31	9.00	10.14	10.22	10.35	9.62	8.40	7.69	6.62	6.37
44	6.49	6.58	8.30	9.06	10.26	10.38	10.49	9.70	8.41	7.63	6.49	6.21
46	6.34	6.50	8.29	9.12	10.39	10.54	10.64	9.79	8.42	7.57	6.36	6.04
48	6.17	6.41	8.27	9.18	10.53	10.71	10.80	9.89	8.44	7.51	6.23	5.86
50	5.98	6.30	8.24	9.24	10.68	10.91	10.99	10.00	8.46	7.45	6.10	5.65
52	5.77	6.19	8.21	9.29	10.85	11.13	11.20	10.12	8.49	7.39	5.93	5.43
54	5.55	6.08	8.18	9.36	11.03	11.38	11.43	10.26	8.51	7.30	5.74	5.18
56	5.30	5.95	8.15	9.45	11.22	11.67	11.69	10.40	8.53	7.21	5.54	5.89
58	5.01	5.81	8.12	9.55	11.46	12.00	11.98	10.55	8.55	7.10	5.04	4.56
60	4.67	5.65	8.08	9.65	11.74	12.39	12.31	10.70	8.57	6.98	4.31	4.22

(SOURCE: GRAY, 1970)

## APPENDIX TABLE 3.2

## BLANEY-CRIDDLE FORMULA DATA

<u>YEAR</u>	<u>MONTH</u>	<u>% OF MAXIMUM ANNUAL SUNSHINE</u>	<u>TEMPERATURE °F</u>
1965	MAY	10.75	46.7
	JUNE	11.01	60.1
	JULY	11.08	62.2
	AUGUST	10.05	60.1
	SEPT.	8.47	42.5
1966	MAY	10.75	47.7
	JUNE	11.01	60.1
	JULY	11.08	67.4
	AUGUST	10.05	61.2
	SEPT.	8.47	55.0
1967	MAY	10.75	52.9
	JUNE	11.01	59.1
	JULY	11.08	64.3
	AUGUST	10.05	62.2
	SEPT.	8.47	59.1
1968	MAY	10.75	46.7
	JUNE	11.01	57.0
	JULY	11.08	62.2
	AUGUST	10.05	57.0
	SEPT.	8.47	55.0
1969	MAY	10.75	46.7
	JUNE	11.01	51.9
	JULY	11.08	62.2
	AUGUST	10.05	67.4
	SEPT.	8.47	52.9
1970	MAY	10.75	50.0
	JUNE	11.01	64.0
	JULY	11.08	66.4
	AUGUST	10.05	63.3
	SEPT.	8.47	52.9
1971	MAY	10.75	50.8
	JUNE	11.01	61.0
	JULY	11.08	60.0
	AUGUST	10.05	65.0
	SEPT.	8.47	52.5

A P P E N D I X 4

DATA FOR THE MEYER FORMULA

## APPENDIX TABLE 4.1

### SATURATION VAPOUR PRESSURE OVER WATER AND OVER ICE, IN MILLIBARS

(VALUES OVER WATER AT SUBFREEZING TEMPERATURES IN ITALICS)

Tens	Temperature, °C									
	Units									
	0	1	2	3	4	5	6	7	8	9
40	73.777	77.802	82.015	86.423	91.034	95.855	100.89	106.16	111.66	117.40
30	42.430	44.927	47.551	50.307	53.200	56.236	59.422	62.762	66.264	69.934
20	23.373	24.861	26.430	28.086	29.831	31.671	33.608	35.649	37.796	40.055
10	12.272	13.119	14.017	14.969	15.977	17.044	18.173	19.367	20.630	21.964
+0	6.1078	6.5662	7.0547	7.5753	8.1294	8.7192	9.3465	10.013	10.722	11.474
-0	6.1078	5.623	5.173	4.757	4.372	4.015	3.685	3.379	3.097	2.837
	<i>6.1078</i>	<i>5.6780</i>	<i>5.2753</i>	<i>4.8981</i>	<i>4.5451</i>	<i>4.2148</i>	<i>3.9061</i>	<i>3.6177</i>	<i>3.3484</i>	<i>3.0971</i>
-10	2.597	2.376	2.172	1.984	1.811	1.652	1.506	1.371	1.248	1.135
	<i>2.8627</i>	<i>2.6443</i>	<i>2.4409</i>	<i>2.2515</i>	<i>2.0755</i>	<i>1.9118</i>	<i>1.7597</i>	<i>1.6186</i>	<i>1.4877</i>	<i>1.3664</i>
-20	1.032	0.9370	0.8502	0.7709	0.6985	0.6323	0.5720	0.5170	0.4669	0.4213
	<i>1.2540</i>	<i>1.1500</i>	<i>1.0533</i>	<i>0.9649</i>	<i>0.8827</i>	<i>0.8070</i>	<i>0.7371</i>	<i>0.6727</i>	<i>0.6134</i>	<i>0.5589</i>
-30	0.3798	0.3421	0.3079	0.2769	0.2488	0.2233	0.2002	0.1794	0.1606	0.1436
	<i>0.5088</i>	<i>0.4628</i>	<i>0.4205</i>	<i>0.3818</i>	<i>0.3463</i>	<i>0.3139</i>	<i>0.2842</i>	<i>0.2571</i>	<i>0.2323</i>	<i>0.2097</i>
-40	0.1283	0.1145	0.1021	0.09098	0.08097	0.07198	0.06393	0.05671	0.05026	0.04449
	<i>0.1891</i>	<i>0.1704</i>	<i>0.1534</i>	<i>0.1379</i>	<i>0.1239</i>	<i>0.1111</i>	<i>0.09961</i>	<i>0.08918</i>	<i>0.07975</i>	<i>0.07124</i>
-50	0.03935	0.03476	0.03067	0.02703	0.02380	0.02092	0.01838	0.01612	0.01413	0.01236

(SOURCE: BYERS, 1959)

## APPENDIX TABLE 4.2

## MEYER FORMULA DATA

YEAR	MONTH	TEMPERATURE °F	RELATIVE HUMIDITY %	$E_s$ in. Hg	$E_a$ in. Hg	WIND m.p.h.
1965	MAY	46.7	63	.3211	.2023	9.1
	JUNE	60.1	66	.5243	.3460	8.3
	JULY	62.2	75	.5644	.4233	5.9
	AUGUST	60.1	79	.5243	.4142	6.3
	SEPT.	42.5	75	.2731	.2048	6.8
1966	MAY	47.7	60	.3330	.1998	8.0
	JUNE	60.1	67	.5243	.3513	7.0
	JULY	67.4	67	.6764	.4532	6.6
	AUGUST	61.2	72	.5444	.3920	6.1
	SEPT.	55.0	67	.4369	.2927	7.4
1967	MAY	52.9	77	.4029	.3102	8.2
	JUNE	59.1	59	.5039	.2973	7.5
	JULY	64.3	58	.6062	.3516	7.1
	AUGUST	62.2	55	.5644	.3104	6.8
	SEPT.	59.1	58	.5039	.2923	7.8
1968	MAY	46.7	64	.3211	.2055	8.7
	JUNE	57.0	67	.4694	.3145	7.4
	JULY	62.2	70	.5644	.3951	7.1
	AUGUST	57.0	78	.4694	.3661	6.8
	SEPT.	55.0	72	.4369	.3146	7.1
1969	MAY	46.7	68	.3211	.2183	8.0
	JUNE	51.9	70	.3882	.2717	7.1
	JULY	62.2	70	.5644	.3951	6.9
	AUGUST	67.4	68	.6764	.4600	7.1
	SEPT.	52.9	76	.4029	.3062	7.2
1970	MAY	50.0	66	.3631	.2396	8.0
	JUNE	64.0	68	.5993	.4075	7.4
	JULY	66.4	71	.6530	.4636	7.4
	AUGUST	63.3	66	.5848	.4269	6.9
	SEPT.	52.9	73	.4029	.2941	5.5
1971	MAY	50.8	54	.3725	.2012	7.6
	JUNE	61.0	71	.5402	.3835	5.1
	JULY	60.0	73	.5225	.3814	6.2
	AUGUST	65.0	71	.6229	.4423	6.8
	SEPT.	52.5	69	.3971	.2740	7.6

A P P E N D I X 5

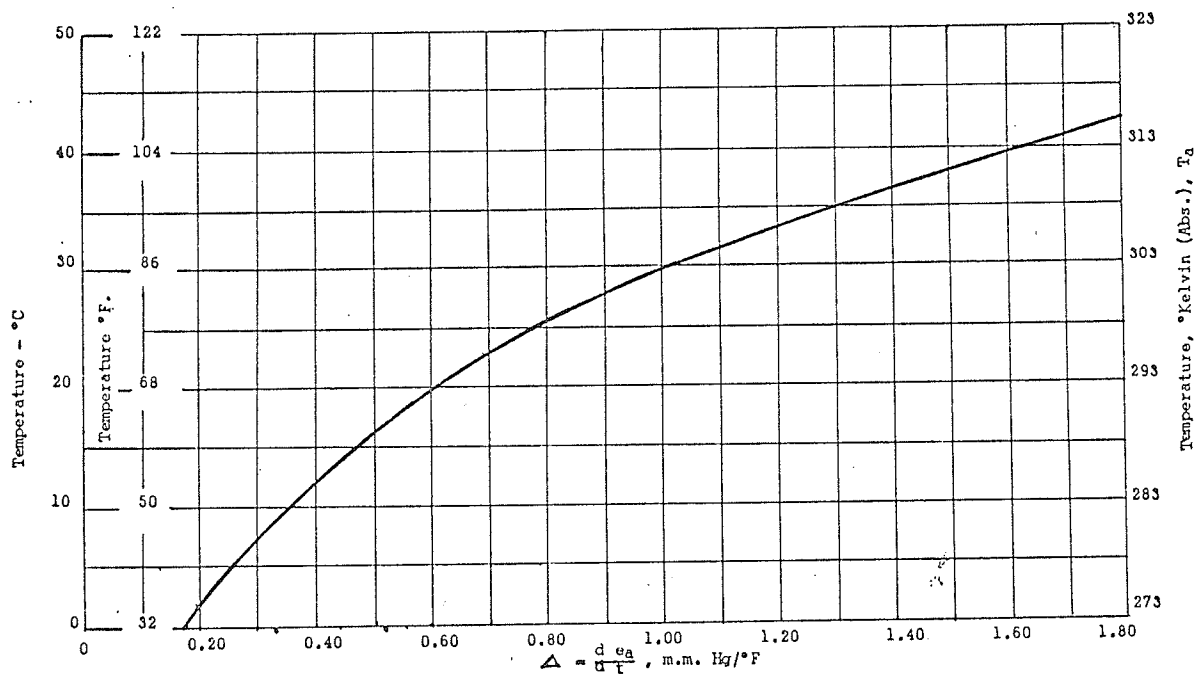
DATA FOR THE PENMAN FORMULA

## APPENDIX TABLE 5.1

MID MONTHLY INTENSITY OF SOLAR RADIATION ( $R_A$ ) ON A HORIZONTAL  
SURFACE IN M.M. OF WATER EVAPORATED PER DAY

	Northern Hemisphere										Southern Hemisphere									
	90°	80°	70°	60°	50°	40°	30°	20°	10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	
Jan.	--	--	--	1.3	3.6	6.0	8.5	10.8	12.8	14.5	15.8	16.8	17.3	17.3	17.1	16.6	16.5	17.3	17.6	
Feb.	--	--	1.1	3.5	5.9	8.3	10.5	12.3	13.9	15.0	15.7	16.0	15.8	15.2	14.1	12.7	11.2	10.5	10.7	
Mar.	--	1.8	4.3	6.8	9.1	11.0	12.7	13.9	14.8	15.2	15.1	14.6	13.6	12.2	10.5	8.4	6.1	3.6	1.9	
Apr.	7.9	7.8	9.1	11.1	12.7	13.9	14.8	15.2	15.2	14.7	13.8	12.5	10.8	8.8	6.6	4.3	1.9	--	--	
May	14.9	14.6	13.6	14.6	15.4	15.9	16.0	15.7	15.0	13.9	12.4	10.7	8.7	6.4	4.1	1.9	0.1	--	--	
June	18.1	17.8	17.0	16.5	16.7	16.5	15.8	14.8	13.4	11.6	9.6	7.4	5.1	2.8	0.8	--	--	--	--	
July	16.8	16.5	15.8	15.7	16.1	16.3	16.2	15.7	14.8	13.5	11.9	10.0	7.8	5.6	3.3	1.2	--	--	--	
Aug.	11.2	10.6	11.4	12.7	13.9	14.8	15.3	15.3	15.0	14.2	13.0	11.5	9.6	7.5	5.2	2.9	0.8	--	--	
Sept.	2.6	4.0	6.8	8.5	10.5	12.2	13.5	14.4	14.9	14.9	14.4	13.5	12.1	10.5	8.5	6.2	3.8	1.3	--	
Oct.	--	0.2	2.4	4.7	7.1	9.3	11.3	12.9	14.1	15.0	15.3	15.3	14.8	13.8	12.5	10.7	8.8	7.1	7.0	
Nov.	--	--	0.1	1.9	4.3	6.7	9.1	11.2	13.1	14.6	15.7	16.4	16.7	16.5	16.0	15.2	14.5	15.0	15.3	
Dec.	--	--	--	0.9	3.0	5.5	7.9	10.3	12.4	14.3	15.8	16.9	17.6	17.8	17.8	17.5	18.1	18.9	19.3	

(SOURCE: CRIDDLE, 1958)

APPENDIX FIGURE 5.1 TEMPERATURE VS  $\Delta$ 

(SOURCE: CRIDDLE, 1958)

## APPENDIX TABLE 5.2

VALUES OF  $\delta T_A^4$  FOR VARIOUS TEMPERATURES

Temperature		Temperature	
° Abs.	mm H <sub>2</sub> O/day	° F.	mm H <sub>2</sub> O/day
270	10.73	35	11.48
275	11.51	40	11.96
280	12.40	45	12.45
285	13.20	50	12.94
290	14.26	55	13.45
295	15.30	60	13.96
300	16.34	65	14.52
305	17.46	70	15.10
310	18.60	75	15.65
315	19.85	80	16.25
320	21.15	85	16.85
325	22.50	90	17.46
		95	18.10
		100	18.80

Note: Heat of vaporization was assumed to be constant at 590 cal./gm of H<sub>2</sub>O.

(SOURCE: CRIDDLE, 1958)

APPENDIX TABLE 5.3

PENMAN FORMULA DATA

YEAR MONTH	R <sub>A</sub>		τ	n	N	T <sub>a</sub>	e <sub>s</sub>	R.H.	e <sub>a</sub>	√C <sub>a</sub>	eT <sub>a</sub> <sup>4</sup>		u <sub>2</sub>
	mm.	H <sub>2</sub> O									mm.	H <sub>2</sub> O	
	day	day	hours	hours	°F	mm. Hg	%	mm. Hg	mm. Hg	mm. Hg	mm. Hg	mm. Hg	m.p.d.
1965	MAY	15.34	.15	246	479	46.7	8.156	63	5.138	2.268	12.62	.30	117.6
	JUNE	16.69	.15	292	490	60.1	13.317	66	8.788	2.964	13.97	.48	108.0
	JULY	16.07	.15	328	493	62.2	14.336	75	10.752	3.276	14.21	.52	76.8
	AUGUST	13.82	.15	269	450	60.1	13.317	79	10.521	3.200	13.97	.48	81.6
	SEPT.	10.40	.15	138	382	42.5	6.937	75	5.202	2.283	12.21	.28	88.8
1966	MAY	15.34	.15	304	479	47.7	8.458	60	5.075	2.253	12.71	.33	103.2
	JUNE	16.69	.15	250	490	60.1	13.317	67	8.923	2.989	13.97	.48	91.2
	JULY	16.07	.15	311	493	67.4	17.181	67	11.511	3.392	14.81	.59	86.4
	AUGUST	13.82	.15	250	450	61.2	13.818	72	9.957	3.155	14.09	.49	79.2
	SEPT.	10.40	.15	232	382	55.0	11.097	67	7.435	2.278	13.45	.41	96.0
1967	MAY	15.34	.15	280	479	52.9	10.234	77	7.879	2.807	13.24	.39	105.6
	JUNE	16.69	.15	286	490	59.1	12.799	59	7.551	2.747	13.87	.47	98.4
	JULY	16.07	.15	347	493	64.3	15.397	58	8.931	2.984	14.44	.56	91.2
	AUGUST	13.82	.15	361	450	62.2	14.336	55	7.884	2.807	14.21	.52	88.8
	SEPT.	10.40	.15	253	382	59.1	12.799	58	7.424	2.727	13.87	.47	100.8
1968	MAY	15.34	.15	252	479	46.7	8.156	64	5.220	2.288	12.62	.30	112.8
	JUNE	16.69	.15	247	490	57.0	11.923	67	7.988	2.827	13.65	.44	96.0
	JULY	16.07	.15	332	493	62.2	14.336	70	10.036	3.165	14.21	.52	91.2
	AUGUST	13.82	.15	221	450	57.0	11.923	78	9.299	3.049	13.65	.44	88.8
	SEPT.	10.40	.15	191	382	55.0	11.097	72	7.991	2.832	13.45	.41	91.2
1969	MAY	15.34	.15	253	479	46.7	8.156	68	5.545	2.359	12.62	.30	103.2
	JUNE	16.69	.15	267	490	51.9	9.860	70	6.901	2.831	13.13	.38	91.2
	JULY	16.07	.15	310	493	62.2	14.336	70	10.035	3.064	14.21	.52	88.8
	AUGUST	13.82	.15	320	450	67.4	17.191	68	11.684	3.417	14.81	.59	91.2
	SEPT.	10.40	.15	159	382	52.9	10.234	76	7.777	2.792	13.24	.39	93.6
1970	MAY	15.34	.15	256	479	50.0	9.223	66	6.086	2.470	12.94	.36	103.2
	JUNE	16.69	.15	282	490	64.0	15.222	68	10.351	3.266	14.41	.56	96.0
	JULY	16.07	.15	305	493	66.4	16.586	71	11.775	3.432	14.81	.58	96.0
	AUGUST	13.82	.15	366	450	63.3	14.854	66	10.843	3.296	14.33	.54	88.8
	SEPT.	10.40	.15	187	382	52.9	10.234	73	7.470	2.732	13.24	.39	72.0
1971	MAY	15.34	.15	373	479	50.8	9.462	54	5.110	2.258	13.02	.37	98.4
	JUNE	16.69	.15	264	490	61.0	13.721	71	9.741	3.120	14.07	.50	67.2
	JULY	16.07	.15	322	493	60.0	13.272	73	9.688	3.110	13.96	.49	79.2
	AUGUST	13.82	.15	330	450	65.0	15.822	71	11.234	3.352	14.52	.57	88.8
	SEPT.	10.40	.15	187	382	52.5	10.086	69	6.960	2.641	13.19	.39	98.4

A P P E N D I X 6

DATA FOR THE ENERGY BUDGET

## APPENDIX TABLE 6.1

## ENERGY BUDGET DATA

YEAR	MONTH	R <sub>net</sub> cal/cm. <sup>2</sup>	T <sub>s</sub> °C	T <sub>a</sub> °C	RELATIVE HUMIDITY %	e <sub>s</sub> mbars	e <sub>a</sub> mbars	R <sub>B</sub>
1969	MAY	7809	10.9	8.2	68	13.034	8.863	.414
	JUNE	7950	14.3	11.1	70	16.297	11.408	.419
	JULY	8463	18.9	16.8	70	21.831	14.845	.193
	AUG.	7950	21.8	19.7	68	26.116	17.759	.161
	SEPT.	4134	12.6	11.6	76	14.588	11.087	.183
1970	MAY	8126	12.0	10.0	66	14.017	9.251	.269
	JUNE	7666	20.2	17.8	68	23.671	16.096	.203
	JULY	8303	21.8	19.1	71	26.116	18.542	.228
	AUG.	7872	20.1	17.4	66	23.522	15.525	.216
	SEPT.	4134	12.6	11.6	73	14.588	10.649	.163
1971	JULY	8794	18.6	15.6	73	21.430	15.644	.332
	AUG.	7177	20.6	18.3	71	24.266	17.229	.211
	SEPT.	3113	12.0	11.4	69	14.017	9.672	.088

Note: May, 1971 and June, 1971 data not available