STATE OF WASHINGTON
Albert D. Rosellini, Governor

DEPARTMENT OF CONSERVATION

Earl Coe, Director

DIVISION OF WATER RESOURCES

Murray G. Walker, Supervisor

Water Supply Bulletin No. 12

Water Resources of the Nooksack River Basin

and Certain Adjacent Streams

with a contribution by the

UNITED STATES GEOLOGICAL SURVEY

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Price: $2.00, Division of Water Resources, Olympia, Wn.

FOREWORD

This report represents initiation of a new but vitally needed service by the Division of Water Resources, for the people of the State of Washington. Not only will it permit the re-evaluation of our basic data programs, but it will enable us to administer the laws more intelligently and provide background material for planning the ultimate development of the waters in this area. The Nooksack River basin was chosen for the initial inventory report primarily because of its size and, secondarily, because of the availability of base maps and previous studies such as ground water, power, and flood control. Beginning such a study meant requesting a biennial budget increase to salary and operations money such that a staff of five technicians and one secretary could be added. Our request received endorsement of the governor and approval from the legislature for the 1959-1961 biennium. As a result, recruiting began in June of 1959 and the staff was finally completed as of June 16, 1960. Considerable time was spent in arriving at the contents and scope of the report and the experience gained in the mechanics of preparation will enable us to proceed on future studies at a much faster pace. Also, it should be noted that this report was limited to readily available information and data and no concerted attempt was made to expand or project the information, or to cover potential or future requirements or uses of the water supply.

Murray G. Walker
Supervisor
Division of Water Resources

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WATER RESOURCES OF THE NOOKSACK RIVER BASIN AND CERTAIN ADJACENT STREAMS

ABSTRACT

The quantity and quality of water within the Nooksack River basin is adequate to meet the area's municipal, industrial, agricultural, and domestic needs for many years to come. With a planned and orderly development, the basin has a water resource potential at least tenfold the present known demand. The Nooksack River system contains adequate dam and reservoir sites with capacities for 100 percent flood control and development of 123,200 kilowatts of firm power. These figures represent single purpose evaluations of each storage site and would necessarily require some refinement for multiple-purpose projects. Further study of each site will be required to determine the extent to which multiple uses would be compatible.

Water right permits and certificates place a low-flow demand of 255.26 cubic feet per second or 26.7 percent of the average low flow of the Nooksack River as gaged at Lynden (fig. 61). This figure includes 100 cubic feet per second for pollution abatement and fish passage purposes. There remain in the stream available for appropriation 700 cubic feet per second or approximately three times the present demand of record.

Approximately 90 percent of the total mean annual runoff of the Nooksack River system discharges into Georgia Strait without being put to beneficial use. Peak flows occur during water-surplus periods, October to May. With full development of storage sites in the upper Nooksack basin, flow characteristics of the Nooksack River and its major tributaries can be beneficially altered to bring flows more in line with periods of demand. Figure 62 shows the total mean annual water budget of the Nooksack River at Lynden to be 2,540,000 acre-feet. Of this, 282,400 acre-feet have been appropriated, leaving 2,257,600 acre-feet available. Major storage sites that have been studied have capacities for salvaging 1,150,000 acre-feet of this total, leaving 1,107,600 acre-feet of unsalvable water.

Many of the small but related streams discussed in the report have been entirely appropriated. Others are heavily appropriated but still have early and late irrigation water available. Additional water supplies for those areas will have to be developed from ground-water supplies, small storage projects, or a comprehensive river development program.

Rock systems in the Nooksack River basin range in age from Devonian to Recent with Tertiary sedimentary and pre-Tertiary metamorphic rocks predominating in the Eastern Upland and Pleistocene glacial sands and gravels and Recent alluvium being the chief materials of the Whatcom Basin. Tertiary and pre-Tertiary rocks in the study area produce only small amounts of ground water, and in most cases where production is obtained from those rocks, the water quality is poor.

Major production of ground water is restricted almost entirely to the glacial sands and gravels and river valley alluvium found in the Whatcom Basin and along valley floors of the Nooksack River and its three major forks. Wells produce from a few gallons per minute in areas of poor production to several hundred gallons per minute from the more permeable recessional outwash gravels of the Whatcom Basin. No complete quantitative figures are available for the study area. However, observation wells indicate that the maximum safe sustaining yields of the major aquifers have not been attained, and much additional development can be made utilizing that water source.

Geo-hydrologic and climatic conditions of the Nooksack River basin suggest that present naturally occurring water supplies can be materially increased by the application of artificial recharge and weather modification as those processes become better refined.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

This investigation was made by the Division of Water Resources of the Washington State Department of Conservation for the purpose of inventorying the water resources of the Nooksack River basin and certain adjacent streams. A section of the report was prepared by the U. S. Geological Survey.

The report was prepared under the general direction of Murray G. Walker, Supervisor, Division of Water Resources, and under the direct supervision of Robert H. Russell and Glen H. Fiedler. Contributing authors and their contributions in the order they appear are: climate and precipitation analysis by S. E. Shumway; geology and ground water by Dee Molenaar; surface water and hydrology by M. E. Garling; flood control by G. M. Hastings; water quality and reservoirs by E. R. Henken; and water use by W. R. Smith and E. R. Henken.

A section on basic streamflow data and history of floods was prepared by E. G. Bailey, U. S. Geological Survey.

The demand for additional water supplies to satisfy the ever-increasing requirements for domestic, municipal, industrial, and irrigation purposes within the State of Washington has resulted in the need for a thorough understanding of the occurrence and distribution of the State's total water resource. The 1959 session of the Washington State Legislature at the request of Mr. Earl Coe, Director, Department of Conservation, and Mr. Murray G. Walker, Supervisor, Division of Water Resources, provided funds for a start of an inventory of the State's water resources on a watershed basis. This report, "Water Resources of the Nooksack River Basin and Certain Adjacent Streams," covers the first watershed to be studied under this program.

Work was started on the Nooksack River basin study in July, 1959 and completed in September, 1960 and represents a total effort of approximately three man-years of time. The investigation required a complete compilation of existing data; an evaluation of previous works; geologic and hydrologic mapping of areas where existing data were incomplete or entirely lacking; and a thorough geo-hydrologic evaluation of ground-water occurrence, precipitation, and runoff patterns within the watershed and related areas.

The Nooksack River report is presented as an inventory of the water resources of the area designed to serve as a guide to assist municipalities, industry, and other public and private agencies in an orderly and complete development of the area's water resources. In presenting the material, the authors have tried to answer as completely and accurately as possible the following four question:

1. What is the total water budget (quantity and quality) of the area under investigation?
2. What is the present known demand against the total supply?
3. How much water is still available for appropriation and where are these supplies located?
4. How much additional water can be made available and how can streamflow patterns be improved by the application of artificial recharge, upstream storage, and weather modification practices?

LOCATION AND EXTENT OF AREA

The area under investigation includes a total of approximately 959 square miles, situated almost entirely in Whatcom County in the northwestern part of Washington State. It is bounded on the north by the Canadian border; on the west by Georgia Strait; and on the east by Mt. Baker, Mt. Shuksan, and the Skagit Range. The southern boundary consists of an irregular northwest-southeast trending line lying generally north of the City of Bellingham and Lake Whatcom. This line constitutes the hydrologic boundary of the Nooksack River drainage. Parts of four townships (36 N., Rges. 5, 6, 7, and 8 E.) lie within Skagit County.

Several small streams and three land areas closely related to the Nooksack River basin, but not actually within its watershed boundaries, are included in the discussion.

PREVIOUS INVESTIGATIONS

Although there were a number of early studies which include parts of the Nooksack River basin, none dealt specifically with the geo-hydrologic features of the area. Perhaps the first significant investigation was made by J Harlen Bretz (1910-13) in his study of the glaciation of the Puget Sound region. Bretz discussed the glacial drift of the Whatcom Basin. R. O. Helland (1941) discussed water utilization in the Nooksack River with emphasis on dam sites, reservoir capacities, and power potential. Erdman and Warren (1942) prepared a preliminary report on the geology of miscellaneous dam and tunnel sites in the upper basin of the Nooksack River system.

Much of the geology and ground-water hydrology of the Whatcom Basin was adopted from a cooperative report by the Geological Survey, Ground-Water Branch, and the Washington State Division of Water Resources. The report by Newcombe, Sceva, and Stromme (1949) discusses the ground-water resources of western Whatcom County.

The Corps of Engineers, U. S. Army, Office of the District Engineer, Seattle District (1952) prepared a review of reports on flood control of the Nooksack River. Bodhaine and Thomas (1960) of the Geological Survey reviewed the

magnitude and frequency of floods in the State of Washington.

Streamflow hydrographs and flow-duration curves were prepared from stream gage records taken from the Division of Water Resources Water-Supply Bulletin No. 6 (1955) and related Geological Survey water-supply papers and miscellaneous streamflow records. Geology of the Nooksack River dam sites was adopted from a report in progress by Erdman and Bateman of the Geological Survey which describes the geology of dam sites at four utilization areas above Deming.

A number of reports which treated various phases of the Nooksack River basin, but not cited here, are included in the selected bibliography.

ACKNOWLEDGMENT

The writers wish to acknowledge assistance rendered by a number of agencies and individuals. James Pluntze, Washington State Department of Health; Ray Buswell, Whatcom County Health Department; L. B. Laird and J. F. Santos, Quality Branch U. S. Geological Survey for their assistance in matters pertaining to water quality. Earl L. Phillips of the U. S. Weather Bureau, R. D. Perry, W. S. Perry, and other weather station operators who were helpful in furnishing precipitation records and comment on climatology. Byron Mosier of the U. S. Soil Conservation Service and his staff were extremely helpful with land classification and water use matters. The assistance of Dale Rockey of the Whatcom County Highway Department is also graciously acknowledged.

Dr. Peter Misch, Professor, Department of Geology, University of Washington and the staff of the State of Washington Division of Mines and Geology were helpful in working out the geology for areas not yet studied in detail.

The assistance of Messrs. Fred Veach, A. A. Garrett, and Fred Johnson of the Geological Survey was appreciated.

A special note of gratitude is extended to Aileen Jacobs and Margaret Holland for their valuable assistance in editing and typing the report.

CHARACTERISTICS OF THE REGION

PHYSICAL DESCRIPTION

The area under discussion in this report, Nooksack River basin and certain adjacent streams, occupies a large part of northern and western Whatcom County in extreme northwestern Washington State. It extends from Bellingham north to the Canadian border and east to Mt. Baker, Mt. Shuksan and the Skagit Range and is bounded on the west by Georgia Strait.

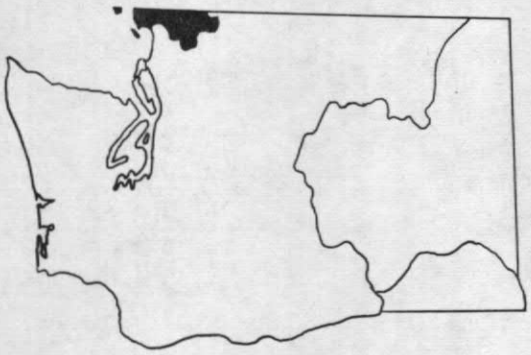


Figure 1. LOCATION MAP OF REPORT AREA

For convience in this report the area has been divided into two major physiographic provinces, those being: (1) The Whatcom Basin, or that part of the area lying west of the foothills of the Cascade Mountains and entirely within the Puget Trough of the Pacific Border physiographic province,[1] and (2) The Eastern Upland which includes those parts of the Cascade Mountains lying within the Nooksack and Sumas River Drainages.

SIZE OF AREA

Total area in the report includes 959 square miles within the United States and 51.0 square miles of contributing drainage area in Canada. This includes 4.9 square miles of Point Roberts, Eliza Island with 0.2 of a square mile, and Lummi Island with 9.2 square miles. Of the total area, all but 51.0 square miles in Canada and parts of four townships in north central Skagit County lie within Whatcom County.

[1] Fenneman, N. M., 1917, Physiographic division of the United States: Assoc. of Amer. Geographers Annals, v. 6, p. 95, pl. 1.

PHYSIOGRAPHY

The Whatcom Basin west of Lawrence is typical hummocky glacial topography with till-capped uplands overlooking broad river valleys. The valleys and uplands are interconnected by gentle slopes or terraces mantled with recessional outwash materials. The till-covered uplands, because of their resistance to erosion, stand out as dominant topographic features.

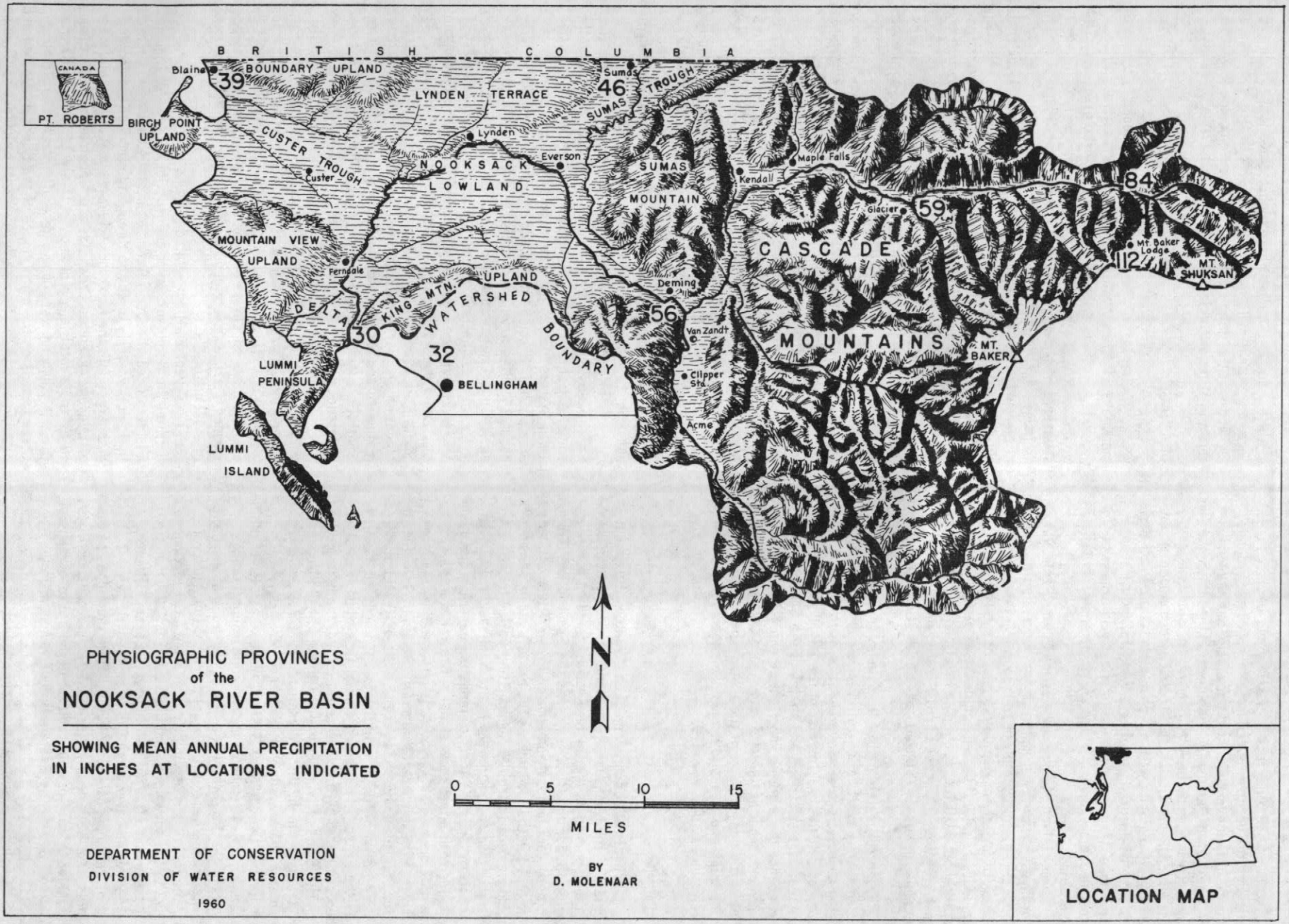
There are six significant upland or plateau areas within the Whatcom basin that warrant discussion (fig. 2). They are: (1) The small peninsular area southwest of Blaine, herein called the Birch Point Upland; (2) The large area extending eastward from Blaine and across the international boundary into Canada generally referred to as the Boundary Upland; (3) The Mountain View Upland west of Ferndale; (4) The King Mountain Upland extending north from Bellingham to the Nooksack River valley; (5) The Lummi Peninsula; and (6) Lummi Island. The inter-upland river basin lowlands constitute a seventh significant physiographic province. Point Roberts, a small peninsular projection of Canada, but a part of Whatcom County, is also discussed in the report.

Birch Point Upland, which is till-capped, comprises an area of about 4 square miles and is bounded on three sides by steep sea cliffs; Drayton Harbor on the north; Georgia Strait on the west; and Birch Bay on the south. The upland attains a maximum elevation of about 265 feet above sea level.

Mountain View Upland, west of Ferndale, is diamond shaped and embraces an area of about 42 square miles. It too is a till-capped rolling hilly surface and rises to an elevation of about 385 feet. This upland is bordered on the west by Georgia Strait where steep sea cliffs drop from the upland surface to the beach below. It is bordered on the north by the Custer Trough and on the east and south by the Nooksack River and Lummi River floodplains. Many large erratics found on the upland surface were ice rafted to the area from their source in Canada to the north. The relatively impermeable till surface supports several swamps and one small lake. The Mountain View Upland, like other low plateaus in the Whatcom Basin, was forested in its native state; but since has been logged and is now mostly cultivated. The land is dry during most of the summer and requires additional water for irrigation.

Boundary Upland, immediately east of Blaine, is about 10 miles long and 3 miles wide and is a part of a larger upland extending northward into Canada. Its surface rises to a maximum altitude of nearly 500 feet and is a smoothly rolling, stony till surface formerly forested but now cutover and partially taken by brush and second growth.

The rolling till surfaces of the King Mountain and Squalicum Mountain Uplands rise to the south from the Nooksack River valley to a maximum elevation of approximately 500 feet to where the till laps upon the slopes of the Cascade


PHYSIOGRAPHIC PROVINCES
of the
NOOKSACK RIVER BASIN
SHOWING MEAN ANNUAL PRECIPITATION
IN INCHES AT LOCATIONS INDICATED
DEPARTMENT OF CONSERVATION
DIVISION OF WATER RESOURCES
1960
BY
D. MOLENAAR
MILES
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5
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N
LOCATION MAP
CANADA
PT. ROBERTS
B R I T I S H C O L U M B I A
Blaine
39
BOUNDARY UPLAND
BIRCH POINT
UPLAND
CUSTER TROUGH
Custer
LYNDEN TERRACE
Lynden
NOOKSACK
LOWLAND
Everson
Sumas
46
SUMAS TROUGH
SUMAS
MOUNTAIN
Kendall
Maple Falls
Glacier
59
84
CASCADE
MOUNTAINS
Mt. Baker Lodge
12
MT. SHUKSAN
MT. BAKER
MOUNTAIN VIEW
UPLAND
Ferndale
DELTA
KING MTN.
UPLAND
WATERSHED
BOUNDARY
30
32
BELLINGHAM
Deming
56
Van Zandt
Clipper Sta.
Acme
LUMMI
PENINSULA
LUMMI
ISLAND

Figure 2.

foothills. Knobs of older rock of Tertiary age in places protrude through the unconsolidated materials. These uplands, too, consist of cutover brushland and cultivated farmland.

The Lummi Peninsula, a southern extension of the Nooksack River floodplain, was formerly an island whose connection to the mainland was affected by deposition of fine-grained deltaic deposits with a probable Nooksack River derivation. The peninsula is a relatively low rolling till-capped surface whose maximum elevation is slightly in excess of 100 feet above sea level. There are no perennial streams on the peninsula.

Lummi Island, lying southwest of Lummi Peninsula, is a northwest-southeast trending island about 9 miles long and about 1½ miles in width whose topography is an external expression of underlying geologic formations. The submountainous, heavily timbered southeastern part of the island averaging about 300 feet above sea level and reaching a maximum elevation in excess of 500 feet is underlain by resistant metamorphic and igneous rocks of the Leach River group.

The northwestern part of the island, in contrast to the rugged southern part, is a low rolling till-capped surface averaging about 150 feet above sea level with a maximum elevation of 360 feet. This part of the island is underlain by less resistant sandstone and shales of the Chuckanut formation. Since there are no important perennial streams on Lummi Island, most of the inhabitants have settled near the beaches of the northern part of the island where sufficient water for stock and domestic purposes can be obtained from relatively shallow drilled wells.

LOWLANDS

Lowlands or bottom lands of the Whatcom Basin consist largely of the Nooksack River floodplain and two branching lowlands known as the Custer Trough, trending northwest to Drayton Harbor and Birch Bay, and the Sumas River Trough, leading northward into Canada and the Fraser River drainage. Also included in the lowlands is the broad Lynden Terrace extending westward from the Sumas River valley to the Boundary Upland and southward to the Nooksack and Custer Trough bottom lands. These lowlands are generally flat lying and mantled with either recessional outwash materials of Vashon glaciers or glacial materials re-worked by the Nooksack River. These lowlands generally lie below 100 feet in elevation, but the Lynden Terrace rises to 150 feet or more.

The Sumas River, a misfit stream, occupies a valley used by the Fraser River during glacial time when it was crowded southward by the continental ice advancing from the north. The Sumas River, now a distributary of the Nooksack River, drains a sub-basin in Washington of 69.9 square miles in area, northward to the Fraser River.

East of the Whatcom Basin, the Nooksack River drainage occupies a west slope of the Cascade mountain range. Just west of Deming, where the Tertiary bedrock of the Cascades disappears beneath the glacial drift of the Whatcom Basin, the foothills rise abruptly from about 200 feet above sea level to the snowfields and glaciers of 9,127 foot high Mt. Shuksan and 10,778 foot high Mt. Baker. Glaciers and perennial ice cover about 11.3 square miles[1] or 1.1 percent of the Nooksack River basin. Here the slopes of the mountains have been deeply dissected by the Nooksack River and its major tributaries. In contrast to the old topography of the Whatcom Basin, the Eastern Upland is mature in the foothills, and to the east where higher elevations prevail, it becomes youthful with narrow, steep sided valleys. The valley floors of the three major forks of the Nooksack River are partially filled with glacial drift andRecent river alluvium.

DRAINAGE

As the last of the continental ice receded to the north, the Nooksack River and associated streams returned to courses generally occupied prior to the advance of the glaciers. The Nooksack River, whose drainage was temporarily diverted southward from Deming and Van Zandt to the Skagit River drainage, again flowed westerly to Everson, Ferndale, and into Lummi or Bellingham Bay. However, immediately prior to about 1860 the river discharged into Lummi Bay. The change to its present discharge into Bellingham Bay was originally caused by a log jam but was later made permanent by construction of a dam across the headwaters of the Lummi River. The present dendritic drainage pattern has remained more or less unchanged since the close of the Pleistocene (ice age) epoch about 10,000 to 15,000 years ago.

Genetically, the three forks of the Nooksack River are consequent streams; their courses being dictated by topography and natural land slope rather than by geologic structure or jointing and faulting.

The North Fork (above the confluence of the North Fork and Middle Fork) drains a total area of 292.9 square miles of which 4.9 square miles are in Canada. The North Fork heads on the north slopes of Mt. Shuksan and flows westerly for about 30 miles to where it courses southwesterly and joins the Middle Fork about 4 miles east of Deming. This tributary drains the west slopes of the Skagit Range and the north slopes of Mt. Shuksan and Mt. Baker and has a total length of approximately 40 miles.

The Middle Fork (above its confluence with the North Fork) heads on the south slopes of Mt. Baker and drains the southwest slopes of Mt. Baker and the northeast slopes of Twin Sisters Mountain. The Middle Fork drainage has an area of 101.2 square miles and courses northwesterly for about 17 miles to where it joins the main stem of the Nooksack about 4 miles east of Deming.

The South Fork drains the regions south and west of Mt. Baker and the western slopes of Twin Sisters Mountain. Mt. Baker does not actually contribute to this drainage. The South Fork heads on the southeast slopes of Twin Sisters Mountain and scribes a semicircular pattern eventually flowing northward and entering the Nooksack River at Deming. The South Fork has a total length of approximately 36 miles and a watershed of 181.6 square miles.

An area of about 69.9 square miles lying generally north and east of the town of Everson, is drained by the Sumas River which flows in a northeasterly direction and discharges into the Fraser River in Canada. The Sumas River receives runoff from the west slopes of Sumas Mountain, the east slopes of Lynden Terrace, and ground water discharging from contiguous alluvial materials.

Seven small but related streams drain the general area north of the Nooksack River and west of the town of Lynden. Fishtrap Creek heads in Canada north of Lynden and courses in a southwesterly direction through the town of Lynden and discharges into the Nooksack River about 4 miles southwest of Lynden. Fishtrap Creek has a drainage area of 30.6 square miles and a total length of approximately 13 miles. Bertrand Creek, lying just west of and generally parallel to Fishtrap Creek, heads on the north slopes of the Boundary Upland and discharges into the Nooksack River just below its confluence

[1] U. S. Geological Survey Quadrangle Maps.

with Fishtrap Creek. Bertrand Creek, about 6 miles long, has a drainage area of 43.5 square miles. Dakota Creek drains the south slopes of the Boundary Upland and the northern part of the Custer Trough; it heads in the western half of Twp. 40 N., Rge. 2 E., and flows northwesterly and discharges into Drayton Harbor. Dakota Creek, approximately 9 miles long, has a watershed area of 28.3 square miles. Lying just south of and parallel to Dakota Creek, California Creek drains an area of 22.8 square miles of the southern half of the Custer Trough and the northeastern slopes of Mountain View Upland. California Creek has a total length of approximately 9 miles. Terrell Creek drains an area of 17.2 square miles of the western slopes of the Mountain View Upland. It heads in Terrell Lake and flows northwesterly for about 5 miles and discharges into Birch Bay. The Lummi River, once an outflow channel of the Nooksack River but now dyked off, drains the south slopes of Mountain View Upland and the lowland generally south of Ferndale and north of the Nooksack River drainage. The Lummi River courses southwesterly and empties into Lummi Bay. Tenmile Creek, about 10 miles in length, drains an area of 34.0 square miles of the north slopes of King Mountain and Squalicum Mountain. Tenmile Creek flows southwesterly and discharges into the Nooksack River just north of Ferndale.

All of the small related streams just discussed course across the glacial drift of the Whatcom Basin and are maintained primarily by ground-water discharge from the glacial material with the exception of periods of high precipitation when surface runoff contributes to their flow.

Silver Creek, a small stream of about 5 miles in length, drains an area of about 15.8 square miles of the northwest slopes of King Mountain Upland lying south and east across the Nooksack River from Ferndale.

The balance of the area under study, namely 172 square miles, is drained by ground-water discharge or small streams.

Point Roberts, Eliza Island, and Lummi Island are included in this report but do not support major surface streams and residents rely almost entirely upon springs, lakes, and ground water for water supplies.

VEGETATION

The Nooksack River basin originally was heavily forested except for small open meadows and marshes. Douglas fir, western hemlock, and western red cedar are the dominant forest trees. Cottonwoods are common along stream bottoms and Alder predominates in cutover and poorly drained areas. Birch, maple, dogwood, and willow are also commonly found. Underbrush is usually very thick. Most common shrubs are devils club, madrona, manzanita, Oregon grape, salal, cascara, rhododendron, huckleberry, and numerous types of thorny berry bushes. Ferns form a dense cover in open areas.

Most of the virgin timber has been cut except in the higher mountains and on national forest land. River bottoms and many of the lower benches have been brought under cultivation. Cutover areas not suitable for farm crops sustain a thick second growth of fir, cedar, and hemlock.

The western lowlands of the Whatcom basin are now a highly developed agricultural area. Much of the land is planted to hay, pasture, and other forage crops required to support the modern dairy industry.

CLIMATE

INTRODUCTION

In describing the climate of the Nooksack River basin, which is typical of all of western Washington, it would be difficult to overemphasize the importance of several unique, natural aspects which combine in bestowing on this land the distinction of being one of the earth's best watered regions.

Nowhere on the globe are the climatic controls of latitude, air mass source region, and topography more advantageously blended for the production of large quantities of high quality water.

The dominant control affecting the climate of this region results from its geographic position. Due to the tilt of the earth's axis relative to the plane of its annual circular journey around the sun, the northern and southern hemispheres are alternately exposed to excessive heating and cooling from solar radiation. Without the protective shield provided by the atmosphere, the equatorial regions bathed in solar radiation for twelve hours every day would become progressively hotter while the polar zones would be fluctuating every six months between torrid heat and bitter cold.

Fortunately, the atmosphere and in a similar way the oceans provide the medium by which these excesses of heat and cold can be distributed over the globe. History assures us this mechanism has been very effective in maintaining relatively constant, local mean annual temperatures all over the earth.

To maintain this temperature balance, enormous quantities of heat energy must be transported poleward by the air-ocean mediums. Governed by known physical laws this exchange is conducted in the atmosphere essentially by gigantic eddies of air, some of which are thousands of miles in diameter. Depending on the rotation of the eddy, configurations of air similar to mountains and valleys are formed above the surface of the earth. The "mountains," which rotate clockwise, are referred to as high pressure areas or anticyclones; the "valleys," with the opposite rotation, are called low pressure areas, cyclones, or storms.

One of the major eddies in the earth's atmospheric circulation is the Pacific High, so called for its semipermanent location over the Northeastern Pacific Ocean. In response to the seasonal fluctuations in solar energy, this mountain of air will migrate northward during the summer and recede slowly southward with the sun in the fall. It is this oscillatory movement that accounts for the dramatic seasonal change in climate experienced twice a year.

In the vicinity of the Aleutian Islands, another semipermanent feature of the atmospheric circulation occurs. Here nature favors the generation of somewhat smaller eddies which rotate counter-clockwise. These low pressure areas, once set in motion, usually drift eastward and are the storms experienced in this region.

Although somewhat fewer lows are generated during the summer months, it is the position of the Pacific High that dictates the frequency of storms entering this area. During the late spring, the northward extension of this vast mountain of air effectively diverts the storm track to higher and higher latitudes. After reaching maximum development, in July and August a gradual deterioration and southerly

recession of this revolving air mountain permits the more numerous and active disturbances to batter the coast at increasingly lower latitudes. Because of the coincidence of maximum eddy development in the Aleutian area, with an unimpeded storm path, this region experiences an unusually wet winter season.

Because of two other permanent protective barriers to airflow from the east being provided by the Rocky Mountain Range and the less formidable but more immediately effective Cascade Mountain Range, western Washington climate is predominately maritime and is unprotected for a full 180° to the west. Practically all air masses entering this region have been subject to some modification by the Pacific Ocean. Since water bodies absorb and expend heat at considerably lower rates than do land masses, they exert a significant moderating effect on both winter and summer temperatures. The range of extreme temperatures in this region is as small as in any other similar latitude zone.

The foregoing climatological features are not uncommon to many regions on earth situated in temperate latitudes downwind from large expanses of water. However, it is the effect of the topographic control on western Washington climate and resultant hydrology that is distinctly unique.

It is the existence of the Cascade Range, a substantial north-south mountain barrier athwart the mean storm path, that fulfills the potential hydrologic capabilities of this climate. The configuration of these mountains and their stream valleys are particularly well adapted for the conversion of precipitation to a high quality water resource. All these valleys are oriented nearly parallel to the moisture laden wintertime airflow. Furthermore, these natural catchment basins are distinctive in that the valley floors maintain an unusually low gradient for a considerable distance into the mountains. Elevations of the valley floor of 2,000 feet at less than 10 miles from the watershed boundary crest are not uncommon. The importance of this abrupt rise in topography is twofold. In addition to the influence of the sudden orographic lifting, materially increasing the quantity of water precipitated from winter storms, these mountains are of principal importance in effecting a spectacular change in climate within the short horizontal distance of only a few miles.

As a natural consequence of the lower temperatures experienced in this mountain climate, practically all precipitation during the winter falls in the form of snow. Here, a delicate balance of temperature and precipitation results in one of the most distinctive manifestations of the character of this climate: the existence of large permanent ice fields and glaciers. For example, the Nooksack River basin alone contains almost as much glacier covered area as the combined total in the states of Oregon and California! Approximately eighty percent of the area of glacial ice in the forty-eight contiguous states is concentrated on the Olympic and Cascades Mountains in the State of Washington.

Although the reduction in temperature provided by the mountain environment is necessary to the development and perpetuation of glaciers, the essential difference with most mountainous areas of the world is the concomitant occurrence of extremely heavy precipitation during the winter (probably in excess of 200 inches of water equivalent in the most favorable areas). These enormous quantities of snow are protected from melt by a common and inherent ability to reflect solar energy. An additional immunity against wastage is provided by the unusual atmospheric environment in which these snow fields thrive. Swathed in air previously cooled and moistened over the Pacific Ocean and shielded from the desiccating effect of dry continental air masses, these snowfields are able to survive complete depletion. Because of the larger amount of precipitation at the higher elevations, the surplus of snow at the end of each year is gradually compressed into ice. Consequently, ice fields or glaciers build at the high elevations and, because of their own weight, flow downhill into the warmer zone to be melted.

The importance of these naturally controlled snow and ice reservoirs to the water resources of this basin cannot be overemphasized.

PERIOD OF STUDY

Weather is a very complex phenomenon. In order to reduce the extreme variability of meteorological data, it is necessary to incorporate as large a number of observations as possible. The period studied should be as long as the data will allow. From the mean tendencies revealed in records collected over comparable periods of time from several observation points, it is possible to gain some insight of the nature of the major regional climatic controls.

Since this study is directed toward an evaluation of the water resources of the Nooksack River basin, the hydrological records from that region were a prime factor in determining the length of the period.

Streamflow records were collected in the Nooksack River basin as early as the 1920's. However, it was not until the middle 1930's that permanent and continuous records were started. Generally, climatological data records from this region were well established by this time.

Fortunately, a period for study compatible with the available data was suggested for a beginning in the year 1934, following one of the particularly high precipitation years of record. Equally convenient was the re-occurrence of a similar year in 1959. This twenty-six year period affords a cyclic range of data for summation that will be least affected by antecedent conditions.

GENERAL CLIMATIC TRENDS

The Clearbrook climatological data station was selected to depict the general trend of precipitation distribution throughout the past 57 years. This excellent record was chosen because of the uninterrupted location of the instruments and the near perfect continuity of daily observations, particularly since July 1, 1919. It was at this time that Mr. R. D. Perry of Clearbrook, Washington, assumed the responsibility of reading climatological instruments every evening, 365 days a year for a period of over 32 years; after which his brother, Mr. William S. Perry, assumed these same duties such that the Perry family has to date contributed almost one-half of a century of their time to the maintenance of this climatological station.

Figure 3 represents the general trend of precipitation amounts in the lower Nooksack River basin as recorded at the Clearbrook station since 1903. Because of the year to year variability in precipitation amounts, it is sometimes advantageous to represent the cyclic patterns by a moving series of averages, each of ten consecutive year periods. For example, the period 1903-12 is characterized by one point on the graph and represents the average annual amount of moisture precipitated during that decade. The 1904-13 period and each succeeding ten year period are similarly computed and plotted as an ordinate quantity point above the abscissa year ending the decade. General conclusions can

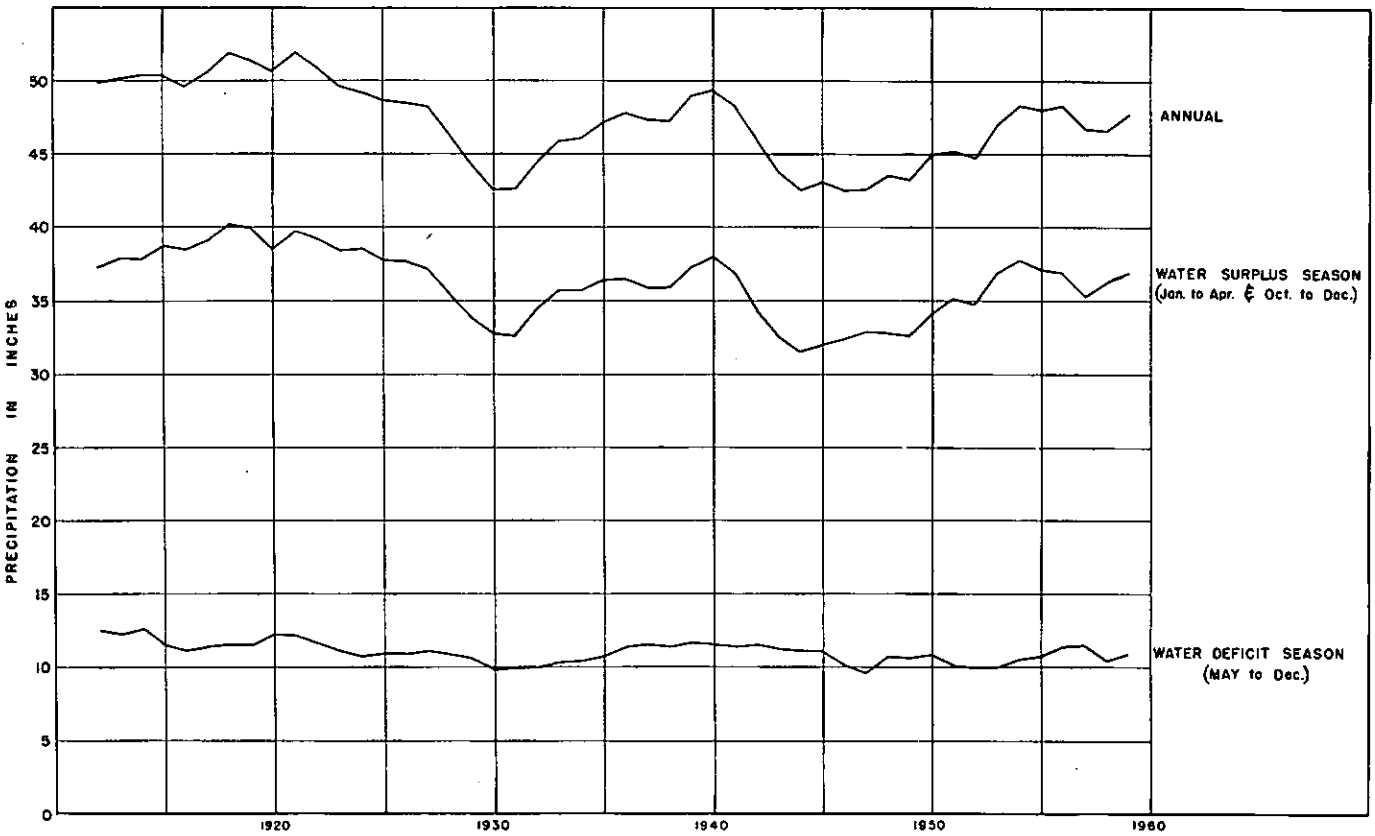

Figure 3. 10-YEAR MOVING AVERAGE PRECIPITATION AT CLEARBROOK STATION.

be deduced from this graph. Decadal data has been computed and curves are drawn for annual amounts and also for both the surplus and deficit seasons. The last two periods will be defined in subsequent paragraphs.

In general, the annual graph indicates three relatively wet periods of decreasing amplitude centered around 1920, 1940, and 1955 with intervening dry periods in the early 1930's and middle 1940's of similar amplitude but increasing duration. As would be expected, the surplus season, which represents over 76 percent of the average year's total precipitation of Clearbrook, closely parallels the annual curve. The curve of decadal means for the deficit season shows some departure from annual and surplus seasons, although there is generally close agreement. In these data the deficit period intervenes the surplus season and some interrelationship is inevitable. A cursory re-examination using data for concurrent seasons showed considerable more dispersion.

A comparison of the annual average for the 1903-59 period of record and the 1934-59 period selected for study shows the latter period to be deficient by 1.77 inches per year or about 3.75 percent below the longer term record. This percentage departure was slightly higher during the surplus season.

AVAILABLE DATA

The primary purpose of this examination of climatological data is to evaluate the areal precipitation distribution over the Nooksack River basin. In an area of only 1,010 square miles, but ranging from sea level to above 10,000 feet, a considerable variability of precipitation amounts in both time and space was expected.

To begin the examination, it was deemed advisable to divide the basin into elevation areas. Since stream gage data would be used intensively in this study, the watershed area above each stream gage was measured in 1,000 foot elevation intervals. These data revealed that the distribution of area with each 1,000 foot interval was essentially constant up to the 4,000 foot elevation constituting over three-quarters of the basin area. Ninety-nine percent of the basin is below 7,000 feet, and the residual 1 percent is distributed over rapidly diminishing 1,000 foot interval areas with less than one-tenth of 1 percent above 10,000 feet.

There are a total of five stations recording precipitation in the Nooksack River basin, three of which are below the 1,000 foot elevation contour. In addition, there are four stations in the United States and several in Canada adjacent to the basin which have been useful in this study. Unfortunately these, too, are all lowland stations. The remaining two stations are located near Shuksan at 2,030 feet and Mt. Baker Lodge, elevation 4,150 feet.

The station at Shuksan, attended by the State Highway Department, began continuous operation in 1956. The Mt. Baker Lodge record, while extending back prior to the study period, is riddled with missing data such that the period 1934-59 contains less than 50 percent of the total record and only 3 complete calendar years. Consequently, this study had available only a limited amount of actual data on precipitation above 1,000 feet elevation in this basin.

Figure 2 shows mean annual precipitation for the period of study at approximate locations of the recording stations. Due to the wide variation in amounts of precipitation with different exposures and changes in elevation and because

of the obvious insufficiency of actual data, no attempt was made to delineate zones receiving equal amounts of precipitation.

Stream gage records contain valuable information regarding precipitation over the watershed area. However, due to the aforementioned unusually low gradient of the principal river valleys in the watershed area, gaging sites are located at relatively low elevations. For example, the stream gage above Cascade Creek on the North Fork of the Nooksack River, at the comparatively low elevation of 1,245 feet, measures only 13 percent of the Nooksack River drainage. Consequently, this record is the integrated sum of all runoff from an area ranging between elevations of 1,245 feet and the 10,778 foot summit of Mt. Baker, the highest point in the watershed. A more extreme situation exists at the gage near Wickersham on the South Fork of the Nooksack River. Here, the elevation of the gage is only 385 feet, yet it also samples a mere 13 percent of the total Nooksack River watershed.

Undoubtedly, the most serious problem confronting a thorough understanding of our available water resource is the effect of topography on precipitation. It is well known that the cooling resulting from forced ascent of moist air over mountain barriers increases condensation and the subsequent precipitation on the windward slopes. However, this orographic effect will vary from storm to storm and also with season. From the data available for examination, a quantitative evaluation of these phenomena in the Nooksack River basin was not possible. Lacking sufficient density of data in the Nooksack River basin, it was necessary to expand the field of investigation. Being bounded on the east by the data-barren Cascade Mountains, the periphery of investigation could be extended only to the south, west, and north. Included in the study but not shown are four stations in the Skagit River valley, one on the San Juan Islands, and four selected stations located in British Columbia. Thus, a total of seventeen climatological data stations distributed over an area of roughly 4,000 square miles have been examined.

With the period for study established as the 26-year interval of 1934 through 1959 inclusive, daily precipitation data for these seventeen stations were assembled. Missing data, which were negligible except for Glacier Ranger Station, were computed by means of the normal-ratio method of comparing similar periods of two adjacent stations to the station with the missing data.

Annual means were computed for the 26-year period and in addition similar means were computed for the surplus and deficit periods.

Whenever possible, graphs have been prepared with the time scale being along the horizontal axis (abscissa) and the element being compared with time being scaled along the vertical axis (ordinate). In graphing variates that are discontinuous in time such as precipitation, it is technically incorrect to join computed points with a continuous line. Actually, it is only the point on the line directly above the time interval noted on the abscissa that is significant. In most figures, the significant points on the line have been circled. After this word of caution, it is believed for the purposes of this study that the line joining the points depicts the essential variations more efficiently than the customary bar chart.

SURPLUS AND DEFICIT PERIODS

Besides being customary in most studies, it is quite useful to differentiate between seasonal precipitations. The year usually is divided into summer and winter halves. In the climate under study, however, the transition from wet, cool winters to warm, dry summers is quite naturally resolved by the concept of water utilization exemplified by the pseudo-climatic elements--surplus and deficit periods. As illustrated from mean values at Clearbrook station in Figure 8, almost without exception the surplus period begins each year in October. At the time of the autumnal equinox, the amount of solar radiation intercepted by the earth's surface at this latitude is decreasing at the maximum rate. Interconnected with the decrease of insolation is an abrupt change in the atmospheric circulation exhibited in the recession of the Pacific High to more southerly latitudes. Consequently, the number of moisture laden cyclonic storms crossing this area are rapidly increasing while the effects of evapotranspiration by solar energy are diminished, not only as a result of the shorter days, but also from the reflection of solar radiation by the increased cloud cover. For the remainder of the period, precipitation exceeds evaporation and the surplus moisture is expended as runoff.

The transition from the surplus to the deficit period is only slightly less persistant and usually occurs during late April or early May. At this time, the northward extension of the Pacific High results in fewer storms with diminishing precipitation. Simultaneously, the rapidly increasing length of the day and clearing skies cause evapotranspiration to become the dominant hydrologic factor. When evapotranspiration amounts exceed the supply of moisture contributed by precipitation, a deficit condition exists. This natural climatological division of the year, thus, defines the surplus period as October through April and the deficit period as the remaining five months, May through September.

PRECIPITATION

Precipitation patterns throughout the area under study exhibit a marked consistency in temporal distribution. Although total annual accumulations vary from 30 to possibly 200 inches, the monthly percentage contributions to the annual are remarkably similar. Therefore, to avoid a repetitious discussion, the Clearbrook location has been chosen as representative of the entire basin. Variations from this station, especially over the basin, are essentially those of quantity. Figure 4 shows graphically the mean monthly precipitation recorded at this station during the period 1934 to 1959, inclusive. The height of the line immediately above the months along the abscissa indicates the quantity of precipitation in inches as scaled vertically on the left. Similarly, the percent of the monthly contribution to the annual mean total is along the right margin. The solid line in figure 5 depicts the probability, in percent, of the occurrence of 0.01 inches of precipitation on any day during each month scaled along the left. The dashed line indicates the mean intensity in inches of water precipitated scaled along the right during each probable rainy day of the month. The latter data can be can be considered as an average rainfall rate at the Clearbrook location.

Less than 4 percent of the total mean annual precipitation falls in the form of snow at this station. The maximum snowfall occurs during January averaging about 6.5 inches in depth for the month. Snowfall is primarily limited to the months of November through March. Measurable amounts do occur in October and April, but these become insignificant when averaged over a long period of time. Precipitation from thunderstorms is insignificant. This area averages about five thunderstorm days per year, these occuring mostly during the

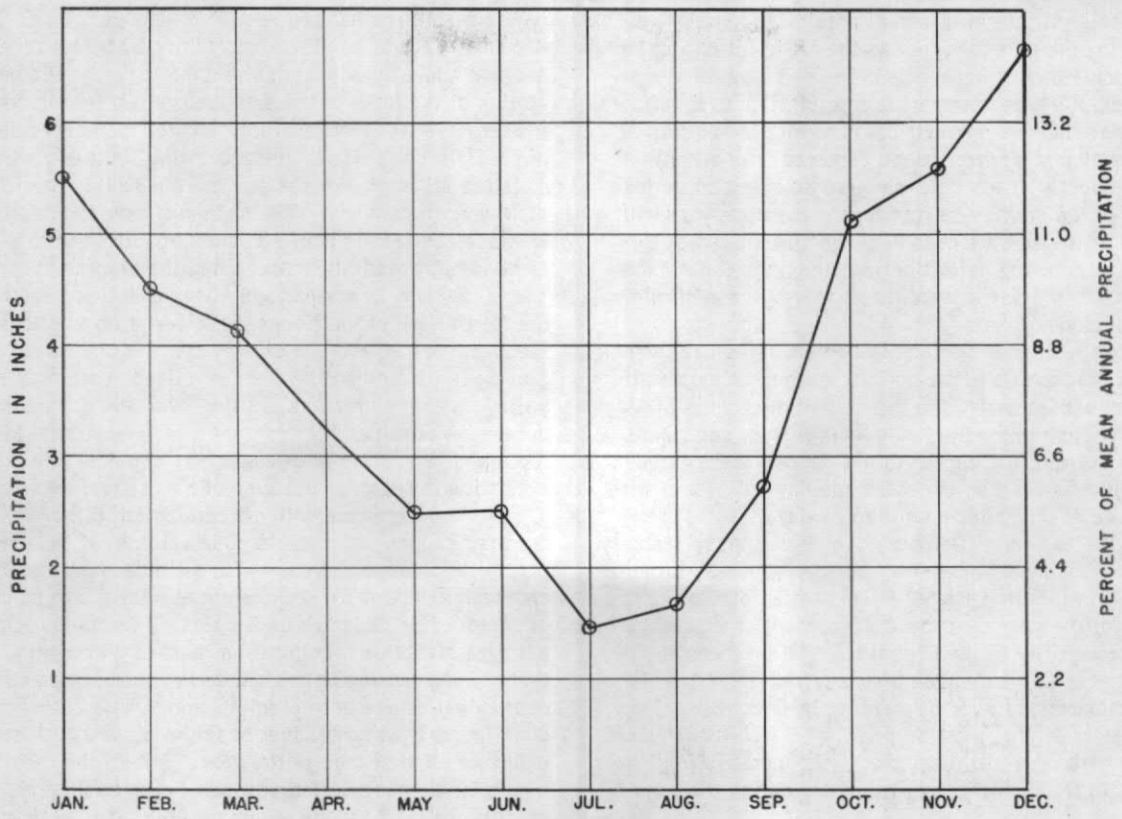

Figure 4. MEAN MONTHLY PRECIPITATION AT CLEARBROOK STATION.

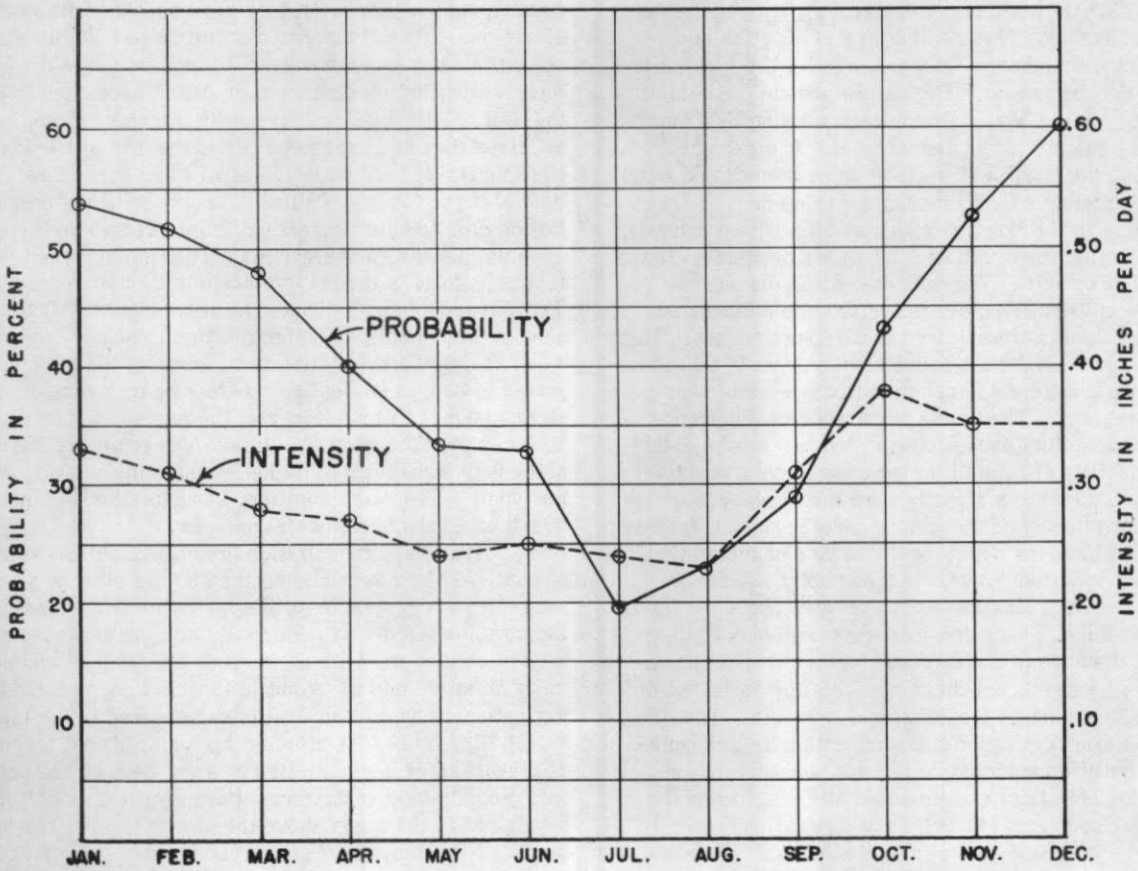

Figure 5. MEAN PROBABILITY AND INTENSITY OF PRECIPITATION AT CLEARBROOK STATION.

months of May through September.

Generally all compilations of precipitation data are published using the calendar year as the basis for comparison. Following such a procedure in this climate is somewhat cumbersome especially when comparing precipitation to runoff. Figure 4 shows that the symmetrical precipitation pattern at Clearbrook is almost a mirror image centered on the month of July. Consequently, each calendar year summary combines the last half of the surplus season for the previous year with the first half of the surplus season of the current year. Because of the intervening deficit period, the natural persistency that is known to exist in weather patterns is lost in this unnatural grouping.

At the Clearbrook station, 24 percent of the mean annual precipitation is recorded in the deficit season. Almost half of this amount occurs during the two transition months of May and September such that June, July, and August contribute only 12.3 percent to the annual total. During these three months precipitation can be expected one day out of four with an average rate of 0.25 inches per rainy day.

With the coming of October, cyclonic storms, steadily increasing in number and intensity, invade this area, hitherto blocked off by the Pacific High. Precipitation during the last three months of the year contribute 38 percent of the annual total. The probability of the Clearbrook station recording rainfall during the day increases from a low of 19.6 percent in July to a maximum of over 60 percent in December. The average intensity of precipitation per rainy day is a much more conservative parameter, exhibiting a slight increase from 0.24 inches to 0.35 inches per rainy day during the same period.

During the four following months, January, February, March, and April precipitation is essentially a reverse order reoccurrence of the September-December period, each month varying only slightly in intensity and probability from its corresponding reflection. This decline in precipitation occurrence, beginning in January, is a precursor of the inevitable return of the deficit season. The deficit season (generally) begins in the month of May. Precipitation during this month contributes 5½ percent to the annual total. Approximately ten days during the month will receive some rainfall and when combined, will average 0.25 inches per rainy day.

Contrary to the reaction expected from known controls, precipitation during the month of June shows a slight increase over the previous month. The perturbation on the smooth contour of the distribution curve becomes more pronounced when the short months are adjusted to 31-day amounts. This interesting anomaly in June precipitation appears to be associated with unusual meteorological conditions existent near mountainous regions. The timely occurrence of the phenomena with maximum actual evapotranspiration may not be coincidental. Probability of rainfall during June is only slightly less while the intensity is slightly more than in May.

Although there is some indication that annual amounts of precipitation increase with inland distance of the station, by far the most important control is topography. Areal precipitation on the Nooksack lowlands averages about 30 inches per year along Puget Sound and increases uniformly to near 50 inches at the base of the Cascade foothills. For the remainder of the basin the amount of precipitation varies within wide limits, depending on elevation and exposure. The paucity of actual precipitation measurements over this mountainous area nullifies any possibility of a quantitative assessment of the effects of exposure and altitude. From the data available, supported by records of streamflow from this area, some insight of the topographic mechanism is inferred.

As an example of the effect of exposure, a Canadian recording station located east of Vancouver, B. C., near Alouette Lake at an elevation of only 516 feet receives an average annual precipitation of 105 inches. Obviously, this station at the base of the extremely steep terrain north of the Fraser River is most favorably located to receive the maximum of precipitation. Here, the prevailing southerly winds slam moisture laden air masses against a mountain barrier perpendicular to the airflow. The sudden lifting and resultant cooling of these air masses cause a large proportion of this moisture to be precipitated while ascending the heights.

By way of comparison, Glacier Ranger Station well up the North Fork of the Nooksack River at an elevation of 937 feet receives an average of only 59.49 inches per year. This station is located on the floor of a deep, narrow, meandering valley, and any air mass passing over this station has already undergone considerable orographic modification. In spite of the higher elevation at this station, considerably less precipitation is recorded because of the unfavorable exposure.

In accordance with meteorological principles, which are also supported by ample observations, it is known that precipitation does increase with altitude. But due to the decrease in temperature with height and the progressive inability of air to retain moisture as it cools, it is obvious that at some optimum elevation precipitation reaches a maximum. From that point an increase in altitude is accompanied with a corresponding decrease in precipitation. This optimum elevation, even in the Nooksack River basin, will vary with storm type, exposure, and season of the year. Due to the insufficiency of high altitude observation stations in the basin and, in fact, over the entire Cascade Mountain area, it is practically impossible to determine if this optimum elevation would be above or is below the mean crest of the divide.

Streamflow data were used to supplement the lack of quantity and quality of precipitation observations in the higher elevations. Runoff computed at the stream gaging station was redistributed over each watershed studied to yield a figure representing net precipitation in inches necessary to produce the flow. This quantity represents the gross precipitation from all elevations and exposures minus the sum of the losses. Unfortunately, very little is known about the nature and magnitude of these losses. Initially, a portion of the precipitation falling on a forested watershed is intercepted on the canopy of needles, leaves, and branches. The rain and even more effectively snow is then evaporated from this vulnerable exposure. This loss has been estimated to be as high as 10 to 15 percent of the annual gross precipitation in heavily forested areas. The remaining precipitation upon reaching the ground is subjected to additional depletion before being measured at the stream gage. Evaporation from the ground, water, and snow surfaces plus the more significant loss to vegetation by the process of transpiration further reduces the quantity available for runoff. Evapotranspiration, computed for the lowland area, averages 25 inches of water per year.

The evapotranspiration process is closely related to the amount of solar radiation absorbed by the plant or ground surface. It is conceivable in this high mountain watershed that the combination of low reflectivity and the enormous surface area of conifer trees living in an environment of higher incident solar radiation and lower humidity would cause considerably more evapotranspiration than is experienced in the lowlands.

One other loss of potential runoff almost independent of climate is deep percolation of water through the soil profile into ground-water reservoirs. However, this is believed to be negligible in the areas above the stream gages used in this study. Also, any short term ground-water storage would be

averaged out over the 26-year period examined.

To supplement the lack of direct information on the extent and magnitude of these losses, streamflow data have been of material assistance in this study. For example, the maximum mean precipitation in the basin at Mt. Baker Lodge, as adjusted to the 26-year period, is 112.11 inches. However, streamflow measurements from this area average 98.78 inches of runoff per year. Assuming an interception loss of 10 percent plus an evapotranspiration loss estimated conservatively at 30 inches per year, a total mean annual precipitation averageing 143 inches over the entire watershed would be required to produce this runoff. Since the elevation of the watershed above the Cascade Creek gage varies from 1,245 feet to 10,778 feet atop Mt. Baker and because of a knowledge of the increase in precipitation with altitude and exposure, it is reasonable to expect a precipitation maximum in excess of 200 inches per year in the most favorable locations.

The effect of elevation on precipitation is not constant throughout the year. Figure 6 is a graphic representation of the extremes of the elevation effect. Mean monthly precipitation data from four stations varying in elevation from 64 to 4,150 feet were computed and plotted against elevation. Only the months of December and August have been selected for display, the other months being intermediate in character. During the colder months, which also represent the rainy season, the effect of elevation on precipitation is quite significant, increasing in December from 6.61 inches at Clearbrook to 16.99 inches at Mt. Baker Lodge. In August at these same two stations the effect is considerably less, increasing only from 1.65 to 2.93 inches.

Obviously, these mountains operate with uncanny efficiency for the production of a valuable water resource in this area: initially, by stimulating what would normally be only a modest amount of precipitation; secondly, by providing a climatic region in an otherwise temperate zone capable of converting this augmented rainfall into snow, an environment also particularly well adapted for the retention of large quantities of water in the solid form but with a sensitive release mechanism operated in conformity with water demand; finally, the magnitude of the orographic influence on precipitation is in phase with the optimum time--that is, during periods of large amounts of precipitation, this effect is maximum and throughout the summer months, when practically all precipitation is lost to evapotranspiration, the effect is negligible.

Perhaps the culmination of all the intricate built-in mechanisms operating to maximize runoff from this area is the natural immunity of snow covered areas to significant evaporation losses. A snow surface can never attain a temperature above 32° F, the temperature of melting ice. The ability of air to absorb water and retain these vapors is primarily a function of temperature. For example, air at a temperature of 50° F is capable of holding twice as much water as air at 32° F and almost nine times more than air at 14° F. Usually, in this climate during the period when sufficient solar energy is available for appreciable melt, the temperature of the air is

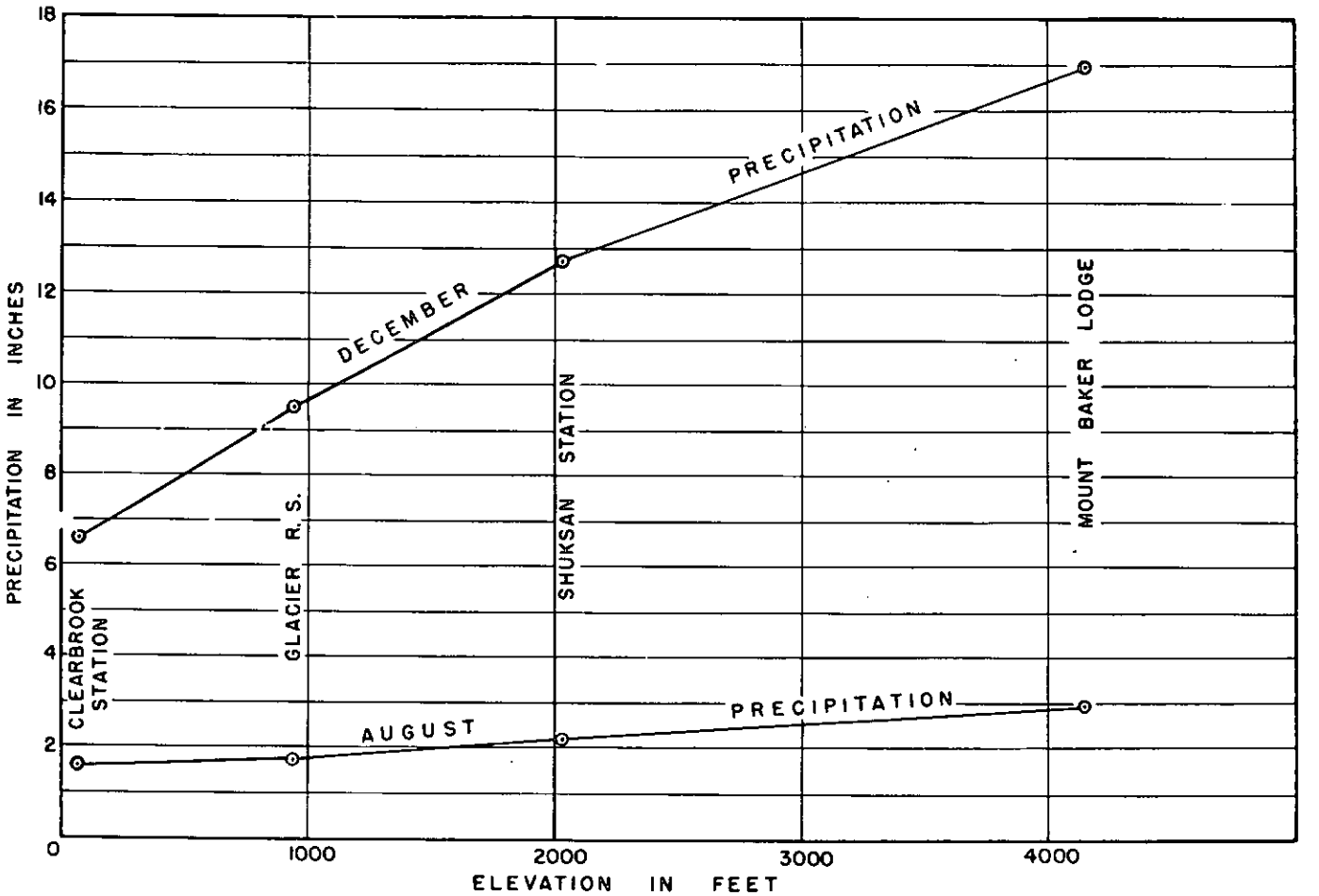

Figure 6. COMPARISON OF ELEVATION EFFECT ON SUMMER AND WINTER PRECIPITATION.

above freezing. Upon contact with the snow its temperature and associated water holding capacity are reduced and evaporation is inhibited. Actually, the snow has a slight affinity for the vapor if all other factors are equal. Research observations in this climate indicate that the amount of water lost to evaporation from snow surfaces is replaced in almost equal volume by the reverse process of condensation.

Additional conservation of potential runoff from snow covered areas can be attributed to an almost complete utilization of summer rain falling on the pack, whereas precipitation falling on bare ground at high altitudes during the summer is evaporated or transpired almost in entirety.

EFFECT OF TOPOGRAPHY ON RUNOFF

An examination of the records from the gage on the North Fork of the Nooksack River above Cascade Creek yields an average net precipitation, measured as runoff, equal to 98.78 inches annually. The area-elevation data computed from the watershed above this gage, which is at an elevation of 1,245 feet, are shown in the following table in the second column.

Runoff records measured at the gage on the South Fork of the Nooksack River near Wickersham, at an elevation of 38 feet, yield average net precipitation equal to 97.21 inches per year. Area elevation figures are shown in column 3 of this table.

Elevation Interval	Above Cascade Creek	Near Wickersham
0 to 1000 ft	0% of total area	8.0% of total area
1000 to 2000 "	3.3% "	19.5% "
2000 to 3000 "	16.4% "	28.1% "
3000 to 4000 "	22.4% "	32.5% "
4000 to 5000 "	29.4% "	10.7% "
5000 to 6000 "	20.8% "	1.1% "
6000 to 7000 "	6.2% "	.1% "
7000 to 8000 "	1.2% "	0 "
Above 8000 "	.3% "	0 "

Although these two areas are practically identical in size, the South Fork watershed is considerably lower in elevation. Despite a lower elevation, this watershed is much more favorably exposed to the direction of the prevailing rain-bearing winds. Also, there are no appreciable barriers to the flow of air from the southwest. Consequently, this basin, elevation for elevation, receives more precipitation than the North Fork watershed although the total runoff is practically the same.

It is indeed fortunate that measurements from these two areas are available for comparison, not only to demonstrate the effect of exposure on precipitation, but for yielding dramatic statistics on the value of the mountain snowpack reservoirs to the water resources of the region. In figure 7, the mean monthly hydrograph for these streams is drawn for comparison.

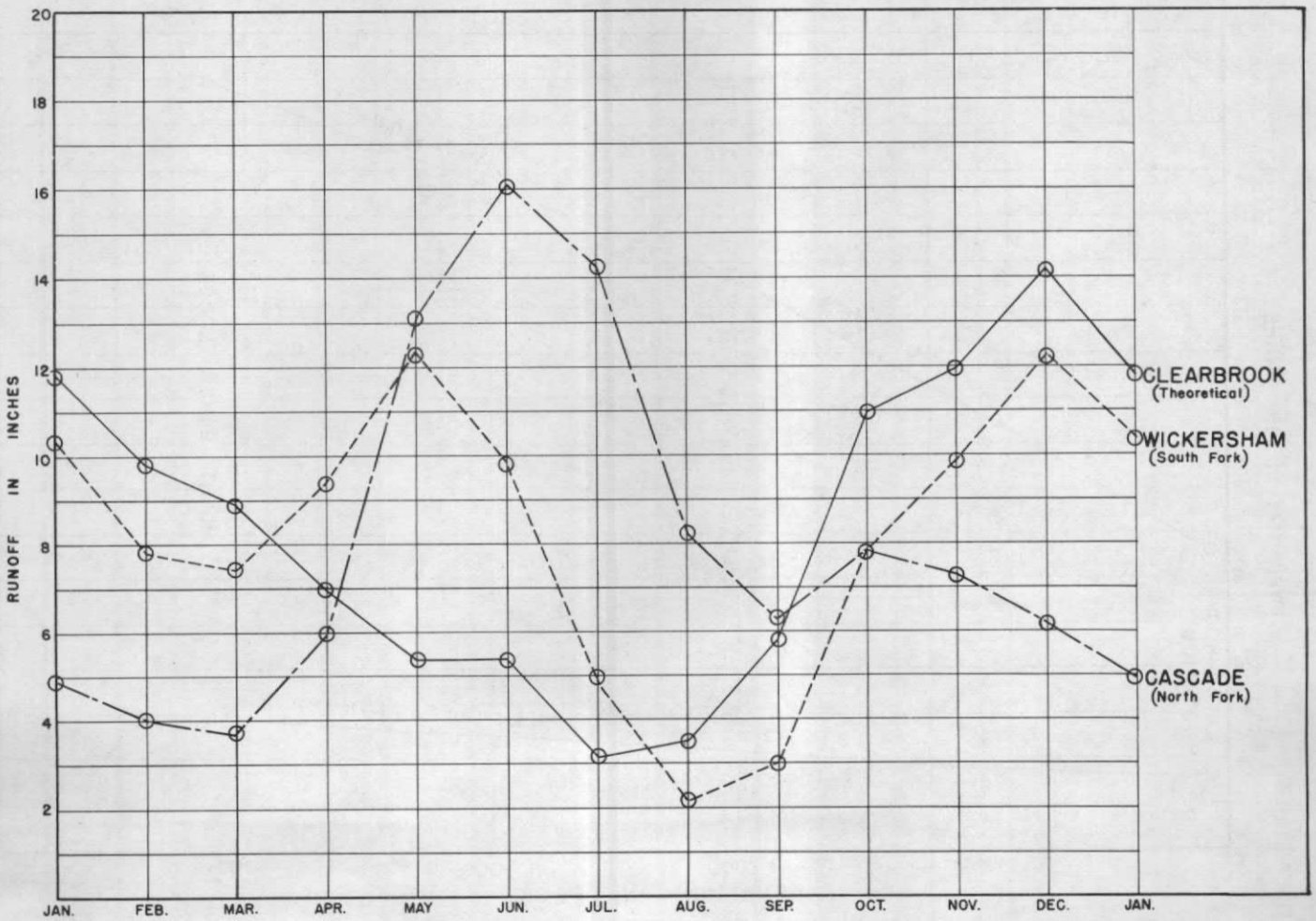

Figure 7. COMPARISON OF RUNOFF ON NORTH AND SOUTH FORKS OF NOOKSACK RIVER.

Because of the close relationships between rainfall and runoff in this region, the quantity of precipitation recorded at Clearbrook has been adjusted to equal the runoff from these two areas. Theoretically, this would represent the monthly distribution of runoff from a watershed devoid of losses or delayed recessional flows.

These monthly distribution curves are presented merely to show qualitatively the effect of topography on climate and runoff. As would be expected, runoff from both areas fall below the hypothetical precipitation curve during the colder months of the year indicating storage of water in the snowpack. The lower elevation and more favorable exposure results in streamflow from the South Fork being almost twice that of the North Fork during most of the winter months. With the warmer temperatures experienced during April, depletion of the snowpack combined with a higher incidence of precipitation in the form of rain over both basins cause streamflows to rise. These effects continue on into May. At this time runoff exceeds precipitation, indicating that depletion and ablation of the snowpack are becoming dominant contributors.

Tabulated below for the months of May through September in column 2 are the differences of runoff between the North and South Forks. Column 3 is a conversion of this runoff in acre-feet to the runoff in inches from a 27-square mile area.

Month	Runoff in Acre-Feet	Runoff in Inches
May	3,195 acre-feet	2 inches
June	33,746 "	23 "
July	51,584 "	36 "
August	33,613 "	23 "
September	18,038 "	13 "
Total	140,176 acre-feet	97 inches

The data involved in the area-elevation figures tabulated on page 14 were computed from a total area of a little over 100 square miles. Consequently, these figures can be considered, interchangeably, either as percentages or as total area in square miles. For example, 28.2 percent of the area on the North Fork is above 5,000 feet. This is approximately 28 square miles. Similarly, only 1 square mile is above this elevation on the South Fork watershed. Fortunately, for ease in comparison of these two streamflows, no permanent ice fields exist on the South Fork watershed.

If the runoff characteristics of the two streams were similar at all elevations below 5,000 feet, the excess flows in the foregoing tabulation could be attributed to the large difference in the area above 5,000 feet on these two streams. The North Fork has approximately 27 square miles more watershed above the 5,000 foot elevation than does the South Fork.

Actually because of the concentration of area over the lower elevation and the more favorable exposure to solar radiation on the South Fork, the comparison is somewhat biased in favor of the contention suggested in the last paragraph. However, these elevation and exposure effects would be expected to become less important as the summer season progresses.

After May the value of the high altitude watershed becomes conspicuous. Referring again to figure 7, at a time when precipitation is rapidly decreasing and runoff on the South Fork has reached its peak, streamflow on the North Fork is still rising.

During the same five-month deficit period when the Clearbrook station is recording only 24 percent of its mean annual precipitation, the North Fork produces 59 percent of its mean annual runoff. Actually, the contribution of the deficit period precipitation to the total at the higher elevations is probably only 10 to 15 percent.

The benefits derived from these climatically controlled glacier and snow field reservoirs on the North Fork are threefold. Obviously, a mean annual retention of 140,176 acre-feet of water for release during the season of maximum demand is extremely valuable to this region. In addition, the glaciers on the North Fork, estimated to cover 6.2 square miles of the watershed, are inherently capable of effecting cyclic storage. During periods of above normal precipitation and below normal temperatures, usually associated with years of water surplus, these glaciers grow in volume, storing water for inevitable return of a dry cycle. Finally, the water stored in glaciers and snow fields is withdrawn during the season of high runoff which results in a reduction of the downstream flood potential.

EVAPOTRANSPIRATION

Climatologists and ecologists working independently have come to realize the close association between the processes of evaporation and transpiration. The primary source of energy required for both of these processes is solar radiation. In most problems involving a water budget, these two consumptive withdrawals, evaporation (directly from the water-bearing surface) and transpiration (indirectly through the structures of plants), are usually combined. Hence, the term "evapotranspiration."

One of the most widely used methods of computing evapotranspiration was developed by Dr. C. W. Thornthwaite. Simply stated, Dr. Thornthwaite reasoned that the dissipation of solar energy was distributed among three primary heat consumers. A portion is expended in heating the air. The residual is expended either in heating the ground or is available for evapotranspiration. Although the magnitude of these three processes vary with wide limits, the ratio of the portion absorbed by each consumer is fairly constant. Therefore, the temperature of the air becomes an efficient indicator of the potential evapotranspiration. Using lysimeters, a device wherein plants are grown under known conditions of solar radiation, temperature, and moisture, Dr. Thornthwaite has derived an empirical formula based on temperature and latitude or length of possible duration of sunshine. Although there are more exact and sophisticated methods using actual measurements of solar radiation, wind movement, and humidity data, the Thornthwaite method, requiring only the conventional and readily available climatological data, is one of the most practical tools for evaluating evapotranspiration.

Figure 8 is a graphic representation of the water budget at the Clearbrook station compiled with this method. The coordinates are: months of the year along the abscissa and inches of water along the ordinate. The solid line denotes mean monthly precipitation, the dashed line mean monthly potential evapotranspiration, and the dotted line actual evaporation.

Beginning in January, which is really the middle of the surplus season, precipitation exceeds evapotranspiration by more than five inches. This surplus condition normally persists until mid-May, at which time the declining precipitation is just sufficient to meet the rising evaporatranspiration demands. This point marks the beginning of the deficit season.

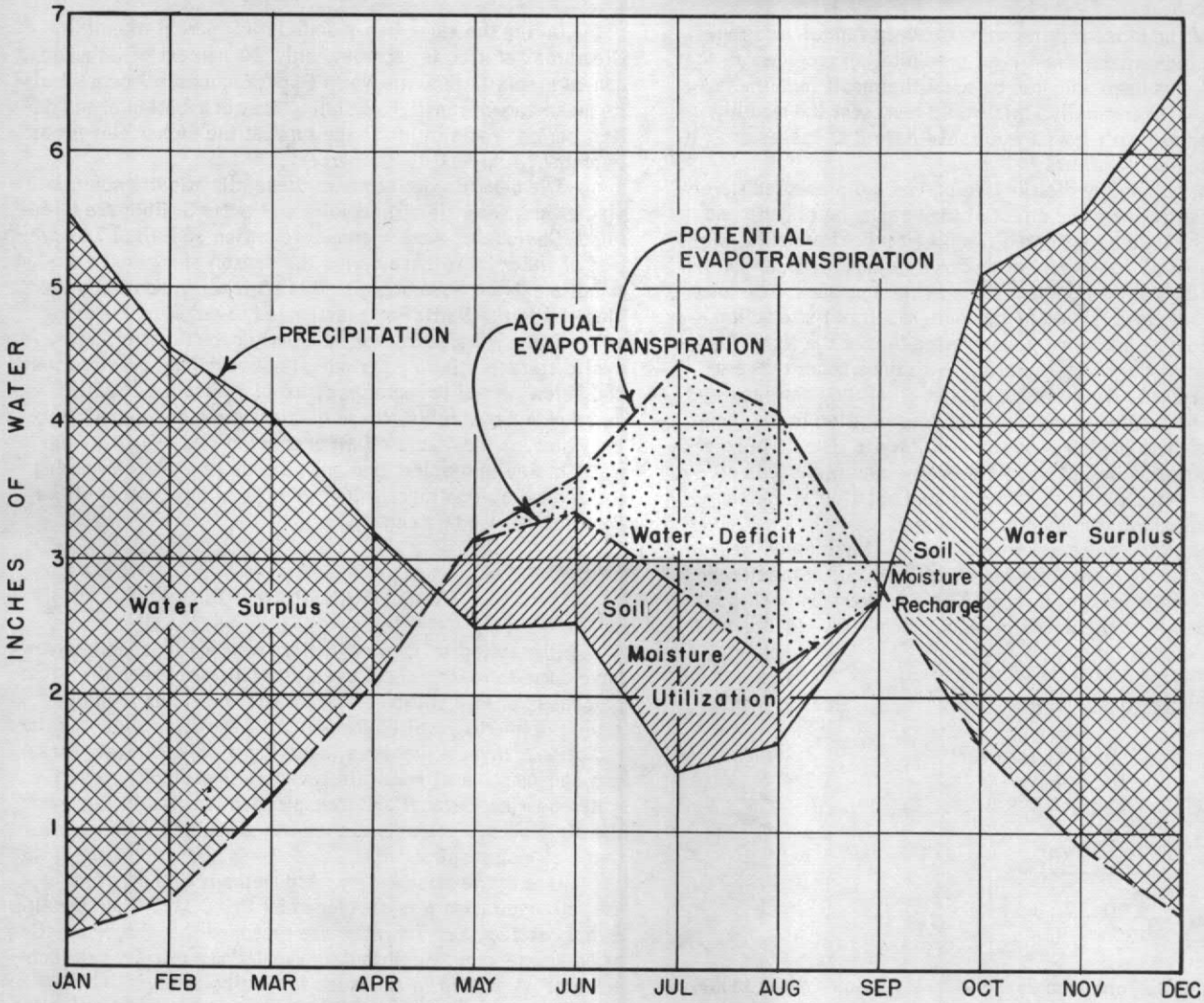

Figure 8. MEAN ANNUAL WATER BUDGET AT CLEARBROOK STATION.

Throughout the remainder of this season, evapotranspiration is the dominant hydrologic factor with a potential for evaporating 18.18 inches of water. Precipitation during this same 5 month period equals only 10.83 inches.

All through the surplus season and for a short time after the beginning of the deficit season the evapotranspiration rate is equal to the potential. Thereafter, since precipition is inadequate, the actual evapotranspiration is less than the potential. During this period there is a depletion of the water stored in the soil. At Clearbrook this field capacity is estimated to be 4 inches of water. As the deficit season progresses, increasingly higher potentials are required to evaporate the same quantity of water. For example, in September an evapotranspiration potential of 0.14 inches is required to evaporate only 0.02 inches of moisture from the desiccated soil profile.

Early in October the southward migration of the rain-bearing storm track signifies the end of the deficit season. Simultaneously, decreasing daily duration of sunshine accompanied by lower air temperatures cause a rapid reduction in the evapotranspiration potential. Precipitation once again is in excess. For a short interval this excess is utilized in recharging the depleted soil profile. Usually the ground becomes saturated by the end of October and further contributions of precipitation, less the now negligible evapotranspiration requirements, are expended as runoff.

In applying this principle to agriculture and especially to the needs for application of supplemental water, the concept of soil moisture can be neglected. Obviously for optimum plant growth and maximum irrigation efficiency, the soil profile should be maintained at or near field capacity throughout the growing season. Therefore, at the beginning of the deficit season supplemental water, just sufficient to meet the difference of the evaporation potential minus the precipitation, should be applied to the plant for optimum growth. Additional water is required to compensate for the efficiency of the irrigation system.

This graph illustrates a very important and somewhat insidious feature of Puget Sound climate. All during the winter the abundance of rainfall is most impressive. Although there is a pronounced decline in precipitation beginning after the first of the year, the ground remains saturated until late April or early May. Since temperatures are relatively high even during the coldest month, averaging 35.2°F during January at Clearbrook station, a luxuriant shallow-rooted vegetation is developed. The deficit in May, requiring only 0.66 inches of water to maintain complete saturation, represents a negligible draft on the soil profile. Even as late as June precipitation is only slightly below water demands. But after the first of July there is an abrupt change in growing

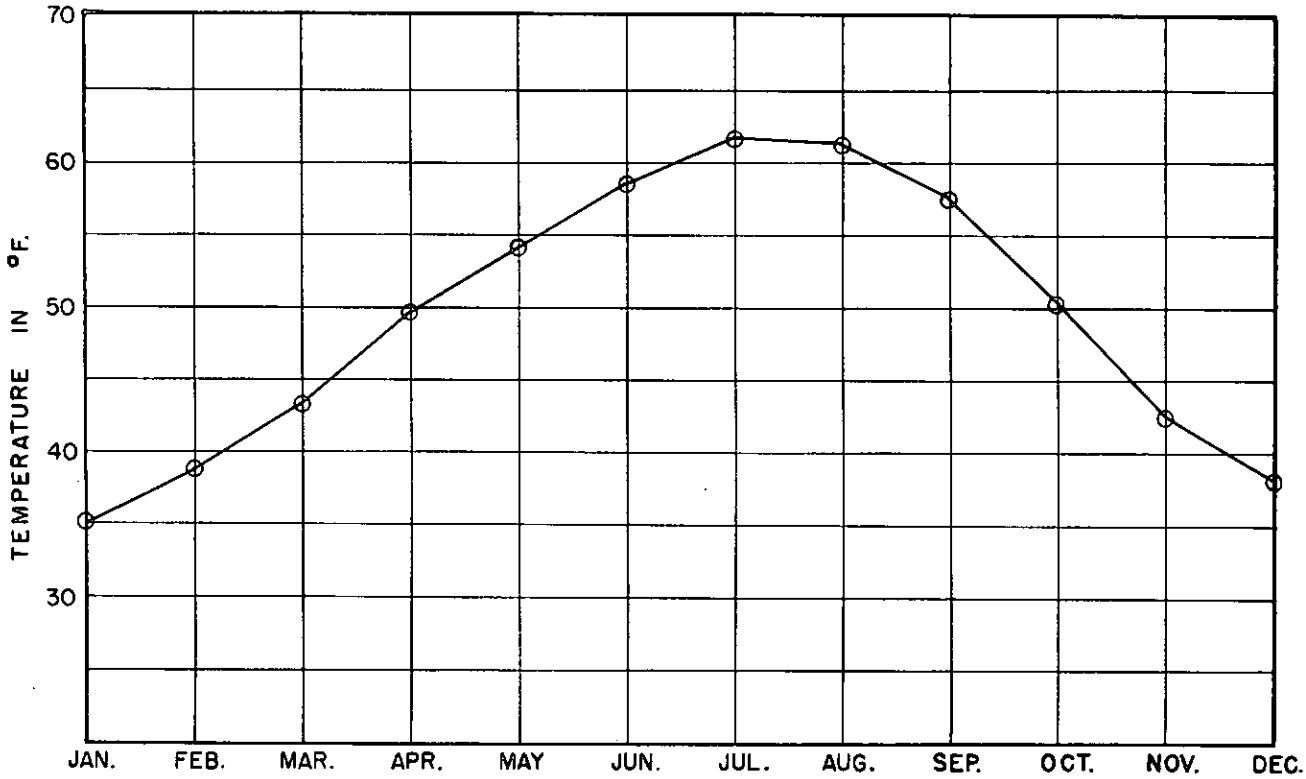

Figure 9. MEAN MONTHLY TEMPERATURE AT CLEARBROOK STATION.

conditions. A decrease in precipitation also affords a maximum of clear skies, which causes the evaporation potential to rise sharply. Quite suddenly in the midst of an environment of plenty a moisture deficient situation occurs. The moisture stored in the soil has been depleted to ineffectiveness and plant growth without supplemental irrigation is left to wither and die. Since this feature of the climate is a persistent annual occurrence, the practice of irrigation in this region of relatively high annual precipitation has proven to be practical.

TEMPERATURE

The graph of the mean monthly temperature recorded at Clearbrook shown in figure 9 is typical of temperature throughout the Nooksack basin lowlands. Maximum mean temperatures occur in July with slightly lower temperatures during August. Minimum temperatures occur in January. The mean annual temperature of the coldest month recorded at any station in the lower basin is above freezing.

The distribution of temperature throughout the year reflects the moderating influence of the ocean on the climate. Winters are particularly mild and summers are relatively cool for this latitude. Mean ocean temperatures at the mouth of the Strait of Juan de Fuca range from a warm 45°F in January to a cool 53° F in July!

The mean maximum temperature at Clearbrook is 75.8° F in both July and August and the absolute maximum for this station is 102° F which occurred in July. The mean minimum temperature is 29.5° F and occurs in January. The absolute minimum recorded was -4° F and occurred also in January. This decidedly low range in extremes of only 106° F is indicative of a maritime type climate. The average frost-free season at Clearbrook is the 148 days between May 5th and September 30th.

Cold weather at Clearbrook usually results from a spillover of an air mass originating over the extremely cold land surfaces in the Arctic. The Fraser River Gorge extending through the Cascade Range aids in conducting sporadic outbreaks of this cold Canadian air during the winter. The effect is generally confined to the Nooksack valley and is respectfully referred to as a "Northeaster."

ECONOMICS OF THE REGION

The economy of the Nooksack River area is based primarily on agriculture with intensive farming of relatively small farms. The area has an estimated population of 33,000 for a population density of 34 people per square mile which compares with a state-wide average of 41 people per square mile. When the unpopulated mountainous area is not considered, the density increases to 87 people per square mile, which is very high for an agricultural area. There are six incorporated cities, all located within the western half of the basin and all with populations of less than 3,000.

CITIES AND TOWNS

BLAINE

Blaine is situated in the extreme northwest corner of the basin, which is the most northwesterly portion of the 48 contiguous states. Blaine merits its title "The International City" and is famous for its "Peace Arch" and surrounding International Park dedicated as a monument to the peace which has existed between the United States and Canada.

The present city of Blaine was originally called

Semiahmoo and was a thriving community during the Fraser River gold rush of 1859. Its name later was changed to Concord and shortly after was platted as Blaine in 1884. Although the gold rush was a passing thing, Blaine continued to grow due to its location on Drayton Harbor. Abundant fishing, an excellent harbor, and fertile tidelands helped to attract settlers, and for many years Blaine was the largest city within the study area. Following incorporation on May 20, 1890, Blaine had grown to 2,289 persons by 1910. Blaine continued to thrive as long as fishing and logging prospered, but with the decline of these industries in the thirties Blaine also declined reaching a low in population of 1,524 in 1940. More recently, Blaine has participated in tourist trade and again is growing with a population of 1,800 in 1959. Blaine is the second largest city in the basin with three fish canneries and fish receiving stations being its major commercial industries. Blaine's harbor has been improved in recent years, and its present facilities are adequate to have 101 commercial boats and 160 pleasure and gill-net craft.

The ever increasing tourist trade and present trend of people moving to waterfront areas are contributing factors in Blaine's continued growth. Blaine serves as a trading center for many farmers in the region in addition to the numerous resorts. Point Roberts is closely associated with Blaine since the latter is the nearest major American trading center.

EVERSON

Everson is a small trading community located on the Nooksack River in the heart of the basin's richest agricultural land. Everson originated when the old Bellingham Bay and British Columbia Railroad established a depot there in 1891. Everson was incorporated on May 4, 1929, and has enjoyed a consistent growth to its present population of 420.

One large fruit and vegetable cannery contributes considerably to the economy in the area by providing both employment and a cash market for agricultural crops. Formerly a milk processing plant was located in Everson, but with the advent of bulk milk tanks on farms this has been closed. This building is now used by the Whatcom County Highway Department as a maintenance shop.

FERNDALE

Ferndale is located on the Nooksack River five miles above its mouth. Prior to 1877 a large log jam blocked the river at the present site of Ferndale, and at that time this area was officially called Jam. Ferndale, like Everson, has enjoyed a consistent but not spectacular growth since its incorporation in March 19, 1907, and presently has a population of 1,405.

Fruit orchards were established in the area at an early date, and at one time, Ferndale boasted a cannery in addition to three sawmills and one shingle mill. At the turn of the century, Ferndale was largely a lumber center; but as the forests were depleted, agriculture became prominent. Present industries include a large berry and vegetable frozen food processing plant that employs several hundred during the peak season, while just west of town is located the area's first refinery, which contributes a great deal to Ferndale's present growth.

LYNDEN

Lynden was incorporated on March 16, 1891, and is situated four miles from the Canadian border on the Lynden Terrace and Fishtrap Creek overlooking the Nooksack River. There were several shingle and sawmills in Lynden as long as timber was available in the area, but agriculture has always been the mainstay of the Lynden economy. At one time, bulb-growing was a major agricultural item, and the largest azalea business in the state is still located there. However, the dairy and poultry industries presently comprise the bulk of the area's agriculture. Located in the heart of the state's largest dairying region, Lynden has enjoyed a steady, consistent growth and now is the largest city in the study area with a population of 2,501. It is the major trading and service center for the county's farmers with the major farming implement and supply companies located there.

The dairy industry is centered at Lynden, with a large processing plant situated there. Lynden has progressed along with the major dairying changeover to bulk milk tanks on farms, and a Lynden firm manufactures automatic milk tank cleaners. Other industries include three seasonal frozen food processing plants which process strawberries, raspberries, blueberries, peas, corn, cauliflower, and other vegetables and fruits. Lynden's two parks are popular with tourists,and Canadians especially avail themselves of the excellent grounds and facilities for picnicking and general outdoor recreation.

NOOKSACK

Nooksack is a small residential community located east of Everson between the Nooksack and Sumas Rivers. The town was incorporated on December 6, 1912 and has always been associated with the lumber industry with one sawmill still located there. The decline of the lumber industry in this area, however, has had a negative effect on Nooksack, which has a present population of but 322.

SUMAS

The city of Sumas is located on the border just west of the Sumas River. Sumas was incorporated on June 18, 1891 and with many nearby mills and logging camps soon boomed to a population of over 2,000. Despite its excellent border location, Sumas declined in size to 647 in 1930 with the recession of the lumbering industry in the region. More recently, however, Sumas has depended on an agricultural economy, and its population has remained fairly constant, presently being 628.

Feed and grain processing is the main industry in Sumas as nearby dairy farms provide a ready market. It is also a major port of entry to Canada and is often described as the Gateway to the Caribou. Much tourist traffic does pass through Sumas, and the tourist trade will no doubt increase and contribute more to the future growth of Sumas.

AGRICULTURE

As the timber in the lower valleys was logged, it became apparent that the soil was rich and excellent for agricultural purposes. Gradually agriculture replaced lumbering in the lower valley and despite many changes is today the number one industry in this area. Ignoring the Class 10 soils which are not suitable for farming, there are approximately 245,000 acres in the basin. Of this about 160,000 acres or two-thirds of it is Class 2 or better, composing one of the larger good soil areas of western Washington. The bulk of this farming area extends from Ferndale

to Everson and Sumas with Lynden in the center. Because of this strategic location, Lynden has grown to become the trading and processing center for agricultural Whatcom County.

The average farm size is relatively small, being but 58.7 acres in 1959 as compared with a state-wide farm of 363.9 acres. This average includes part-time and residential farms, so the size of an average commercial farm is somewhat larger. The location, climate, and soil lend themselves well to the intensive-type farming necessary for a successful operation on the small farms found here.

Previous cash products such as sugar beets and flower bulbs have been largely discontinued. The county's present crops are tabulated in table 1 and show that peas, potatoes, and strawberries predominate. Although these figures are for the entire county, they accurately reflect the study area where most of the agricultural land is found. Whatcom County leads the state in strawberry production and also leads both the State and nation in the production of White Rose Certified Seed Potatoes.

Dairying and poultry-raising, which involve considerable labor and are suited to smaller farms, are the basis of the area's agriculture. After leading the state for many years in poultry products, Whatcom County has dropped to second place although still producing 17.3 percent of the state's entire egg production and 7.6 percent of the state's chickens, including broilers. Whatcom County is, however, the state's number one producer of dairy products, and the dairying industry is continuing to expand with hay and pasture being the major crops in the county. In the ten years from 1949 to 1959, Whatcom County increased its percentage of the state's dairy production from 14 to 16.1 percent. In contrast to previous years when most of the milk was used for processing into butter, cheese, and condensed milk--increasing quantities of milk are being hauled in bulk tanks for the fresh milk market. Fresh milk from the basin enters the Puget Sound-Washington marketing area and now appears in Seattle homes and markets. The growth of the fresh milk market together with the continued demand for ice-cream, cheese, and other dairy products assures the prosperity and future growth of this rich dairy industry.

Due to the intensive type of farming practiced there, the region has become one of the leaders in developing new and improved methods of farming. The area's farms are above the state average in utilizing labor-saving devices. Agriculture is well mechanized and farming not only is more productive but is becoming an easier and more comfortable way of life.

AGRICULTURAL PRODUCTS PROCESSING

The processing of agricultural products is another major industry particularly during the summer months. Numerous fruits and vegetables are processed in season at the plants in Everson, Ferndale, and Lynden. A large milk processing plant in Lynden provides stable year-round employment as do the several mills which grind and distribute cattle feed throughout the basin.

MANUFACTURING

Manufacturing contributes only a small portion to the economy of the basin. General Petroleum's refinery west of Ferndale is the major industry. Its crude oil is imported both by trans-Canada oil pipeline and by ship. This refinery is located west of Ferndale and has contributed a great deal to that town's economy. Other industries include a Lynden firm that manufactures bulk milk tank cleaners, but for the most part manufacturing is small and of local importance only.

NATURAL RESOURCES

LUMBERING

At one time the economy of the entire Nooksack River area was closely tied to lumbering and shingle industries. As the valleys were logged and cleared for agriculture, lumbering lost its dominant economic hold on the region although it still

Table 1. PRODUCTION OF CASH CROPS IN WHATCOM COUNTY

Crop	1957 Acreage	1957 Yield (tons)	1958 Acreage	1958 Yield (tons)	1958 State Rank	% State Total	1959 Estimated Acreage	1959 Estimated Yield (tons)
Beans	450	2,700	290	2,190	2	19.0	270	1,350
Carrots	90	1,220	90	1,280	6	6.7	135	3,550
Peas (processing)	2,600	5,090	2,400	4,980	6	5.6	3,000	5,440
Potatoes (commercial and seed)	2,350	23,500	2,570	21,170	7	4.0	2,250	29,000
Broccoli	40	120	20	70	6	1.8	110	440
Cauliflower	90	630	100	920	5	10.5	0	0
Cucumbers	90	360	90	540	8	4.7	0	0
Strawberries	1,400	3,920	1,350	3,965	1	20.3	1,000	3,500
Red Raspberries	300	790	300	720	4	9.4	300	900
Blackberries	60	120	40	120	4	3.5	15	60
Blueberries	50	75	50	80	5	5.7	55	130

is very important. Logging is especially important in the Eastern Upland where the mountainous terrain supports much virgin timber and important stands of second growth. The Mt. Baker National Forest occupies a large portion of this area and continuing reforestation and fire prevention programs are insuring a supply of timber for the future. In the lower basin, marginal farms are being planted with conifer primarily for Christmas tree purposes.

FISHING

When Whatcom County was first settled, the fisheries resources seemed unlimited. Thousands of cases of fish were canned every year and shipped to other regions. However, when fish traps were outlawed, the fishing industry suffered a setback and now much of the fish processed in the area is shipped in from Canadian and Alaskan waters. Purse seiners, gill-net, and reef-net fishermen still fish near Lummi Island and Point Roberts, but on the whole the commercial fishing influence on the area is declining.

Boundary Bay, near Point Roberts, is the best producer of Dungeness crabs in the inland waters of the state.

The best port of the basin and one of the best small boat harbors in the state is located at Blaine. Although no sharp increase in commercial boats is likely, pleasure craft are increasing and using the improved facilities more each year.

MINERAL RESOURCES

The Nooksack River basin has a variety of mineral resources. Coal, refractory clay, sand, gravel, and peat are all found in the Whatcom Basin, while limestone, quartz, gold, copper, chromite, olivine, and Shuksan building stone are found in the Eastern Upland. However, present economic conditions have not been conducive for the development of these resources, although potentially they could be of major importance. The chromite deposit, though apparently small, should be further investigated as it is the largest deposit in the state. An olivine deposit in the Twin Sisters Mountain is one of the largest in the United States and could be more completely developed. Extensive drilling for oil and gas has been conducted, and although there has been no commercial production, a minor gas field located west of Custer has produced small quantities for local home use.

RECREATION

The tourist trade appears to hold an important key to the future of the Nooksack River basin. This scenically situated area contains seaside resorts catering to fishing and boating enthusiasts, excellent fresh-water streams and lakes, and rugged mountains, in which is located at Heather Meadows one of America's most beautiful year-round skiing centers. Its strategic location makes it readily accessible to Canadians seeking a vacation or summer and winter sports. Also, increased numbers of residents from the populous lower Puget Sound areas of Seattle and Tacoma are taking advantage of the recreation facilities of the area.

GEOLOGY AND GROUND-WATER RESOURCES

GEOLOGY OF THE REGION

GEOLOGIC HISTORY

The oldest rocks known to exist in the Nooksack River basin occur in the mountainous portions of the Eastern Upland. Here, rocks dating back as far as Devonian age have been identified by fossil evidence. Although this report does not attempt detailed differentiation of rocks of pre-Tertiary age, a brief resume' of the earlier geologic history of this region is outlined for general interest. See "Geologic Map of the Nooksack River Basin" (pl. 1).

PALEOZOIC-MESOZOIC ERAS

The wide variety of rock types and degrees of metamorphism give clear evidence of a complex structural history. During middle through late Paleozoic time, the area covered by this report was under water--a western marginal portion of a vast arcuate seaway know as the Cordilleran Geosyncline which extended generally through the Pacific states from Mexico to Canada. Into this slowly subsiding structural trough was deposited a thick sequence of lime-marl, clay, and andesitic lava flows. Subsequent folding, uplift, and intense deformation of the earth's crust during early and middle Mesozoic time (Triassic and Jurassic Nevadian orogeny) resulted in low-grade metamorphism of these sediments and volcanics to form the crystalline limestones, phyllites, and greenstones now found throughout the mountainous portions of the Nooksack River basin. From late Jurassic through late Cretaceous time, portions of the area were again depressed and invaded by seas to allow deposition of the marine sediments known as the Nooksack formation.

TERTIARY PERIOD

From late Cretaceous to early Tertiary (Eocene) time, large scale thrust faulting resulted in the older Paleozoic rocks being forced over younger rocks, and some granite was intruded locally in the upper watershed area (Nooksack cirque on Mt. Shuksan at the head of the North Fork Nooksack River). The intrusion of a large dunite body also occurred during Eocene time to form the rocks of the Twins Sisters Mountain. Along with deformation in the mountains, a widespread and thick deposition of continental sands, clays, and conglomerates occurred across a coastal plain extending along the western margins of the uplift area. These sediments of late Cretaceous to early Eocene age were then uplifted to form what is now known as the Chuckanut formation composed predominately of sandstones and shales. Today these are found in the foothills of the Cascade Mountains east of the Whatcom Basin, near the surface along the southern margins of the Whatcom Basin from Bellingham to Deming, and in the northern portion of Lummi Island. From late Eocene to Miocene time, the range was subject to further uplift and erosion of the earlier rocks with accompanying extrusion and deposition of the Hannegan volcanics (primarily ash beds) in the Hannegan Pass-Ruth Mountain area of the upper North Fork Nooksack River valley. During Pliocene time, the first north-south uplift affected the earlier northwest-southeast structural trend of the range and the present Cascade Mountain Range and Olympic Mountains were born with accompanying downwarp of the Puget Trough lying between. During the late period of this uplift in late Pliocene to early Pleistocene time, igneous activity occurred along the range to form numerous volcanic cones, with Mt. Baker forming on the eastern boundary of the present Nooksack River watershed. The lowland of the Whatcom Basin became well dissected by streams draining the adjacent mountains, and a very uneven, hilly topography was developed on the Tertiary and older rocks west of the Cascade Range.

QUATERNARY PERIOD

Pleistocene epoch.

Early in the Pleistocene epoch (Ice Age) erosion reduced the newly formed Cascade Range to a stage of mature dissection. River valleys were cut into the mountain flanks and rock waste from the mountains was carried to the Puget Trough where it was deposited, partially filling lowland valleys cut into the Tertiary bedrock. Structural evidence indicates that the Whatcom Basin was formed as the south half of a structural downwarp which extends northward to include the Fraser delta, and that the early Pleistocene deposits filled this basin to depths of at least 560 feet below present sea level, as recorded in well 40/1E-4J1 east of Blaine. See "Geologic Cross Sections of the Lower Nooksack River Basin" (pl. 2).

During middle to late Pleistocene time, climatic changes brought on the growth of vast continental ice sheets which covered most of Canada, Alaska, and the northern fringes of the United States. A mass of ice moved southward into the Puget Trough from the piedmont glacier between Vancouver Island and the Canadian Coast Range and in its earliest stages caused blockage of existing waterways to the extent of forming vast temporary lakes. Into these lakes fine silts and clays were deposited by both the streams issuing from the ice front and from existing streams carrying material from the adjacent mountains. Although the early history of Puget Sound glaciation is vague owing to much of the deposits lying at or below present sea level and having been covered by later glacial deposits, the earliest glaciation is referred to generally as the Admiralty, with the Admiralty clay being the predominate member of these materials. The exact nature of the depositional environment of these clays is not known; some claim that it was pre-glacially deposited into a large fresh-water lake, with some local encroachment of marine waters; others attribute its formation strictly to glacial drift origin. This report does not attempt to present a detailed discussion of the two theories, but will accept the Admiralty clay as of early glacial origin.

The deposition of the Admiralty clay ended abruptly.

The lake into which it was deposited was drained and a stream system developed across the top of the Admiralty. Deep canyons were quickly eroded and reached headward to the hard rocks of the mountain slopes. The Whatcom Basin presented a deeply eroded surface at the beginning of the latest and largest period of glacial advance, known as the Vashon glacial epoch.

During Vashon glaciation, the Puget Trough was occupied by ice as far south as Tenino in southern Thurston County, with probable thicknesses of 3,000 to 5,000 feet, as judged by glacially deposited boulders found at corresponding elevations on adjacent mountain slopes. Thick ice tongues also extended down local Cascade Mountain valleys to join the large Vashon glacier. Numerous temporary lakes were formed where drainages were blocked, and river courses were forced into new channels by the advancing ice mass. The Fraser River in British Columbia was probably forced southward to join the Nooksack River across the Whatcom Basin. In turn, the Nooksack and other streams were diverted southward along the advancing ice margin. As the ice moved southward in the Puget Trough, it pushed up the then existing Nooksack River gorge, at that time located in the present day Custer Trough southeast of Blaine, and it forced the river to seek a new outlet. The river probably flowed temporarily south of the Birch Point Upland, then down the present outlet of the Lummi River, then was gradually forced eastward to where its course through the foothills was completely blocked. Here, in combination with the flow from the north of the diverted Fraser River, a north-south valley was initially cut which permitted the trapped rivers to escape to the Skagit drainage south of Wickersham. As the ice pushed into the foothills and followed these new river channels, the valleys were deepened further and widened by glacial erosion. At the height of its activity the Vashon glacier eventually filled the entire Puget Trough, with one huge lobe pushing westward to the Pacific Ocean through the area now known as the Strait of Juan de Fuca. With a gradual warming of the climate, the ice mass began melting and its front gradually receded northward. The final waning of the "Ice Age," as recently as 14,000 years ago by latest calculations, brought the disappearance of the glacier from the Puget Trough. Sea water invaded the deeply eroded trough and formed the present-day inlets of Puget Sound. Local valley and mountain glaciers receded into the range where today they now occupy only the upper cirques and slopes of the higher peaks.

Recent.

The Vashon glaciated surface of Pleistocene time has been modified but little by erosion during Recent time. As the ice left the Whatcom Basin and adjacent lowland areas, the Nooksack and Fraser Rivers returned to flow again across these lowlands in new courses determined by topography left by the recessional outwash of the ice sheet. In the upper mountain valleys the Nooksack River cut into the recessional materials and carried the re-worked sediments to the lowlands, depositing these gravels, sands, and silts across the broad flood plain. The coarser sands and gravels were deposited just beyond the valley mouths, while the finer, lighter sands and silts were carred downstream to become the growing deltaic deposits. The lower course of the Nooksack River below Ferndale was probably an estuary, and the Lummi Peninsula was then an island. Alluvial deposits have since filled the embayment, producing a near-sea level plain that transformed the island into a peninsula. Owing to a slight topographic rise or natural levee separating the Nooksack River from the base of the west slope of Sumas Mountain, drainage from this slope formed the headwaters of the Sumas River which flowed northward in a flat, meandering course to join the Fraser River in British Columbia. The valley now occupied by Kendall Creek was abandoned by the Fraser River and is today of minor importance to the surface-water flow of the Nooksack River basin, most of the precipitation here disappearing quickly into the gravelly valley fill.

The recession of the Vashon glacier and subsequent adjustment of the drainage to its new environment were succeeded by a short period of adjustment to topography and climate before man entered the scene to find the earth materials, topography, soils, vegetation, and drainage as they are today.

DESCRIPTION OF ROCK UNITS

PRE-TERTIARY METAMORPHIC ROCKS

Briefly, these rocks which predominate in the mountainous upper watershed area include the Paleozoic sediments and volcanic flows which were metamorphosed during mid-Mesozoic time to form shales, argillites, slates, phyllites, schists, greenstones, greenschists, and amphibolites. These dense, compact rocks, being primarily impermeable to either retention or transmission of ground water except through occasional joint and fracture zones, owe their importance to the watershed principally by virtue of their permitting precipitation to be quickly drained off to surface streams for rapid measurement in downstream gaging stations. Although some precipitation is lost through interception by the dense vegetal cover and forest growth, with resultant direct evaporation, or is lost through evapotranspiration, most of the water reaching the soil mantling the bedrock eventually finds its way to the rivers through seepage and springs. It is estimated that approximately 70 percent of the total precipitation falling in the mountains will reach the gaging station at Deming, below the confluence of the North, Middle, and South Forks of the Nooksack River.

The pre-Tertiary metamorphic rocks are also exposed in a few places in the foothills. Sumas Mountain, although covered by varying thicknesses of glacial deposits, shows outcrops of a dark green peridotite at the surface of the west slope. Vedder Mountain east of Sumas is also composed essentially of pre-Tertiary metamorphic rocks, mostly argillites and graywacke sandstones, with minor amounts of greenstone. Other pre-Tertiary rocks in the report area occur in the mountainous southern half of Lummi Island where, according to McLellan 1/, dark colored and usually thin-bedded argillite, graywacke, slate, grit, and conglomerate of the Leech River group of late Paleozoic age occur. The northern tip of the island has a small outcrop of Eagle Cliff ellipsoidal porphyrite which shows a semi-andesitic texture 2/.

TERTIARY ROCKS

So far as is known, the Chuckanut formation of Eocene age forms the bedrock beneath the unconsolidated Pleistocene deposits throughout the Whatcom Basin. This is a thick sequence of sandstones, shales, and conglomerates of continental type, fresh-water deposition. Interbedded in these

1/ McLellan, R. D. 1927, The geology of the San Juan Islands: Univ. of Wash. Publ. in Geology, vol. 2, p. 109.

2/ Ibid., p. 147.

sediments are abundant plant remains and some coal seams that have been mined for many years in the Bellingham area.

These sandstones, shales, and conglomerates are folded into broad, open folds that trend generally northwest-southeast. Prior to burial beneath the Pleistocene deposits of the Whatcom Basin, the folds of the Tertiary had been cut and bevelled by erosion. The exposed knobs and probably the buried surface consist mostly of subdued strike ridges connected by intervening gentler slopes. Records of several drill holes in the Birch Bay district show a relief of as much as 200 feet per mile on the buried surface of the Tertiary bedrock. This surface descends generally northward from the southern and eastern margins of the basin, to where it attains its maximum depth below sea level just north of the international boundary. The Blaine city well (40/1E-4J1) which penetrates to 560 feet below sea level in Pleistocene materials, does not reach Tertiary rocks (pl. 2).

On Lummi Island the Chuckanut formation rocks consist of cross-bedded and poorly consolidated arkosic sandstones and conglomerates which trend northwesterly, occupying the bottom of a distorted syncline in the northern half of the island.[1]

Although of little importance to the water resources of the Nooksack River basin, a few areas of Tertiary igneous rock occur in the mountainous upper watershed area. These include the intrusive, locally serpentinized, dunite mass of Twin Sisters Mountain; the intrusive granitic mass occupying the Nooksack cirque on Mt. Shuksan at the headwaters of the North Fork Nooksack River and the extrusive Hannegan volcanics occurring as well-layered ash beds in the Hannegan Pass-Ruth Mountain area.

QUATERNARY DEPOSITS

Pre-Vashon Pleistocene Deposits.

The oldest known deposits of Pleistocene age can be seen in very few places, and are believed to form the core of the principal low plateaus or upland areas. These materials are exposed in the sea cliffs along the west side of the Mountain View Upland (in the SE¼SW¼ of Sec. 20, Twp. 39 N., Rge. 1 E.) and consist primarily of well-bedded clays having silt or fine sand partings. These clays may include those of the Admiralty drift which have been identified more definitely farther south in the Puget Sound basin. A similar section of these early Pleistocene deposits is exposed in the sea cliff 2½ miles southeast of Marietta (in the SW¼NW¼ of Sec. 23, Twp. 38 N., Rge. 2 E.) where interbedded clays and fine sands are found. Aside from the above described exposures, pre-Vashon deposits are known only from subsurface exploration, mostly by drilling for ground water, and by oil and gas test wells.

Vashon Advance Outwash.

There is an irregular thickness of cross-bedded sands and gravels beneath the till which caps the upland areas in the Whatcom Basin, particularly noticeable in the sea cliffs on the west and on the east slopes of the Mountain View Upland, on the Boundary Upland, and on the north slopes of the King Mountain Upland. These current-laid deposits belong to the advance outwash of the Vashon glacier and were laid down by the numerous streams issuing from the advancing ice front. Elsewhere in the basin, the outwash layer seems to consist of finer materials (sands, silts, and clays) deposited in ponded water.

Vashon Till.

As a massively compact mixture of clay, silt, sand, and pebbly gravel with occasional cobbles and boulders, the Vashon till was laid down as a ground moraine beneath the advancing ice sheet. It is bluish gray in color except near the surface or along joints where it is stained a yellow-red color. The till ranges from a few feet to 50 feet or more in thickness. It extends from the edge of the recessional outwash materials and alluvial deposits of the river valleys over the uplands and up the mountain slopes that bound the Whatcom Basin. The till is a hard, distinctive stratum commonly known locally as "hardpan." The till averages about 20 feet in thickness which is not as great as in Snohomish County, 75 miles to the south, where a thickness of 50 feet is about average.

Vashon Recessional Outwash.

These deposits of the Vashon Glacier consist of sand and gravel and some finer materials, laid down primarily as fluviatile deposits by streams flowing from the melting and retreating ice front. The Lynden Terrace, Custer Trough, and the broad area that extends northward from the King Mountain Upland to the flood plain of the Nooksack River contain the most extensive deposits of the recessional outwash found in the report area. The extensive terrace lands formed by these recessional outwash deposits are now some of the finest agricultural lands in the county. Within the mountainous portion of the Nooksack River basin, the present-day streams have cut into and reworked these deposits, carrying the materials to lower valley bottoms for deposition as alluvium.

Recent Alluvium.

After the recessional materials had been laid down and the rivers again were permitted to flow across this broad lowland area, the Nooksack River excavated its floor to the newer and lower sea level of today. It reworked much of the recessional outwash material, mixing it with river silt and forming a flood plain deposit that mantles the lower level cut in the recessional outwash deposits. These Recent deposits of silt, sand, and gravel along the river channel and stream beds, and mud and peat deposits in swampy depressions are being referred to as Recent alluvium.

SOILS

The following general outline of the soils of the Nooksack River basin is adapted almost completely from the Soil Conservation Service report by E. N. Poulson and R. D. Flannery, "Soil Survey of Whatcom County, Washington" Series 1941, No. 7. For a more detailed description of local soil types and conditions, the reader is referred to the more comprehensive report.

Owing to the characteristics of heterogeneous underlying glacial and stream deposits throughout the Whatcom Basin, and to extreme variations in both surface and internal

[1] Ibid., p. 136.

drainage, perhaps nowhere else in the Puget Sound basin is there such a great diversity of soil types.

However, owing to the occurrence of aggregates or granules hard and durable in water, most of the soils are friable, easy to dig unless very stony, and vegetation grows rapidly on all of them. Because of the combination of water-stable granules and rapid plant growth, erosion is not a serious factor in soil management, and steep road banks are not marred by deep rills and erosion gullies common in finer soils of poor permeability. Though leached by frequent rainfall, the soils here retain considerable inherent mineral fertility. All have acid surface soil and most have a less acid lower subsoil or substratum, which indicates a more healthful condition than if the acidity increased with depth. The soils respond well to fertilization and to good farming practices.

About 60 percent of the Whatcom Basin consists of uplands and terraces from which all the virgin timber has been removed, and large areas of this land are farmed. Highly fertile soils of the alluvial bottoms cover most of the remaining area. A considerable acreage, however, is covered by organic soils, which occur in basins and depressions in all parts of the Whatcom Basin. Practically all stream bottom and organic soils are cultivated.

Excluding differences in the lay of the land, the soils of both the uplands and terraces fall naturally into three classes of drainage, namely, well or moderately well drained (including some with excessive drainage), imperfectly drained, and poorly drained. Each of these groups is readily distinguished by surface color, which has resulted largely from the degree of leaching, oxidation, and incorporation of organic residues.

The well or moderately-well drained soils are yellowish brown when wet. They are strongly acid, and most of them have a friable, mellow, water-stable granular silty surface soil, though sandy and gravelly textures are not uncommon. The soils are fairly low in nitrogen but not necessarily so in other plant nutrients. Application of lime alone does not benefit them significantly, but plants respond well to additions of phosphate or phosphate and lime. The subsoils and substrata vary from dense tight clay to open droughty gravelly material. Soils developed from clay till have a strongly rolling or knobby morainic relief and are generally free from surface stone and gravel, though a few gravelly areas do occur in some. Even on the steepest slopes the dense native vegetation and the water-stable granular surface soil promote rapid infiltration. Runoff is therefore small and erosion insignificant. On incorrectly cultivated steep hillsides, however, the silty surface soil becomes thin and the clay subsoil, when exposed, is more readily susceptible to accelerated erosion.

The imperfectly-drained soils occupy smooth areas in association with those better drained. Slower surface drainage and retarded internal water movement have promoted a more luxuriant vegetation, and larger quantities of organic residues have become incorporated in the surface soil. The organic material, together with retarded oxidation, has created darker soils. The surface soil is weak brown when dry and dusty brown when wet, and the subsoil is pale brown and usually mottled with iron stain. Iron concentration occurs in some soils as accretions and cementations, and ironpans are common. Being less leached the imperfectly-drained soils are generally less acid, have a higher mineral fertility, and retain more moisture than those better drained. This moisture relation is especially important because of the dry summers. These soils generally respond well to the same treatment as that given better-drained soils.

The soils of stream bottom lands are largely fine textured, deep, dark, and of high fertility. The highly organic ones are dark brown or nearly black, whereas those with lesser quantities of organic matter are brownish gray to light brownish gray or somewhat grayish olive. Stream bottom land soils are inherently fertile and have a plentiful supply of moisture. Moisture is commonly excessive where natural or artificial drainage is ineffective or incomplete.

The poorly-drained soils of the uplands and terraces occupy nearly level basins and depressions and, not uncommonly, seepy areas on smooth steep slopes. Soils having this drainage support a luxuriant vegetation, including many deciduous trees, underbrush, and a ground-cover of water-tolerant herbs and grasses. The conditions of drainage and vegetation have created a brownish-gray rather highly organic surface soil and a pale-brown discolored subsoil highly stained with rusty iron. In some soils iron cementations occur as fragments and plates, and dense ironpans are common. These soils have a higher inherent fertility than the associated better drained ones, but they are wet and cold in spring; even where drains are installed they may be suited to only a limited number of crops. The drains now used are largely open ditches. If tile were employed, a greater diversity of crops probably could be grown.

The organic soils are widely scattered in old lake basins, in depressions, on steep slopes, and in low bottom lands of streams. Large areas, often many square miles in extent, occupy old abandoned stream channels and areas adjacent to subsiding lakes. Peats and mucks of varied origin and composition are included. Organic soils form an important agricultural acreage and are highly productive when fertilized and properly drained. Moss peat growing on undrained uncultivated areas has a limited agricultural value, but is dug and sold for commercial use.

The first settlers recognized the value of bottom and upland depression soils, including the organic ones. Their fertility and supply of moisture were appreciated and, as indicated by the density of farm population, these soils are still the most extensively used. Lands of the stream bottoms were from the first readily accessible by water but those of upland depressions and other less favorable locations were difficult to reach and largely unavailable until the lands were logged. These natural factors, together with greater ease of clearing, made expansion on the bottoms more rapid than elsewhere and now little bottom land is uncleared. Railroads and the main arterial highways usually follow the easy grade of the stream valleys or terrace flats these soils occupy, and though power and telephone lines often have more direct courses, they naturally are directed to the more populated areas.

In the early period of settlement most of the stream bottom land was cleared and farmed to meet the growing demand for agricultural products brought about by the rapid expansion of lumbering and other industries. There was not enough stream bottom land to keep pace with industrial development, however, and soils of the upland depressions and wet terrace flats, including the organic soils, came into use after they were logged. Expansion to these soils was later followed by movement to less desirable ones of the uplands and terraces, especially where additional acreage was needed to increase farm units to desirable size.

Many of the soils of the uplands and terraces having naturally imperfect or poor drainage have become highly productive. Those that retain moisture well and do not waterlog at any time are now important fruit-producing soils

because of their freedom from frosts.

The more droughty gravelly soil types have been largely abandoned because they do not retain enough moisture to mature crops satisfactorily. The early settlers frequently sought home sites around industrial or logging centers regardless of the kind of soil. Most logging operations have now moved to the more mountainous interior, but many people still remain on their farm holdings or retain them as a place for part-time employment. In many of the less desirable of these areas occupants change frequently, as the clearings are small and a patch type of part-time farming is practiced.

GROUND WATER

WELL-NUMBERING SYSTEM

In this report, the U. S. Geological Survey's well-numbering system is used, whereby wells and springs are designated by symbols that indicate their respective locations according to the official rectangular public land survey. For example, in the symbol 40/2-27J1, the part preceding the hyphen indicates successively the township and range (Twp. 40 N., Rge. 2 E.) north and east of the Willamette base line and meridian. Because the report area lies almost entirely within the northeast quadrant of the Willamette base line and meridian, the letters indicating the directions, north and east, are omitted, but the letter "W" is included when the range lies west of the Willamette meridian. The first number following the hyphen indicates the section (Sec. 27) and the letter (J) gives the 40-acre subdivision of the section, as shown in figure 10.

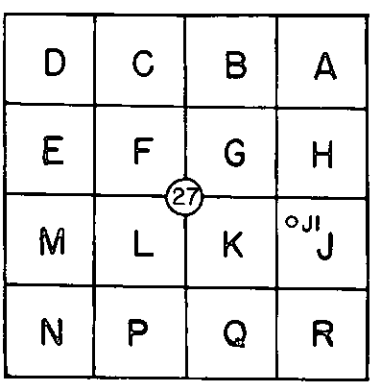

Figure 10.

The last number is the serial number of the well in the particular 40-acre tract. Thus well 40/2-27J1 is the first well listed in the NE¼SE¼ of Sec. 27, Twp. 40 N., Rge. 3 E.

GENERAL CONDITIONS OF GROUND-WATER OCCURRENCE

PERCHED GROUND WATER

The shallow soil-zone wells located on the till-covered uplands of the Whatcom Basin tap water that is held up or "perched" above the regional water table. Impervious clay layers near the surface of some terraces, such as the low outwash terrace just east of the Nooksack River opposite Ferndale, may cause a similar perching effect. Beneath the uplands, clay layers within the otherwise pervious sand and gravel beds may also perch small bodies of ground water at a position above the regional water table.

UNCONFINED GROUND WATER

In areas of the Nooksack River basin where only permeable materials exist, such as in the recessional outwash and Recent alluvial deposits of the lowlands, there is but one water table and all wells drilled in these unconsolidated materials will obtain unconfined ground water when the water table is penetrated. The majority of wells in the report area obtain water under unconfined ground-water conditions.

CONFINED GROUND WATER

Confined, or "artesian" ground water occurs under pressure and head due to its passage beneath an impermeable stratum which prevents its upward movement to the level of the point of inflow. Water encountered by a well penetrating the overlying confining layer will rise in the well casing to that piezometric surface. Although popular usage of the term "artesian well" usually implies one that flows at the surface, the term commonly accepted by hydrologists refers to ground water beneath a confining stratum that will rise in a well above the level at which it was encountered, whether or not it reaches ground surface. In the Whatcom Basin the principal known areas of flowing artesian wells are the Anderson Creek area north of Squalicum Mountain (well 39/4E-31Q1), the east slope of the Mountain View Upland area near Ferndale (well 30/2E-30K1), and the south slope of the Boundary Upland east of Blaine (well 41/1E-31Q1). The presence of these known areas of flowing wells suggests that other areas probably exist but have not yet been discovered.

OCCURRENCE OF GROUND WATER WITHIN STRATIGRAPHIC UNITS

PRE-TERTIARY METAMORPHIC ROCKS

The metamorphic rocks (principally slates, schists, and greenstones) that comprise the bedrock of the Eastern Upland and the southern half of Lummi Island do not contain pores or openings other than small joint cracks and shear zones common to hard rocks and consequently normally carry ground water only irregularly and in small quantities. No wells are known to obtain water from these rocks in the report area and the dense, tight character of these rocks makes them unlikely sources of substantial quantities of ground water.

TERTIARY ROCKS

The Tertiary sedimentary shales, sandstones, and conglomerates which are exposed in the Cascade foothills carry small quantities of fresh ground water in a few places where the pore space permits and where adequate recharge and drainage have flushed out the saline and other highly mineralized water commonly found in these rocks. The yields are low, normally a few gallons a minute for domestic use only. These sandstone and conglomerate materials are rather poorly sorted, quite well cemented, and irregularly and discontinuously stratified, all of which characteristics help to account for their lack of permeability. In fact, drilling records show that in many cases the meager supplies of water obtained from the Tertiary rocks have come from the "broken shale" members of the formation. During the well canvass only a few wells were found obtaining water from the Tertiary rocks; these are at fairly high altitudes, where downward flushing of the strata

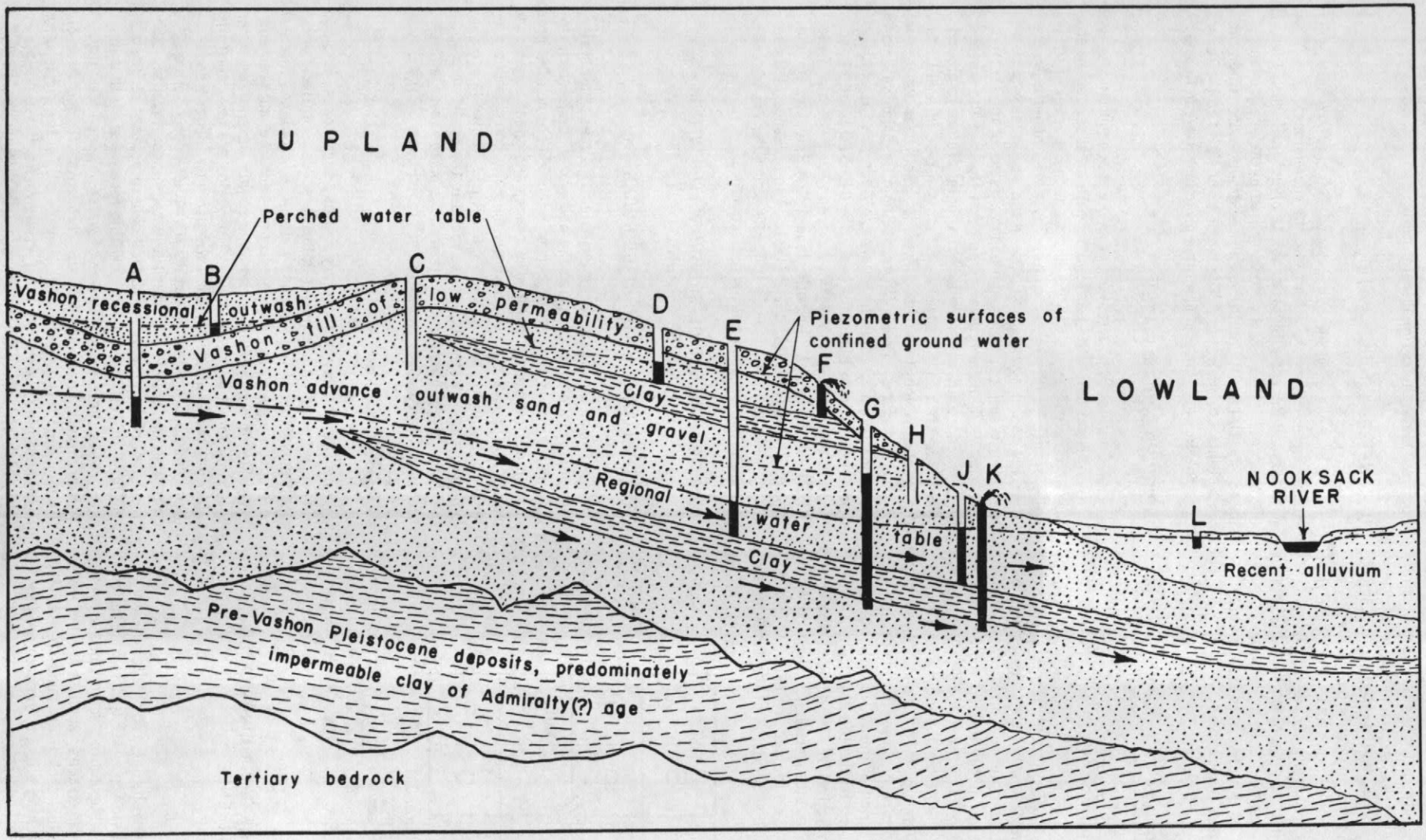

Figure 11. GENERAL CONDITIONS OF GROUND-WATER OCCURRENCE WITHIN THE LOWER NOOKSACK RIVER BASIN. Vertical scale exaggerated. Arrows indicate direction of ground-water movement.

Well A yields unconfined water from below the regional water table; well B yields perched water from a water body perched on glacial till; at well C water was not encountered owing to insufficient depth; well D yields perched water from water body perched on clay zone; well E yields unconfined water from below the regional water table; well F yields confined perched ground water and flows because land surface is lower than the head developed on the water body as a result of the presence of the till cover; well G yields confined water from water body confined by clay zone; at well H water was not encountered owing to insufficient depth; well J yields unconfined water from below the regional water table: well K yields confined ground water and flows because the land surface is below the piezometric surface; and well L yields unconfined ground water from alluvial materials lying below the regional water table adjacent to the river.

by percolating fresh water could be expected to be most vigorous. Of those wells on the lower ground obtaining water from the Tertiary rocks, essentially all produce saline or mineral-charged water. Investigated reports of large flows or large potential yields from these rocks, such as rumors originating in oil test drilling, all proved to be unfounded.

QUATERNARY DEPOSITS

As will be noted in plate 2, the major water-bearing materials found within the Nooksack River basin are the river and glacier-deposited silts, sands, and gravels of Quaternary age. These materials are among those deposited in the following sequence: (1) Pre-Vashon Pleistocene deposits, predominately river-laid silts, sands, and gravels (and including lower clay members of possibly Admiralty age) which preceded the advance of the large ice sheet from the north; (2) Vashon advance outwash, or silts, sands, and gravels laid down by streams issuing from the front of the advancing ice sheet; (3) Vashon till, or the hard, compacted, and relatively impervious layer of unsorted sands, clays, and gravels laid down beneath the advancing ice mass; (4) Vashon recessional outwash, or the water-laid sands, silts, clays, and gravels deposited by streams issuing from the melting and retreating ice front; and (5) Recent alluvium, or the sands, clays, and silts deposited along the flood plain by the present-day streams and rivers of the Nooksack River basin. The foregoing deposits are discussed separately below.

Pre-Vashon Pleistocene Deposits.

Beneath the Mountain View Upland fresh ground water has been obtained from sand and gravel layers in stratified deposits. These deposits probably do not crop out at the surface. Well logs show this material to form the core of the upland, lying beneath the Vashon advance outwash and Vashon till "hardpan" which caps the upland. Separation from the overlying Vashon advance deposits is frequently difficult, since both are composed of similar sedimentary materials. Data obtained for deeper wells from drillers' logs show frequently a sticky blue clay and compact silt layer or "hardpan" lying beneath the Vashon advance deposits which have served to mark the upper members of the pre-Vashon glacial deposits. Some observers have related the blue clay to that of the pre-Vashon, Admiralty drift, material. The pre-Vashon sediments extend downward to the underlying consolidated Tertiary sediments. The water is largely unconfined and occurs in a body whose upper surface has the shape of a broad dome with local high "mounds" (see water table contours on pl. 3). The water-bearing sand and gravel beds of this formation are thin and wells penetrating these materials are of low average yield.

In the Boundary Upland these deeper Quaternary materials are known only from the log of one well (40/1E-4J1) east of Blaine. The large amount of gravel reported for this well may be deceptive since the rotary drilling methods used have frequently given inaccurate records on gravel content elsewhere in the Puget Sound area.

Water encountered in these Pleistocene strata is generally fresh except along the west side of the Mountain View Upland, where considerable saline water has been found. Owing to the capping of impervious Vashon till and upper clay layers, little water can recharge these aquifers beneath the upland by downward percolation from the surface, although some ground-water recharge must so occur, probably through lateral seepage from areas where the till capping is either thin or absent.

The strata beneath the Mountain View Upland has been thoroughly tested and yields found to be low, but those beneath the Boundary and Birch Point Uplands remain largely untested to date.

Vashon Advance Outwash.

Immediately beneath the till capping the Boundary Upland is a thick zone of clean, water-washed, irregularly bedded gravel and coarse sand that crops out around the steep slopes southeast of Blaine. Similar gravel zones are encountered beneath the till in the northeast side of Mountain View Upland, in the area northward from King Mountain to Laurel, and in the small hilly area just west of Sumas. These deposits are advance outwash of the Vashon glacier. Except for a few isolated clay deposits within this material, porous and permeable clean sands and gravels predominate and, below the local water table, they carry large volumes of ground water. Yields of 200 to 400 gallons per minute from 10 to 12-inch cased wells are common in these areas. The evident sources of recharge water for these aquifers is precipitation on the upland above, the water entering the sand and gravel where the till capping is thin or absent. The ground water in these areas has established natural gradients toward points of exit. Larabee Springs (39/2-36D1) and Crystal Springs, half a mile to the north, are natural discharge points for the advance outwash aquifer near the base of the north slope of King Mountain Upland. The city of Sumas springs (41/4-33H1) probably are supplied in part by the gravel aquifer beneath the till. Springs at 40/1-11F1 and 40/2-8N1 and numerous creek sources drain the advance outwash beneath the south slopes of the Boundary Upland, and several small springs probably drain the equivalent zone on the northeast slopes of the Mountain View Upland. The gradient of the water table toward Larabee Spring is but 5 feet or so per mile, and the substantial discharge of the spring is indicative of the high permeability of these advance outwash sands and gravels.

In some places (such as at well 39/1-26B1) this advance outwash gravel lies above the water table; in other places it is penetrated far below the local water table in such a position that the overlying till cap serves as a confining layer and flowing artesian wells are obtained (41/1-31Q1 and 39/2-30K1). These advance outwash gravels and sands are widely used sources of ground-water supply for people living on the lower parts of the upland areas and are among the most satisfactory sources so far developed in the Nooksack River basin.

Vashon Till.

The till or "hardpan" deposited by the Vashon ice mass is largely impermeable and causes much of the precipitation to run off or to be captured as perched water in small local depressions where the till is overlain by permeable surficial sediments. However, occasional sand and gravel streaks within the till provide small supplies of ground water for domestic and stock purposes, and in many upland areas are the most common sources for rural domestic supply. In places these gravel and sand streaks within the till afford a year-round domestic supply, but the great majority of these wells dug into the till run dry in the summer. Sometimes deepening of an inadequate well affords more storage space and occasionally opens up gravel and sand streaks that let in more water, but in some cases well deepening results in perforation of the till capping and loss of water into lower pervious materials.

The Vashon till caps the uplands already mentioned,

also the Lummi Peninsula, the northern half of Lummi Island, and the greater part of Point Roberts. Varying thicknesses of till and associated glacial deposits also fill depressions and mantle slopes of the Cascade foothills; since these are usually well dissected by erosion and drained of ground water by lateral percolation to lower areas and occur in heavily forested or recently logged off uninhabited portions of the watershed, these deposits are of little value as sources of water supply.

Vashon Recessional Outwash.

The greater portion of the Whatcom Basin, from the Cascade foothills westward, and excluding the till-capped upland areas already mentioned, is covered by sands, silts, and gravels deposited by outwash streams of the retreating Vashon glacier. This material forms the Lynden Terrace and Custer Trough, lines the Nooksack River floodplain, and extends far up the three principal tributary valleys of the Nooksack River as primarily valley fill material.

This outwash carries unconfined ground water at rather shallow depth. Much of the area has an insufficient slope for good drainage and in many localities the ground water stands at drainage-ditch level. In the higher area, extending from north of Lynden toward Sumas, the outwash is generally coarser-grained and composed largely of sand and gravel, as compared to the clay, silt, and sand along the Nooksack valley below Ferndale and to similar materials in the Custer Trough and Sumas valley. Much of the ground water of the outwash terraces flows from springs along the river escarpment or is now led off by drainage ditches. In many places water levels in wells show a harmonious rise and fall with the rainfall cycle and with the level of marginal drainage creeks.

Wells obtain large yields when properly constructed in these recessional outwash materials, but many of the present developments are shallow driven, drilled, or dug wells barely penetrating the water table. However, it is from the dug wells in the recessional outwash materials that the major ground-water supplies are obtained for irrigation in the Whatcom Basin.

Some wells tapping recessional outwash materials yield water high in iron content which must be treated to make it satisfactory for household domestic use. Beneath much of the lower part of the outwash-terrace area, deeply drilled wells have encountered saline ground water and some wells flow at land surface. Notable among these is the Kenneth Vander-Griend well (40/3-28M1). Drilled to a depth of 375 feet in 1910, the well originally flowed 50 to 60 gallons per minute before partial plugging reduced the flow to the present 3 gallons per minute. Chemical analysis of this well discloses a chloride content of approximately 4,500 parts per million and a hardness of 1,500 parts per million (tab. 39). It is quite probable that this recessional outwash material was deposited into sea water which then stood 50 to 60 feet above present sea level, resulting in saline water being trapped at depth and not being entirely flushed out by later fresh ground-water movement.

Recent Alluvium.

Along the present flood plain of the Nooksack River and the broad trough occupied by the Sumas River, the recessional outwash materials have been cut to a newer, lower level, over which the present rivers spread during flood periods and have lain down thin deposits of Recent alluvium. These clays, silts, and sands are saturated with water to about river level, the unconfined ground-water level here fluctuating with the rise and fall of the river and with seasonal rainfall cycles. During the winter and spring, the ground water table adjacent to the river drops slightly toward the river and intersects the river level, while during the dry summer months, the water table may occasionally drop slightly away from the river, with river water seeping laterally to charge the adjacent ground-water reservoirs. Ground water from the alluvium is developed for domestic and industrial supplies by shallow driven, drilled, and dug wells. Much of the water contains an excessive amount of iron, and gaseous odors are present in some well water. Zones of iron-rich water seem to occur along the Nooksack River flood plain between Lynden and Deming. The fineness of the material probably accounts for the slow movement and consequent oxidation of the ferrous materials within these sediments.

THE WATER TABLE

The regional water table in the Nooksack River basin is shown in plate 3. The contour lines show the general shape and elevation above sea level of the water table. The elevations were derived from water-level information on wells located throughout the report area. Unfortunately, well development in some upland areas was too sparse to supply data necessary for inclusion of these within the contoured area.

WHATCOM BASIN AREA

As the map shows, the general configuration of the water table approximates the land surface, with the water table higher in the upland areas, particularly noticeable in the Mountain View Upland, where local low "mounds" occur beneath points of surface recharge. In terrace lands, such as those north of Lynden, the water table lies near the surface and slopes toward the streams and drainage ditches or toward springs or lateral escarpments. The lowest level of the regional water table is commonly along the major streams, with the water table beneath the Nooksack River flood plain being in general balance with the river into which the ground water escapes by effluent seepage. The water table slopes toward the stream and downstream in conformity with stream gradient. In the large trough followed northward by the Sumas River the regional water table slopes northward toward the Fraser River in British Columbia. Local depressions of the water table occur adjacent to the Tenmile and Fourmile Creek watershed, indicating that ground water here is effluent to the creeks.

UPPER NOOKSACK RIVER VALLEYS

The water table in the flat-bottomed lower portions of the three major tributary valleys of the Nooksack River, where highly permeable sands, silts, and gravels occur along the river channel, generally follows the river level. The ground water here is effluent to the rivers and the water table rises slightly as it leaves the river and approaches the steeper valley sides. Since most needs for domestic and stock supplies have been satisfied here by shallow dug wells and driven sandpoints and there has been little demand for irrigation from ground water, very little information has yet been obtained on the water-bearing characteristics of the deeper sediments filling these valleys; however, there is no reason to doubt the water-producing capabilities of these deeper, probably well-saturated zones below river level. Only the Kendall Creek valley appears rather limited in ground-water supply, with most of the few scattered wells penetrating 75 to 125 feet of dry

gravels before unconfined ground water is encountered. This valley, owing its origin to a temporary diversion of glacial marginal rivers (Fraser River and/or Nooksack River) and deepened by glacial ice scouring, has today only the annual precipitation and the meager surface flow of Kendall Creek to recharge the ground-water reservoir.

AREAS OF GROUND-WATER RECHARGE

Natural recharge to the ground-water reservoirs in the Nooksack River basin is primarily by direct precipitation and inasmuch as the annual rainfall is moderately heavy (fig. 2), recharge of most aquifers, especially those located within the recessional outwash sands and gravels and Recent alluvium where the permeable zone extends to the ground surface, is in excess of the present rate of withdrawal. In those upland areas capped by Vashon till or extensive impermeable clay layers, ground-water recharge by direct precipitation is less effective and much of the rainfall drains off in surface streams and ditches. The aquifers lying beneath the till must be recharged either by water seeping through occasional permeable sand and gravel beds within the till, or by lateral ground-water movement from areas directly adjoining the till-mantled area. Minor amounts of recharge of aquifers adjacent to major stream channels may occur locally as a result of lateral seepage from the stream itself particularly during the summer months.

The principal areas of ground-water recharge by direct precipitation upon the land surface are those shown in plate 1 as underlain by Vashon recessional outwash and Recent alluvium. These include the broad lowlands of the Whatcom Basin such as the Custer Trough, Sumas Trough, Nooksack Lowland, and Lynden Terrace areas, also the floors of the upper tributary valleys of the Nooksack River.

Areas recharged by small openings in the till capping or by indirect lateral ground-water movement include the Mountain View Upland, the Boundary Upland, the Birch Point Upland, and the King Mountain Upland.

The deeper zones of confined (artesian) ground water are recharged by lateral movement of ground water beneath confining layers from areas of higher elevation. Although no detailed and controlled studies have been made of the direction of movement or rate of flow of these deeper ground waters, some conjecture has been made over the possibility that considerable recharge of the deeper aquifers north of Lynden and beneath the Boundary Upland originates from water percolating through extensive gravel beds lying north of the international boundary.

AREAS OF GROUND-WATER DISCHARGE

Natural discharge of the aquifers in the Nooksack River basin is made by movement either laterally into natural spring zones, lakes, stream and river depressions, or by vertical percolation between aquifers.

As shown by water table contours on plate 3, the regional ground water table is at its lowest elevations along the main channels of the Nooksack River, the Sumas Trough, and the Custer Trough, with minor flextures occuring in the Wiser Lake drainage and the Tenmile Creek-Fourmile Creek drainage. These lows represent the local "base level" for the water table, toward which all ground-water flow is naturally directed by gravity. Where the water table intersects the ground surface, such as in stream headwaters and at spring zones along the lower slopes of the uplands, and along the major stream escarpments, the ground water is discharged and becomes part of the surface-water supply of the basin. Countless springs occur throughout the basin, some representing discharge from unconfined ground water seeping laterally through sands and gravels underlain by impervious strata of till or clay as in spring 39/4-4N1 on the west slopes of Sumas Mountain and the Town of Sumas springs 41/4-33N2 (pl. 2). Others, representing discharge under artesian conditions where an aquifer under a confining stratum intersects the land surface, include Larabee Springs (39/2-36D1) on the north slopes of King Mountain Upland, and springs 40/1-11F1 and 40/2-8N2 on the south slopes of Boundary Upland.

WELL YIELDS

Plate 3 shows generally the distribution of ground-water yields within the report area. The information for determination of well yields was obtained from pump test data supplied by drillers and from pumping information received orally during the well canvass.

AREAS OF HIGH YIELD

The areas of high ground-water yield (200-500 gallons per minute) coincide closely with those areas underlain by Vashon Recessional outwash and Recent alluvium, the broad lowlands and flood plains of the Nooksack Lowland and Sumas Trough. Here the sedimentary materials are highly pervious and are open to recharge by direct precipitation, by lateral seepage from adjacent uplands, and at times from the rivers themselves. These are areas of extensive agricultural development, with available ground water contributing to summer irrigation demands. Recorded water rights (tab. 47) indicate that more land is irrigated from ground water than from surface-water sources in these lowland areas. The greatest withdrawal here is made from shallow dug wells of 36-inch diameter developed in the sands and gravels near the surface, most wells ranging in depth from 10 to 15 feet and with water levels very near the surface. Since yields of 100 to 200 gallons per minute are reported with only 2 to 3 feet of drawdown, it can be assumed that yields in excess of 500 gallons per minute may be obtained from wells designed to permit 5 to 10 feet of available drawdown. Although some areas report high iron content which makes the water unsuitable for domestic use, there appears to be no deficiency in supply for irrigation.

Some areas underlain by Vashon recessional outwash and Recent alluvium supply only moderate quantities (50 to 200 gallons per minute) of ground water. Owing to the fineness of some of the sands, and the inclusion of interbeds of fine silts and clay, some of the lowland areas do not readily yield water in quantity unless the wells are adequately developed and properly screened. As the map shows, areas of moderate yield include the delta lowland of the Nooksack and Lummi Rivers south of Ferndale, the lower portion of the Custer Trough west of Custer, the lower fringes of the bordering upland areas, and the lower portions of the upper three major tributary valleys of the Nooksack River.

AREAS OF LOW YIELD

Areas generally deficient in ground-water supply include the following: (1) Parts of the Mountain View Upland, especially toward the western side; (2) Parts of the Boundary

Upland, notably the higher portion; (3) Birch Point Upland; (4) The King Mountain Upland; (5) Portions of the upper three major tributary valleys of the Nooksack River, including the Kendall Creek valley; (6) Lummi Peninsula; (7) Lummi Island; and (8) Point Roberts.

Mountain View Upland.

On the Mountain View Upland the shallow wells in the till are the chief sources of farmstead domestic supply. These wells frequently go dry in the summer or early fall. Some deeper wells (39/1-29B2) have encountered largely non-water-bearing clayey section beneath the till before entering dry Tertiary bedrock. Tabulation of wells drilled in the western Mountain View Upland shows that ground-water yields are small and water-bearing zones are generally weak, in spite of rumors that large water-bearing zones are encountered at depth in the Standard-Ferndale No. 1 oil test well. The available ground water will sustain domestic needs only, and the conclusion must be drawn that ground water for sustained irrigation or similar uses is not available on the western two-thirds of the upland. Water for irrigation and other uses could possibly be obtained from surface-water sources by developing local lakes and swampy depressions into reservoirs where natural surface water could be stored for irrigation purposes, such storage possibly being supplemented by pumping from the Nooksack River at Ferndale.

Boundary Upland.

The Boundary Upland in its highest portions three miles east of Blaine is an area where ground water may be difficult to obtain, although the situation may be largely due to lack of exploratory drilling beneath the till mantle. Most water in this sparsely populated area comes from shallow wells dug into the till, or from surface runoff reservoirs.

Birch Point Upland.

The Birch Point Upland is also thickly mantled with till. Shallow wells dug into the thin recessional outwash covering the till capture some water for domestic supply but these are unreliable during the summer months. Deeper wells (40/1W-22G1) penetrate 100 to 110 feet of till and hard clay before a thin bed of water-bearing sand is encountered.

King Mountain Upland.

On the north slopes of King Mountain Upland eastward to Squalicum Mountain, the Tertiary bedrock underlies the till, both yielding meager water supplies. Here there is little hope for future development of ground-water supplies, and frequently domestic ground-water supplies must be supplemented by rainfall storage in cisterns during the rainy season, or by development of surface-water sources from springs and small intermittent streams.

Upper Tributary Valleys.

Ground-water supplies in the upper tributary valleys diminishes as the valleys narrow and the bedrock approaches the surface. Coarse gravels and sands adjacent to the major river channels offer the only ground-water supply for local use, with most of the water for domestic and group domestic supplies coming from hillside springs and small reservoirs. The broad valley north of Kendall has a doubtful supply of ground water, generally unconfined but deep beneath the thick gravels filling the valley.

The Lummi Peninsula.

This peninsula was studied in some detail by the U. S. Geological Survey in the spring of 1956 and the following general observations were made at that time.

Vashon recessional outwash sands and gravels mantle the northern end of the upland to depths of 2 to 30 feet, the east and west margins of the peninsula, and scattered areas in the interior of the upland. The greater portion of the upland is underlain near the surface by pebbly clay till to depths of 2 to 75 feet, under which is an undetermined thickness of Vashon advance outwash sands and gravels. The upland is drained by numerous intermittent streams discharging into Lummi Bay on the west and Bellingham Bay on the east. Ground-water supplies are derived either from upper perched aquifers of sands which are thin and discontinuous, and located high on the interior portions of the upland and along the eastern bench extending from Fish Point to Lummi School, or from a lower aquifer beneath the till mantle, from Fish Point south to Portage and near Gooseberry Point and Neptune Beach. Numerous springs also issue along the base of the bench from Fish Point north to Lummi School.

Well yields are generally poor on Lummi Peninsula, averaging 1 to 5 gallons per minute on the upland. The present well withdrawal on the peninsula totals only about 25 acre-feet a year, an average continuous withdrawal of only 15 gallons per minute. Recharge to the upper aquifers is principally by direct precipitation on the land surface, the lower aquifers being supplied by percolation and lateral seepage. The aquifers discharge into springs and swampy areas. Of 22 wells measured on the peninsula, depths ranged from 7 to 22 feet, with water levels averaging less than 5 feet from the surface and with an annual fluctuation averaging 5 to 10 feet.

The most favorable location for development of a ground-water supply on the peninsula is along the beach on the east side (in the sandy bench running from Lummi School south to Fish Point) in 2 to 30 feet of fine- to medium-grained sands having water levels 5 to 20 feet below the land surface. From Fish Point south to Portage a lower aquifer of sand and gravel offers possibilities although wells would have to be extended just below sea level; any deeper penetration may encounter saline water. In the upland portion of the peninsula water must be obtained either from the perched sands or wells must be drilled through the underlying Vashon till to just below sea level.

Lummi Island.

Located off the southern end of Lummi Peninsula, Lummi Island is divided into two geologically different portions. The southern, heavily-forested, mountainous half of the Island is composed entirely of pre-Tertiary rocks, primarily greenstones, which are essentially impervious to water. The only water found here lies in occasional local sand and gravel depressions in the bedrock; otherwise water is limited to surface streams and small ponds.

The northern portion of the island is of a more gently rolling topography, dotted by small farms and with seasonal tourist resorts located along the shore bluffs and beaches. From Village Point to Migley Point on the northwest shore, water is obtained principally from wells drilled to sea level in the glacially-deposited sands and gravels, with occasional perched zones supplying water (5 to 15 gallons per minute) to

shallow dug wells. Since the Tertiary Chuckanut sandstone lies near the surface in the hilly northern quarter of the island, ground water is sparse except where occasional depressions in the underlying sandstone have been filled by recessional outwash sands and gravels. Occasional springs and marshy areas found on the upper slopes of the north half of Lummi Island indicate the presence of water in these materials. Along the east shore from Migley Point to Sunrise Cove water may be found either in these pervious materials lying above the sandstone, or occasionally in minor amounts within fracture zones in the sandstone bedrock. Along the shore at Legoe Bay, and also at Lummi Point, water is obtained from shallow sandpoint wells near sea level. Tidal fluctuations control the water levels in these wells and occasionally saline water is encountered. A synclinal structural feature was observed in the sandstone lying across the northern portion of the island.[1] Exploratory drilling within this basin may encounter some quantities of water in the bedrock, although the overlying sediments must be considered as the principal aquifers on the island. The uneven erosional surface of the Tertiary sandstone is indicated by the great local variations in thickness of these glacial deposits.

Ground water on the island is limited to domestic and stock supply, with the average yield being but 5 to 10 gallons per minute. According to driller Livermore, the highest producing well on the island is that of F. Granger, in the NE¼SE¼ of Sec. 5, Twp. 37 N., Rge. 1 E., which was tested at 17 gallons per minute at the time of drilling.

Habitation is limited primarily to the shoreline around the north half of Lummi Island, with a few small farms and homesteads located inland. Most of the shoreline homes are occupied during the summer months only, the principal economy of the island being based on the summer tourist trade and offshore fisheries recources. Some speculation is being made on development of view property on the mountainous south half of the island, depending upon approval and construction of a proposed bridge linking the island to the mainland. Presumably here the water supply will come from development of surface springs and streams which reportedly flow the year around.

Point Roberts.

Point Roberts, as referred to in this report, is about 2 miles long and 2½ miles wide and includes the entire American portion of the peninsular extension of the Fraser River delta across the international boundary. Primarily of summer resort economy, with a summertime population of 500 to 600 families as compared to a winter population of 75 to 100 families, Point Roberts is reached from Blaine by road through British Columbia.

The highest elevation of Point Roberts is 235 feet above sea level and is located in the east central portion of the upland area. From here the land surface drops rapidly to the east and northeast where a steep, eroded sea bluff of bedded clean sands rises 100 to 200 feet above Boundary Bay. To the west and southwest of the upland the land slopes more gradually, the southwest half mile of Point Roberts being only slightly above sea level. Along the north mile of the west shoreline a bluff rises 100 to 140 feet above the Georgia Strait.

Owing to the problem of limited community water supply, Whatcom County Water District No. 4 initiated groundwater studies here through the services of Howard J. Harstad and Associates, consulting engineers, and Richard J. Rongey, engineering geologist. These preliminary studies, made from a well canvass of the area and electric resistivity tests, presented the following general geologic information.

In the upland areas, Point Roberts is for the most part mantled by 5 to 20 feet of Vashon till and some gravel, under which is an extensive layer of bedded sands and silts. The sand varies from medium to fine and the silt is very fine, approaching clay in appearance. These layers of sands and clays are generally uniform and almost horizontal, with a slight slope generally to the southwest. The ground-water supply is essentially limited to the following aquifers: (1) Perched ground water lying in gravel pockets on top of the till mantle; (2) An aquifer composed of pervious sand layers beneath the till and above a generally impervious hard silt layer at or near sea level; and (3) A shallow aquifer in the dune sands along the west shore of the southwest point.

As a result of these studies, three wells were drilled by the Harold O. Meyer Drilling Company, two of these being located on the highest upland area, within the W½NE¼ of Sec. 2, Twp. 40 N., Rge. 3 W., a third being located near South Beach, in the SW¼SW¼ of Sec. 2. Of these wells, the two on the upland produced 40 gallons per minute and 85 gallons per minute respectively, both obtaining water from the lower aquifer, with the water table being about 80 feet above sea level. The driller's log gives the following information: till: 0-22 feet; sand, gravel, and clay: 22-110 feet; coarse water-bearing sand: 130-136 feet. One of these two wells was drilled to 433 feet, with "hard rock" being reached at 365 feet, and Tertiary sandstone being struck at 388 feet. The well located near South Beach was drilled to a depth of 150 feet and produced about 30 gallons per minute in the initial test. These three wells should provide an adequate supply for the area's present needs, although further drilling or well development may be necessary for full summertime demands.

ESTIMATE OF WATER AVAILABLE FOR FUTURE USE

EXISTING SOURCES

The foregoing discussion of the geologic and hydrologic occurrence of ground water within the report area shows that an abundant supply of ground water exists in most of the lowland areas for all present domestic, agricultural, and industrial needs. Although treatment of iron-bearing waters is necessary for household and industrial uses in a few areas, there appears to be no lack in quantity of water for all purposes and there are no indications that future demands cannot be met for some time to come. As may be seen in figure 12, hydrographs of several observation wells show that over many years natural recharge exceeds annual withdrawals, and no decline has been noticed in the general level of the water table.

In other areas, however, notably in the uplands underlain by till, the water supply for present demands has been insufficient and some hardship has been experienced during the summer months when shallow domestic and stock-supply wells go dry. Drilling for the deeper aquifers is expensive for single household domestic supply, and in many cases local water associations have been formed among neighborhood groups for the purpose of distributing the cost of drilling deep community supply wells. In these upland areas, development of future residential areas will depend largely upon the availability of water, either through the extension of water mains

[1] Ibid., p. 136.

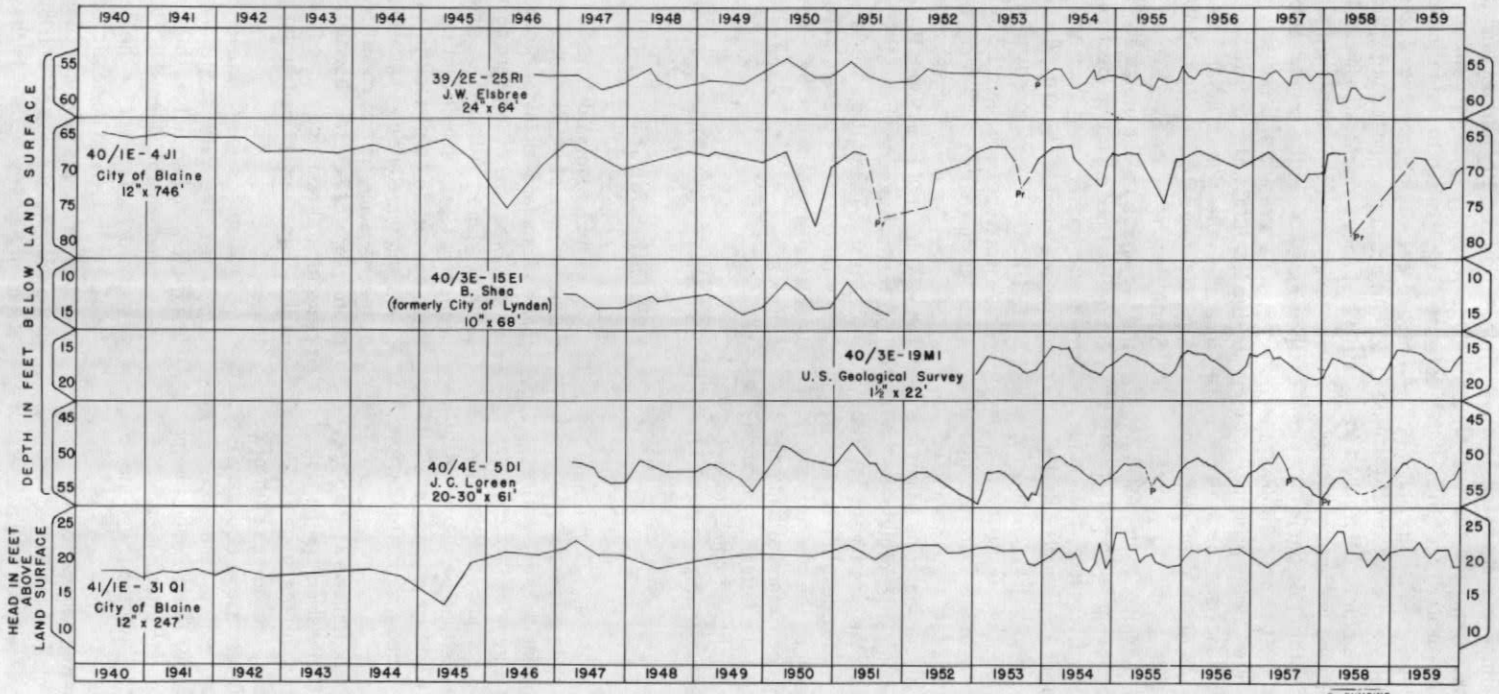

Figure 12. WATER LEVEL FLUCTUATIONS IN OBSERVATION WELLS, LOWER NOOKSACK RIVER BASIN.

from wells now tapping high-producing aquifers, or by deepening and further developing the pumping facilities of wells now barely penetrating the water-bearing materials.

ARTIFICIAL RECHARGE

To date the only artificial recharge within the Nooksack River basin has been through downward percolation of waters incidental to irrigation. However, should future water requirements necessitate artificial recharge of underground reservoirs, it may be worth noting here those areas that may be suitable.

The till-mantled upland areas, because of geologic limitations and topographic expression, do not lend themselves to artificial recharge except on a very local basis where small amounts of water may be added to closed basins supporting perched water bodies. Most of the uplands lack adequate sources of water for recharge purposes.

The ground-water reservoirs most suitable for recharge are those which have a basin-like structure, wherein water may be added without immediately draining off to bordering spring zones and river or lake escarpments. Along the Nooksack River lowland, the sand and gravel aquifers in the Recent alluvium and Vashon recessional outwash may be adaptable to recharge at times when excessive pumping or summer drought conditions cause the water table to fall below the river level. Under these circumstances, it would be conceivable to conduct water spreading operations by ditch or pipeline from the river to adjacent areas underlain by permeable, water-receptive sands and gravels.