REGULATION OF WATER YIELD AND QUALITY IN BRITISH COLUMBIA THROUGH FOREST MANAGEMENT

by

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ABSTRACT

The economy of not only British Columbia but, according to recent water-diversion proposals, much of western North America is dependent on the water resources of British Columbia. Because of its importance, the water resources of the province must be managed properly, requiring information on the amount of the resource, its spatial and temporal distribution, and how these factors may be influenced. Research has shown that forest management influences the yield, regime, and quality of water. A comprehensive review of such research was presented and related to watershed management in British Columbia.

Legislation, administration, and problems of water management were discussed with particular reference to forest management. It was recommended that B.C. Forest Service field staff be increased and that watershed management receive greater emphasis at the Forest Service Training School, Institute of Technology, and the University of British Columbia. The division of jurisdiction between the federal and provincial governments was suggested as the reason for the passive role of the federal government in water resources. Because Canada's present water administration is inadequate for the future, the federal government should assume responsibility for initiating action on water-resource development, and the provinces should be willing to forego some degree of provincial rights in the interest of comprehensive management of the resource.

The water resources of the province were examined and four watershed-management regions were designated (Coastal, Peace River, Interior, and Columbia Mountains) on the basis of climatic factors, water needs,

and flood and erosion potential. Forest-management was related to the objectives of watershed management in each region. One objective of watershed management in the Interior Region is increasing water supplies. Tree Farm License No. 9, in the Okanagan Valley was used to demonstrate forest-management effects on water yield. Yield could be increased five per cent by substituting for the present forest management one based on financial rotations and consideration of water as an important secondary product.

Statistical calibration of Windermere and Sinclair Creeks in the East Kootenays was presented, and the effect of logging on streamflow from Watching Creek near Kamloops was analysed graphically. Water balance and other studies were presented for Terrace Creek watershed on Tree Farm License No. 9. Other watershed research in British Columbia was reviewed and research needs discussed. A comprehensive research program was recommended, to begin with intensely-instrumented research watersheds in the Coastal and Interior Regions.

A rational mathematical rainfall-interception model was developed using forest-stand variables, most of which can be measured on aerial photos, and data from interception studies carried out in British Columbia and the United States.

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CHAPTER I. INTRODUCTION

The report of the first Royal Commission on the forest resources of British Columbia stated that the future of the province depended on water, and recognized the relationship between water yields and forested mountain slopes (Fulton et al. 1910). Recent statements by proponents of water-diversion schemes imply that the economy of not only British Columbia but much of Canada and the United States depends on water from this province. Because of its importance, the water resources of British Columbia must be managed properly, and to properly manage the resource there must be information available as to the amount of the resource, its distribution in space and time, and how these factors may be influenced.

The influence of the forest on such factors of the hydrologic cycle as precipitation and runoff has long been debated, but only in the past 25 years has much research been carried out. Research has shown that forest management has considerable effect on the yield, regime, and quality of water. This research is reviewed in this thesis and related to watershed management in the various regions of British Columbia.

As a resource, water is peculiar in that it flows across political boundaries, and the use to which it is put in one area affects its usefulness in other areas. The British North America act of 1867 set forth the division of governmental powers between the Dominion and provincial governments. Some of the problems of water management in Canada stem from this division. The legislative responsibility of managing the water resource, its implications, and the evolution of water policy in Canada

and British Columbia are discussed herein.

British Columbia's water reaches the province as precipitation and as inflow from other regions. Few of the rivers have their source outside British Columbia, the Columbia, rising in the United States, being the only important river in this category. Inputs in the form of precipitation are compared with the water outputs of evaporation, transpiration, and runoff, to obtain some understanding of the spatial and temporal distribution of the water resource in British Columbia.

Water diversions have been suggested that would transfer water from British Columbia to as far away as Mexico. A widely-held view is that an abundant water supply is very important in attracting industry to this province, so that water transfer has serious implications with regard to development of the province's industrial sector. Some of the more widely-publicized diversion schemes are examined with regard to their economic implications as well as in relation to the evolution of water policy in Canada.

Until 1965, little watershed research had been conducted in British Columbia. In that year the International Hydrologic Decade was instituted, providing impetus for increased study of water resources. In British Columbia, many investigations were begun by federal and provincial agencies and the University of British Columbia. These are discussed in this thesis with particular attention to a research watershed established by the Faculty of Forestry, University of British Columbia, to determine the effects of intensive forest management on water yield and timing in the Okanagan Valley.

Watershed research, especially in the United States, has provided much information on the influence of forest management on water but its transposition to other regions, e.g., British Columbia, is not always valid because of variation in climate, vegetation, and soils. Research must be expanded in British Columbia to provide information on the relation of forest management to water in the different regions of this province. Needs and type of research that may best satisfy these needs are discussed herein.

While there is a lack of knowledge of the influence of forest management on water in British Columbia, use should be made of knowledge that has been gained elsewhere that is applicable to this province. An example of this use is the section in this thesis on erosion control during logging and road building.

Mathematical models are becoming more widely used in forestry to predict the effect of management practices. A case can be made for the use of such models, developed with existing knowledge, to predict the effect of forest management on water yield. The models can be refined as more knowledge becomes available. An example of this is the rainfall interception model, given in this thesis, that has been developed by the author using interception data mainly from the western United States.

CHAPTER II. FORESTS AND THE HYDROLOGICAL CYCLE

To set the stage for discussion of the relation of forest management in British Columbia to the resource, water, it is necessary to consider the influence of the forest on the individual components of the hydrological cycle. The hydrologic cycle denotes the movement of water, either as liquid or vapour, from the atmosphere to the earth and back to the atmosphere, this cycle repeating continually.

This chapter, in reviewing the literature pertaining to the influence of the forest on the hydrologic cycle, indicates those factors of the forest which do have an influence, the degree of this influence, and the scope of the research that has been carried out in this field. Some of the investigations reported here are not necessarily directly applicable to British Columbia in that the species and other conditions, such as climate, are different from those met in this province. However, some knowledge of these investigations is necessary to appreciate the forests' influence on the water resource, to isolate water problems in British Columbia, and to consider ways of alleviating those problems in which the forest plays a part.

1. RAIN

Annual Rainfall

The component of the hydrologic cycle that is most obviously the immediate source of water for use at or near the surface of the earth is precipitation. The effect of forest on precipitation has been debated

for many years by observers who cited various kinds of evidence to support their views. Such views ranged from belief in a decrease in the sum total of precipitation falling on the globe as forest areas have been denuded, to the opposite belief (Belgrand 1854, cited by Marsh 1965). Between the extremes, views were held such as were expressed by Marsh (1965, p. 158): "We may well admit that it (forest removal) has lessened the quantity [of precipitation] which annually falls within particular limits."

The poet Frederick Paludan-Müller (1896, p. 11022), in writing:

> Afric's barren sand,
> Where nought can grow, because it raineth not,
> And where no rain can fall to bless the land,
> Because nought grows there.

expressed the view held by Clavé (1862), Blanqui (1843), Coultas (1860), Herschel (1875), Pavari (1962), and Zon (1927), (Clavé, Coultas, Blanqui cited by Marsh 1965). A similar view is that a wet region furnishes abundant evaporation for the production of more rain (Humphreys 1937 cited by Penman 1963). McKay (1965) stated that showers often follow rainy days because of the evaporation from the wet terrain, yet he did not hold the views expressed by Humphreys.

Warren (1945), using data on precipitation near the Salton Sea in California before and after the forming of the lake, concluded that the body of water (440 square miles in area) had not affected precipitation. Bernard's (1945) data on precipitation and evaporation in the Belgian Congo indicated no forest influence on the amount of precipitation. Penman (1963) agreed with Bernard's conclusion, though not with

his method of arriving at it. Molchanov (1960) also argued against the view that the presence of forests increases precipitation.

The evidence which apparently supports the theory of the forest increasing precipitation is largely circumstantial, according to Penman (1963), who based his opinion on meteorological considerations only. He stated that the addition of moisture to the atmosphere, by evaporation or transpiration, is not a necessary or sufficient condition for an increase in precipitation near the surface from which the moisture has come.

Recently, however, it has been suggested that sublimated tree terpenes may act as condensation nuclei for water vapour in the atmosphere. Hickman (1966) wondered about the possible effect of this on precipitation.

The view was also held that the forest influenced not only the amount of precipitation but other aspects of the weather as well.

Caimi (1857) attributed the increased frequency of hail storms on the fertile plains of Lombardy to the cutting of forests in the Alps and Appennines. Young (1860) reported that after the forests between the Riviera and Montferrat had been cut, greater destruction was wrought by hail in the region of northwestern Italy.

Marsh (1965) wrote that the forest affected local climate, especially temperature. His evidence was the greater depth of frost in soils in the open. Some writers held that the cutting of forests had altered the mean atmospheric temperature of large parts of the globe. Webster (1843) wrote that the weather in the United States was more inconstant after the cutting of large tracts of woodland and that the warm weather

of autumn extended further into winter and cold weather further into summer. Abjornsen (1855) reported the lateness of spring in many districts of Sweden after the forests had been cleared off.

Effect of Wind

Before discussing the influence of the forest on interception, throughfall, and evaporation, its effect on wind should be considered. Much of the influence of the forest on these variables is due to its effect on wind.

Extreme views have been held by some, for example, Dussard (1842) who blamed the destruction of the forests of the Cévennes in south-central France for the mistral, or northwest wind, whose chilling blasts in spring are often fatal to tender vegetation along the Mediterranean coast. However, this section will deal with evidence that is less circumstantial.

As wind moves across a surface, frictional resistance is exerted by the surface, decreasing the wind speed proportional to the roughness of the surface. The wind velocity in the forest is usually only 20 to 40 per cent of that in the open (Kittredge 1948). The wind velocity in the forest gradually increases above the height of the trees, the height at which the open velocity is attained increasing with wind speed. Kittredge, using data from the Shasta Experimental Forest, showed that wind speed is reduced for 15 feet above the forest canopy for a wind speed in the open of 5 m.p.h., and for 70 feet above when wind speed in the open is 15 m.p.h.

Molchanov (1960) described an investigation into the effect of the forest on wind speed in adjacent openings of different widths. Only in openings exceeding 2,200 feet in width did the wind reach 100 per cent of that in open conditions.

Variations in wind speed above, across, and adjacent to a forested area, along with the changing vertical and horizontal wind components cause variations in precipitation at proximate points. Such wind variations also affect interception and evaporation and, therefore, the amount of precipitation reaching any point. Burger (1951), summarizing 20 years of Swiss observation, reported that in large forest clearings the precipitation catch may be more than in nearby open country. Geiger (1965) took measurements of precipitation in seven clearings of different size in a mixed stand of 80-foot pine (Pinus sp.) and beech (Fagus sp.). He reported that four months of summer records showed that least rain (87 per cent of that in the open) fell in the smallest clearings (39 feet in diameter) because of interception by tree crowns; in clearings of 1.47H (where H is tree height) rainfall was five per cent greater than in the open; in clearings of 3.36H rainfall was two per cent greater than in the open. Geiger attributed this to the calmer air, but the downward component of the wind as it passed into the opening may be part of the reason. Hursh (1948) reported a two per cent greater precipitation in a clearing of 3H than in the open.

Evaporation of Falling Rain

Pavari (1962) reported that air temperatures above a pine forest in Italy were constantly cooler (up to 4°C.) than in the open, up to 1,600 feet, and cooler in the morning up to 3,300 feet. If this condition exists during storms, precipitation may be greater on forest areas due to reduced evaporation of the falling rain in the cooler air. If rainfall is greater over a forest it has not been proven to the satisfaction of all observers, as indicated in the section on precipitation. The problems involved in measuring evaporation over forest and non-forest are obvious, and the absence of data on this phenomenon indicates its difficulty of measurement or the view that the differences are insignificant.

Interception

Rain that has been caught and temporarily held by vegetation: (a) returns to the atmosphere by evaporation from the foliage, termed interception loss; (b) is absorbed by the foliage; (c) drips off the foliage to the ground, termed throughfall; and (d) runs down branches and reaches the ground via the stem, termed stemflow.

In many investigations of the hydrologic role of the forest, interception of precipitation has been calculated by the formula:

$$I = Po - Pc$$

where I = interception
Po = precipitation in the open
Pc = precipitation under the canopy

This assumes that Po is equal to the catch that would be received above the canopy. Some investigations cast doubt on this. An Australian report (Anon. 1949) indicated that the average annual rainfall measured above

the canopy was only 77 per cent of that measured nearby in the open. Law (1958) recorded a 13 per cent lower average rainfall catch with tree-top gauges than in the open at ground level. Presumably this difference is due to turbulence created by the tree tops.

Within a stand there are wide variations in the amount of precipitation intercepted by the canopy. Interception by single trees is usually greatest near the bole, decreasing with distance from the bole. In gaps between the trees it varies with the size of the gap. In large gaps interception may be negative, i.e., the precipitation reaching the ground may be greater than in open areas (Burger 1951, Geiger 1965, Hursh 1948).

In a mature stand of Jeffrey pine (Pinus jeffreyi Grev. and Balf.) in southern California, the percentage interception varied from 100 per cent of total precipitation at the base of a tree to 81 per cent under the edge of the crown for rains of 0.01 inches; from 94 per cent to 48 per cent for rains of 0.06 to 0.10 inches; from 74 per cent to 5 per cent for rains of 0.11 to 0.30 inches; and from 53 per cent to 4 per cent for rains of 0.31 to 1.00 inches (Kittredge 1948).

In a dense stand of 40-year old white and red pine (Pinus strobus L. and Pinus resinosa Ait.) in Ontario for the period May to October, interception was 57 per cent at one foot from the bole, 27 per cent under average crowns, and 16 per cent in small openings (Beall 1934). Neiderhof and Wilm (1943) incorporated the distance from any point in an opening to the edge of the nearest crown in mature lodgepole pine (Pinus contorta Dougl.) in the equation:

$$I = 0.234P - 0.102r + 0.423$$

where I = interception in inches
P = precipitation in inches
r = distance from any point in an opening to the edge of the nearest crown, in feet.

A numerical example of the above equation will illustrate its use. When seasonal rainfall, P, is six inches, interception, I, is zero where the distance from the point in the opening to the edge of the crown, r, is 18 feet. When r is zero, i.e., at the edge of the crown, I is 1.82 inches, or 30 per cent of the seasonal rainfall of six inches.

The obvious method of determining average interception, and the standard method in use today, is to average a number of rain gauge catches under the canopy. However, the wide range of interception often requires a large number of gauges to arrive at a reliable average, even for a limited area. Recognizing this, Kittredge (1948) suggested an alternate method. The method he proposed is to gauge interception at different positions with respect to boles, crowns, and openings, and weight these figures by the proportion of the total area occupied by the different parts of the crown and the openings. A sampling scheme using aerial photos might be used to determine the area weighting factors. If adjustment were deemed necessary for speed and direction of wind it could be accomplished by recording interception at the predetermined positions during storms having winds of various speeds and directions. However, by recording interception for a given period, varying wind speeds and directions would probably be sampled in proportion to their average occurrence and give a value sufficiently precise.

Horton (1919) derived equations to estimate the total interception by individual trees and stands. For an individual tree:

$$I = S + KET \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where I = total interception, S = depth of intercepted storage } in inches on the projected area of the crown

K = ratio of evaporating leaf surface to the projected area of the crown

E = evaporation rate in inches per hour

T = duration of storm in hours.

or, expressed as a per cent,

$$I\% = 100 \left[\frac{S + KET}{iT}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where i = intensity of rain in inches per hour.

From equation (2) it is seen that per cent interception decreases as rainfall intensity and duration increase.

For stands, equation (1) becomes:

$$I = S + \left[\frac{KET}{Ps}\right] Ps$$

where Ps = inches of precipitation over the watershed divided by the number of showers for the months when the trees were in leaf.

For any given stand the interception storage, S, and the proportion of the precipitation in any shower evaporated before it reaches the ground, $\frac{KET}{Ps}$, may be considered constant. Without correction for stemflow the relation is a linear function of the precipitation per shower. Horton found that S varied from 0.01 to 0.05 and $\frac{KET}{Ps}$ from 0.01 to 0.23 for a variety of stands and species.

For two stands of ponderosa pine (Pinus ponderosa Laws.) in Colorado, Johnson's (1942) data gave

$$I = 0.04 + 0.06Ps$$

and

$$I = 0.02 + 0.11Ps$$

Rowe (1941) reported a linear trend for the winter months for the partly evergreen brush type of Ceanothus, oak (Quercus sp.) and buckeye (Aesculus sp.), at North Fork, California:

$$I = 0.02 + 0.23Ps$$

Neiderhof and Wilm (1943), working in lodgepole pine in Colorado found evidence that interception decreases with decreasing stand density and volume. Kittredge (1948) graphed the data of Horton (1919) and Mitchell (1930) for elm (Ulmus sp.), basswood (Tilia sp.), maple (Acer sp.), oak, pine, hemlock (Tsuga sp.), beech, ash (Fraxinus sp.), and jackpine (Pinus banksiana Lamb.). Without correction for stemflow, interception ranged from 40 to 100 per cent of precipitation in showers of less than 0.1 inch and 10 to 40 per cent in showers of less than 0.4 inches, with intermediate values for the intervening range.

Eidmann (1959) presented data obtained over a period of five years on 26 European beech (Fagus sylvatica Ehrh.) and 30 Norway spruce (Picea excelsa Link.) stands in the Sauerland Mountains of West Germany. Ages ranged from 20 to 140 years with about one-half of each group in the 60 to 100 year range. Interception per cent decreased as rainfall increased. For rainfall less than 1 mm. (0.04 in.) spruce intercepted 82 per cent,

beech 72 per cent; for rainfall greater than 20 mm. (0.80 in.) spruce intercepted 24 per cent and beech 18 per cent.

It was reported (Anon 1949) that in Monterey pine (Pinus radiata D. Don.) over 40 per cent of light rain was intercepted but only 10 per cent or less of heavy rain. Tanoka (1954) reported similar values for light and heavy rain on seedling trees in Japan (cited by Penman 1963). Hirata (1929) gave data covering a much greater rainfall range in stands of 35-year old sugi (Cryptomeria japonica), height 62 feet, at Meguro, Tokyo. Interception ranged from 63 per cent for rains of less than 3 mm. (0.12 in.) to 5 per cent for rains of 132.8 mm. (5.228 in.).

Variation between species. Kittredge (1948, p. 109) wrote:

> The difference in interception between stands of different species and of different stages in natural succession would be expected to increase as a particular species or type represented a more advanced stage in the succession.

To indicate the successional trend, Kittredge used data for seasonal interception from different localities and pieced them together to arrive at the series: jackpine in Wisconsin, an intolerant pioneer species - interception of 21 per cent (Mitchell 1930); white and red pine in Ontario - 37 per cent (Beall 1934); maple-beech climax in New York - 43 per cent; tolerant climax hemlock in Connecticut - the maximum interception of 48 per cent (Moore 1910).

Pereira (1952) had six years of data for interception by cypress and bamboo plantations at 8,700 feet in the Aberdare Mountains of East Africa, and compared his results with those for hardwoods (oak, hickory

(Carya sp.) and poplar (Populus sp.)) in North Carolina. Interception per cent ranged from cypress (Cupressus sp.), 55; bamboo, 50; North Carolina hardwoods, 58, for rainfalls of 0.25 to 2.5 mm. (0.0098 to 0.098 in.), to 13, 11, and 8 for the three species respectively for rainfalls of greater than 44 mm. (1.7 in.). The mean values were 26, 20, and 23 mm. (1.0, 0.79, and 0.9 in.) respectively.

Luchshev (1940) gave seasonal mean values of interception per cent as: spruce, 28 - 37; pine, 28; and oak, 15 - 22. Stalhfelt (1944) gave a value for interception by spruce in Sweden of 50 per cent (and for the moss and litter on the ground, 9 - 18 per cent). Burger's (1951) measurements on spruce in Switzerland showed 47 per cent interception. Vaughan and Wieke (1947) stated that two-thirds of the rain falling on the canopy in the upland climax forest of Mauritius reached the forest floor. Australian experience with Monterey pine and eucalyptus showed mean interception of 29 and 4 per cent respectively (Millett 1944).

Helvey and Patric (1965) reviewed published and unpublished interception studies carried out in hardwood stands of eastern United States. They found very close agreement among individual studies of mature, mixed hardwoods, and they constructed equations to predict throughfall and stemflow from the data of these studies. The authors speculated that similar unifying patterns might be noted from other regional summaries.

Studies in Alaska in mature coniferous stands indicated that throughfall differed little from that reported in other mature rain forests of western North America (Patric 1966). The author suggested that if the tabulation of those studies that have been carried out in

similar forest types are regarded as random samples from a single forest population, additional throughfall measurements are not needed.

In Patric's (1966) study, throughfall was 72.5 per cent of the 40.8 in. of rainfall that fell from July 13 to December 23, 1965. Throughfall was negligible during storms of 0.05 in. or less, and variations in basal area per acre had no consistent effect on throughfall.

Variation with season. Investigations carried out during different seasons of the year indicate that time of year also influences interception. Eidmann (1959) reported that the per cent interception was greater in the May-October period than in the November-April period for both spruce and beech, the percentages being 31 and 20 for spruce, and 11 and 4 for beech. In Russia, Luchshev and Petrovski (1939) reported that for spruce the maximum interception of summer rainfall was 5 mm. (0.2 in.) and 3 mm. (0.1 in.) for autumn rains. Leyton and Carlisle (1959), from their measurements for Lawson cypress (Chamaecyparis lawsoniana (A. Murr.) Parl.), reported a decreasing interception from the peak in July-August of 17-18 per cent to 3 per cent in November.

In a sugar maple (Acer saccharum Marsh.) -hemlock (Tsuga canadensis (L.) Carr.) forest in northern Wisconsin, Mitchell (1930) recorded interception of 24.6 per cent during the spring when trees were in leaf and 15.8 per cent after the leaves fell in the fall. Old mixed hardwood in western North Carolina intercepted 17 per cent of the precipitation in summer and 6.6 per cent in winter (Kittredge 1948). Old shortleaf pine (Pinus echinata Mill.) in the same locality had interception of 15.7 per cent during winter months and 16.1 during summer.

For most evergreen species a large proportion of the annual leaf fall is concentrated in the autumn and the new foliage develops in the spring. There is less foliage in winter, the difference being reflected in interception. Another reason for the decreased interception loss of conifers in winter might be that because of lower air temperature and higher humidity less water is evaporated. Interception loss, which by definition (p. 9) is precipitation that has been intercepted by and evaporated from foliage, is therefore less and throughfall greater.

An example of this was given by Pearson (1913) for ponderosa pine at 7,250 feet elevation in Arizona. Interception was 40 per cent, a higher value than would be expected from this species in that region where it grows in open stands and has foliage of low density. In other investigations the interception was, for mature stands of ponderosa pine in Idaho, 22 per cent and 27 per cent (Connaughton 1935), and for young stands in Colorado, 18 per cent (Johnson 1942). The reason suggested by Kittredge (1948) for the surprisingly high figure of 40 per cent is the high "evaporative power" of that region.

Variation with stand density and age. Delfs et al. (1958) compared interception and stem-flow in pure spruce stands of different ages in the Oberharz Mountains during 1952-1955. Measurements were made on "normal" crown cover, those on the plantation being shortly after crown closure. The results showed that interception is greatest in sawtimber, averaging 36 per cent, followed by poles, 28 per cent, saplings, 21 per cent, and in the young plantation, 0.6 per cent.

In Maine, interception under spruce and balsam fir (Abies balsamea (L.) Mill.) was 37 per cent, whereas stands containing a component of light-foliaged white birch (Betula papyrifera Marsh.) with the spruce and fir had a value of 26 per cent (Kittredge 1948). A mature stand of Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) in Washington, with a crown density of 65 per cent, intercepted 34 per cent of the rainfall, while a 25-year old stand with dense canopy intercepted 43 per cent (Simson 1931). Kittredge (1948) also reported that the interception per cent decreases as indices of density, such as number of trees and basal area per acre, decrease.

Variations with the age of the stand may be illustrated by the following figures for beech in Switzerland (Zon 1927):

Age in years	20	50	60	90
Mean annual interception in per cent	2	27	23	27

The maximum interception per cent occurred at 50 years which was the age at which current annual increment culminated. Kittredge (1948) suggested that although the trends of interception and increment do not exactly correspond, interception in well-stocked stands is similar to the curve of current growth which in turn is a function of the amount of foliage.

Interception relative to precipitation and crown density was studied in the Utah juniper (Juniperus osteosperma (Torr.) Little) and alligator juniper (J. deppeana Steud.) types on the Beaver Creek watershed in Arizona (Skau 1964). Interception was calculated by deducting stemflow and throughfall from gross precipitation, and canopy density was determined by the use of the canopy camera. Stemflow, which was

only one to two per cent of total precipitation, began after the comparatively large value of 0.20 to 0.30 in. of precipitation had fallen. Throughfall was predicted with reasonable accuracy for either species by the equation Y = 0.044 + 0.865 (gross precipitation in inches) - 0.216 (canopy density index as a decimal fraction of 1.000).

Stemflow. Stemflow has been found to increase with the amount of precipitation per shower and, for some species and stands at least, the relation is linear (Kittredge 1948). Stemflow begins only after a certain amount of rain has fallen, the amount differing for different species.

Stemflow may start at an amount of rain as low as 0.01 in. for smooth-barked trees, or as high as 0.7 in. for rough-barked trees (Kittredge 1948). Wilm and Niederhof (1941) computed regression equations for three species at 9,500 ft. elevation in Colorado. For lodgepole pine,

$$Sfv = 3583Pr - 1090$$

For alpine fir (Abies lasiocarpa (Hook.) Nutt.),

$$Sfv = 1603Pr - 387$$

For Engelmann spruce (Picea engelmannii Parry),

$$Sfv = 1053Pr - 301$$

where Sfv = stemflow in cubic inches
Pr = precipitation per shower in inches

In this investigation it was found that stemflow started only after 0.3 in. of rain had fallen.

In a 25-year old plantation of Canary pine (Pinus canarienses C. Smith) at Berkeley, California, the equation for the stand was

$$Sfd = 0.03Pr - 0.02$$

where Sfd = inches depth on the area of the projected crown

For individual trees in this stand the Y intercept varied from -0.002 to -0.036, and the regression coefficient from 0.005 to 0.11. No relation was found for this variation but a relation was shown with the excess or deficit of height relative to that of surrounding trees. The relatively tall and relatively short trees showed high stemflow, 2.5 to 9 per cent of precipitation compared to one per cent for those of average height.

A nearly linear relation between annual volume of stemflow and basal area of individual trees was found by Wicht (1941) for gray poplar (Populus x canescens (Ait.) Sm.) in South Africa. The author reported that the ratio of stemflow from sample trees to stemflow from all trees on an acre equalled the ratio of basal area of the sample tree to total basal area on the acre.

Hoppe's (1896) data also indicated that for European beech the volume of stemflow increased linearly with the stem basal areas and crown areas of the trees (reported by Kittredge 1948). On the other hand, the stemflow as a per cent of precipitation decreased with increasing crown area, from 19 per cent at less than 108 sq. ft. of crown area to 15.5 per cent at 150 sq. ft.

Twenty-five year old shortleaf pine stands in North Carolina yielded one to five per cent of precipitation as stemflow (Munns and Sims 1936; cited by Kittredge 1948). Mature lodgepole pine in Colorado yielded less than 0.1 per cent of precipitation as stemflow. A 32-year old stand

of lodgepole pine yielded 1.5 per cent of the total seasonal precipitation whereas a nearby aspen (Populus sp.) stand of the same age yielded only 1.1 per cent (Dunford and Neiderhof 1944). This low stemflow value for the smooth-barked aspen is contrary to the evidence of high values for smooth-barked trees.

An 86-year old beech stand in Austria had stemflow starting at 0.1 in. of rain, reaching 21 per cent of precipitation in rains greater than one inch. The average for rains of all intensities was 15.4 per cent for beech, 2.3 per cent for spruce, and 0.7 per cent for the rough-barked pine. In rains greater than 0.6 in. per cent stemflow exceeded per cent interception for the beech (Hoppe 1896; reported by Kittredge 1948).

Hamilton and Rowe (1949) reported that trees with smooth, upright stems carried 25 per cent of the rainfall to the ground, whereas trees with spreading branches and rough bark carried only about seven per cent. Kittredge (1948) presented a graph of amount of stemflow over rainfall by species. In order of increasing stemflow they are: shag-bark hickory (Carya ovata (Mill.) K. Koch), oak, hemlock, basswood, pine, elm, ash, maple, and beech.

Fog drip. Fog drip can occur where fog impinges on vertical surfaces and drips from the foliage. The effect is limited to where fog is prevalent and is usually an edge effect only, not reaching far into a forest.

Data for the Taurus Mountains in Turkey indicated that in a very foggy month the "rain" at the edge of a forest may be three times as

great as that in the open, and over a period of four years it was one and one-half times as great (Linke 1921, reported by Penman 1963). At Kisantu in the Belgian Congo, fog drip accounted for 12 per cent of the annual rainfall of 63 in. (Aubreville 1949). Isaac (1946) reported that on a ridge in Oregon, two miles from the ocean, the rainfall under the trees was one and one-quarter times as great as in the open.

The amount of fog water caught by a stand of Taiwan spruce (Picea glehnii sensu Matsum. and Hay.) in Japan was six to ten times the amount deposited on the ground in the open (Hori 1953). Kashiyama (1956) showed the effect of a model shelter belt of conifers 6.5 ft. high and 43 ft. wide, on the coast of Japan. Intercepted fog reaching the ground under the trees was about 0.04 in./hr. on the windward fringe, or about 100 times the rate in the flat, treeless grassland.

The extremes that have been recorded are from one of the best-known examples, Table Mountain, S. Africa. Monthly values ranged from 217 mm. (8.54 in.) to 398 mm. (15.67 in.) (Nagel 1956).

Oberlander (1956) measured fog drip during a period of 40 summer days without rain in the San Francisco peninsula, California. Under a 20-ft. tanoak (Lithocarpus densiflorus (Hook. and Arn.) Rehd.), 59 in. of fog drip were recorded, more than the total rainy-season rainfall in the surrounding area. In contrast, Kittredge (1954) reported that fog drip rarely reached 0.01 in./day at Berkeley, California.

Grunow (1955) reported that in Austrian spruce forests interception can be compensated for by fog drip. Hirata (1929) (cited by Kittredge 1948), in Japan, indicated that for the months of April and July, 1922,

there were apparently positive contributions by fog drip, i.e., total rain recorded under the canopy, taking into consideration the loss due to interception, was greater than in the open.

Rubner (1932), (reported by Kittredge 1948), studying spruce forests in Germany, came to the conclusion that fog drip was proportional to the ratio of vertical crown area to horizontal crown area. Fog drip under ceanothus (Ceanothus leucodermis Greene) increased as the height of the shrub increased (Kittredge 1948).

Water loss. It has been generally accepted that precipitation interception by foliage causes a loss of water from the site. However, the results of recent studies seem to indicate that there is little, if any, net loss of water from the site because of a compensating reduction in transpiration caused by the evaporation of the intercepted moisture.

Burgy and Pomeroy (1958) reported that in a study using grasses and sunflower plants in nutrient solutions in a greenhouse, transpiration was less from wet leaves than from dry leaves. McMillan and Burgy (1960) carried out a similar study with grasses in lysimeters in which soil moisture was maintained by irrigation between field capacity and 50 per cent of field capacity. Results were similar to those reported by Burgy and Pomeroy (1958).

Goodell (1963) discussed the results of the studies noted above and made several points concerning the apparent compensation for interception by reduced transpiration. He questioned the magnitude of the compensation in view of (1) the fact that plants regulate transpiration when water availability is limited, (2) the probability that more energy is

available for evapotranspiration from wet leaves due to heating of the water film by radiation from the leaf. On dry leaves this escapes into the air, and (3) in cold winter climates, soil moisture availability more than energy may limit transpiration. Interception may then increase the amount of water evaporated by increasing the amount of water to which the excess energy can be applied.

In summary, interception varies from a very small percentage of rainfall for heavy rains to 100 per cent for very light rains. Interception increases with increasing stand volume and density, and varies with species, age, and season. Stemflow begins after a certain amount of rain has fallen (as low as 0.01 in. for smooth-barked trees and as high as 0.7 in. for rough-barked trees), increases as rainfall intensity and amount increase, and ranges from zero to 25 per cent of rainfall. Fog drip as high as 45 in./month has been recorded and in localized areas may contribute as much water as does rainfall.

Evaporation from Foliage

Most of the water intercepted by foliage, other than stemflow, is evaporated. "Most" is used because of evidence of direct intake of water by aerial plant tissue. Pine seedlings whose tops were kept in a moisture-saturated atmosphere with roots sealed in empty flasks, transferred water from the atmosphere to the flask through the roots (Stone et al. 1956). Moisture movement was attributed to the vapor-pressure gradient between the saturated atmosphere and the air in the flasks. Slatyer (1956) also demonstrated this phenomenon. The importance of this in the hydrologic cycle is not known, but such atmospheric and soil conditions would not be expected to occur often in most climates.

Moisture Storage in Vegetation

Satterlund (1959) indicated that the change in moisture content of the vegetation itself can be an appreciable factor in the water balance of a watershed. By calculating the possible changes in moisture content of different species throughout the season he concluded that a rough, and probably conservative, estimate of possible vegetation storage ranged from 0.05 in. for an 80-year old beech stand on a poor site (1,030 cubic feet/acre) to 0.81 in. for a Douglas fir stand, age 100, on a good site (19,820 cubic feet/acre).

Condensation

Whether condensation of water vapor from the atmosphere, i.e., dew, is a significant part of the moisture reaching the ground is doubtful. According to Zon (1927) dew and frost in northern latitudes amount to only 0.4 to 0.8 in. annually. In meadows in England one inch of dew annually has been reported (Kittredge 1948). Harrold and Dreibelbis (1945) reported that monthly averages for the years 1943 and 1944 ranged from 0.12 in. in July to 0.85 in. in January in lysimeter studies at Coshocton, Ohio. However, it was later found that the lysimeter weight changes were affected by grease seals on the lysimeters. The authors stated (Harrold and Dreibelbis 1962) that the previously published values of dew are much too large.

At the Fernow Experimental Forest in West Virginia, 0.259 in. of dew was recorded during the period May - November, 1962. The July - September amount was only 1.2 per cent of the 10.76 in. of precipitation

that occurred during that period (Hornbeck 1964). Lloyd (1961) reported that total dew recorded in northern Idaho for the July - September, 1958, period was 0.39 in., or 13 per cent of the 2.96 in. of rainfall during that time.

The values given in the previous paragraph are for dewfall in the open. Lloyd (1961) found no dewfall under a closed forest canopy but heavy dew on top of a closed canopy of alder. Geiger (1965) stated that dew falling in the open was greater than in the forest, the dew being deposited on the upper crown surface in the forest. It appears, then, that the amount of dew, whether on the crown in the forest, or on the ground in the open, is usually a small percentage of the precipitation. That which is deposited on crowns is lost to evaporation, but transpiration losses are probably reduced because of this. Probably soil moisture loss by evaporation is reduced also by evaporation of dew on the ground. Therefore it appears that the influence of the forest on this variable in the hydrologic cycle is slight.

2. SNOW

Interception

There is wider variation in snowfall measurement than in rainfall measurement because of the greater affect of wind on the falling snow. Snow interception has usually been estimated by subtracting gauge or snow course measurements taken beneath the canopy from similar measurements taken in forest openings. However, the sum of intercepted snow and accumulation under the canopy does not necessarily equal snow accumulation

in the open. In storms of low wind speed and wet snow, the annual catch at crown level is about the same as the catch in small openings (Rowe and Hendrix 1951), but the relation is not known for single storms, especially when snow is dry and wind speed is high.

Another factor clouding the issue of comparisons of snowfall in forest and in openings is the effect of wind turbulence on the accumulation in the open. The accumulation in the open is used as the base but is itself affected by turbulence, which in turn is influenced by such factors as size and orientation of opening, and height and roughness of tree crowns.

The effect of roughness of the upper surface of the forest canopy on falling snow has received very little study as well. Komarov (1963, cited by Miller 1964, p. 2) stated that deposition of snow "depends on the difference between at least the cube of the initial and final velocities" of the wind, so that a small decrease in wind speed results in a large deposition of snow. Where the roughness of the forest canopy is increased, e.g., where there is a forest opening, greater deposition of snow would be expected.

Another aspect of the problem is the definition of interception as applied to snow. In a preceding section, interception loss was defined as that moisture which is caught by the foliage and evaporated. Snow that has been intercepted by tree crowns may remain there for a considerable time (Lull and Rushmore 1961). A thaw or high winds may cause the snow to be deposited on the ground. Therefore, the moisture loss involved is not equal to the initial interception, but only to the amount of sublimation and evaporation that has occurred while the snow

was lodged in the crowns.

In the studies reported below, interception is snow intercepted by crowns and interception loss means only that part evaporated.

Penman (1963) quoted a study by Rutkovski and Kuznetsova (1940) indicating that maximum snow was held under mature broad-leaved stands, young stands holding about the same as in the open, and conifers usually less. Interception of snow at an elevation of 4,500 ft. in southern Idaho amounted to 30 per cent of the total fall in an old stand of ponderosa pine with a partial understory (Connaughton 1935). In a similar stand without the understory the value was 25 per cent, and in an open stand of ponderosa pine and lodgepole pine, 20 to 30 ft. high, only five per cent.

Interception loss from a dense pine stand at the Central Sierra Snow Laboratory in April, 1958, was eight per cent of the precipitation (West and Knoerr 1958). Interception during snow storms in an 80-year old ponderosa pine stand at Bass Lake, California, was 10 per cent of precipitation (Rowe and Hendrix 1951). Kittredge (1953) reported similar data for other forest types. Interception losses during an average-size storm of two inches were 11 per cent for mature ponderosa pine, 15 per cent for mixed conifers, and 16 per cent for dense stands of mature red or white fir (Abies concolor (Gord. and Glend.) Lindl. and A. magnifica A. Murr.). The effect of forest cutting on interception losses is about proportional to the amount of the cut. Kittredge (1953) reported for a selectively-cut forest, a 50 per cent decrease in interception for a 50 per cent removal of the tree canopy.

Miller (1964), in analysing data published by Kittredge in 1953, concluded that selective logging influences interception less by changing crown cover than by removing dominant trees that project above the canopy, and perhaps by making forest edges more porous. Both conditions act directly upon snow which, because of the wind, has a large horizontal component to its fall.

Goodell (1959) reported that a dense coniferous forest in Colorado can, by interception of snow and direct evaporation, allow a loss of up to 30 per cent of annual snowfall. Reductions in loss due to logging were estimated by Anderson and Gleason (1959) for a winter in which precipitation was 38 to 41 in.; 3.4 in. for a strip-cut area, 2.3 in. for a block-cut area, and 1.6 in. for a selection-cut area.

As an indication of the weight of snow which may accumulate on foliage the results of Seppanen's (1959) investigations are given. In pine stands of medium density at nine snow stations in Finland the snow lodging on branches averaged 2,600 kg./100m.^{2} of ground area, or 104 tons/acre, on January 16, 1959. The range was from 1,400 to 4,500 kg./100m.^{2} (56 to 179 tons/acre).

Accumulation

The effect of wind on the catch of rain was discussed in a previous section. The effect of wind on snow accumulation is much greater because of the greater buoyancy of snow flakes compared to rain drops. The effect is more obvious also because the snow does not generate runoff immediately, and the precipitation of many storms often accumulates before

melting and running off.

The following literature survey indicates the forest management practices which may affect snow accumulation, and the size of the influence.

In the open. In the lee of a shelterbelt in South Dakota at the end of February 100 in. of snow accumulated, whereas to windward, and beyond the influence of the belt to leeward, the depth of snow was less than 20 in. Maximum drifts were at 3H (H is the height of the tree or stand) and the effect was noticeable as much as 8H to leeward (Stoeckeler and Dortignac 1941).

Ffolliot et al. (1965), working in the Coconino National Forest, Arizona, measured the water equivalent of snow on the day following each storm. The study areas all had north-east aspect with slope less than 10 per cent, and the wind direction during the study was south-west. Snow accumulation in inches of water equivalent was a maximum at 1H, while the snow-melt rate was least at the edge of the opening, increasing to approximately $1\frac{1}{2}$H where it levelled off.

Martinelli (1965) investigated the depths of snow accumulated behind slat-and-wire fences in alpine areas of central Colorado. The results are pertinent in that they show the effect on snow deposition of air flow barriers and the extent of the effect. In the investigation, snow fences of 1.2 and 2.4 m. (3.9 and 7.9 ft.) were used to determine if such barriers would produce snow fields that would persist until late summer. The research showed: (1) a positive effect on snow accumulation

usually extended 8H to 12H beyond the fences, occasionally extending to 20H on level terrain, (2) in steeper areas, especially where wind flowed downslope before striking the fences, this distance decreased to 6H to 8H, (3) the values for level terrain fall close to the 10H to 25H reported by Schneider (1959), (4) the more frequent values of 8H to 10H also agree with that found using the equation attributed to German workers by Pugh (1950, cited by Martinelli 1965),

$$L = \frac{36 + 5H}{K}$$

where L = length of drift in feet
H = height of fence in feet
K = proportionality factor of 0.9 for the type of fence,

(5) the maximum depth of snow was at 3H to 5H, (6) maximum depth of snow varied from 0.5H to 0.6H at one catchment, to 1.2H to 1.5H at another.

In the forest. Hoover and Shaw (1962), at the Fraser Experimental Forest, Colorado, determined that a forest opening is most effective as a snow trap if it is at least 2H wide, and that openings should not be greater than 10H wide.

Many studies show that snow accumulation is maximum in openings of approximately 1H in width and the opening should be in the form of a cut strip of that width (Church 1912, Kittredge 1953, Anderson 1956, and Anderson, Rice and West 1958).

Anderson and Gleason (1959) gave a graph of snow accumulation in forest openings which showed that snow depth leeward of the opening was less than to windward, indicating that snow was "stolen" from the leeward forest, i.e., total accumulation in the open was made at the expense of

accumulation in the forest. However, in such drifts the snow pack persists longer, prolonging runoff.

In mature 70-foot lodgepole pine near Fraser, Colorado, Wilm and Collet (1940) found that from under the crowns out into the openings between the trees the water equivalent of the snow increased linearly at the rate of one inch in 15 ft. The relation was maintained from a distance of 30 ft. beneath to 30 ft. beyond the edges of the crowns into the openings.

A study of the effect of crown cover of ponderosa pine on snow accumulation near Flagstaff, Arizona, showed: in an opening in the forest accumulation was 15.6 per cent greater than in an extensive opening; under little cover accumulation was 7.4 per cent greater; under partial cover, 5.8 per cent less; and under complete cover 32.5 per cent less (Jaenicke and Foerster 1915).

Many studies of the relation of crown cover to snow accumulation fail to describe adequately the forest densities, but use such terms as "little", "partial", and "full". In a study by Eschner and Satterlund (1963) density was described quantitatively and is therefore more meaningful. Table 1 is a combination of two tables from their report. Depth of snow and water equivalent were measured weekly from November, 1961, to April, 1962. Column 4 is the maximum water equivalent recorded on the site during the period, and column 5 is the sum of the positive increments between sampling dates.

Table 1. Snow accumulation under different cover conditions in central New York (From Eschner and Satterlund 1963.)

Cover	Basal area per acre sq. ft.	Winter crown density per cent	Max. accumulation on ground inches water equivalent	Total accumulation Nov. 30-Apr. 27 inches water equivalent
Open land....	0	0	2.25	6.07
Brushy hardwoods..	31	2.8	5.15	9.23
Northern hardwoods..	133	7.6	4.90	7.28
Thinned red pine...	109	85	4.90	6.44
Dense red pine...	196	93	4.05	5.33
Thinned Norway spruce.	163	94	3.05	5.13
Dense Norway spruce.	139	96	3.25	4.80

Dils and Arend (1956) investigated the accumulation of snow under red pine of different stand densities in Michigan. The accumulated depth of snow decreased as the basal area of the stand increased (from 18 in. in the open, to 12 in. in a stand of 80 sq. ft./acre, to 9 in. in a stand of 190 sq. ft./acre). The snow intercepted by tree crowns was reported as lost by evaporation and sublimation.

Evaporation from Snow

Because the snow pack persists for some time before melting is complete, the amount of moisture lost from the pack by evaporation has

been the subject of numerous investigations. One method of estimating such loss is by periodic weighing of glass jars containing snow.

A study at 7,000 ft. elevation in Utah using glass jars showed a mean evaporation rate of 0.017 in./day for November 7 to May 4. During the snow season (180 days) the total evaporation was three inches, or 14 per cent of snowfall. Evaporation increased at an accelerated rate with increasing air temperature (Baker 1917). Croft (1944) reported mean evaporation of 0.04 in./day for May at 8,700 ft. elevation in the same area. On May 8, evaporation from snow cores in pans was 0.05 in. where exposed to wind and 0.02 in. where there was no wind movement. The effect of solar radiation was small as shown by the difference in evaporation between sun and shade of only 0.002 in.

Church (1934) reported the following November - March evaporation for a study conducted with pans of snow at tree-crown level at Lake Tahoe, Nevada: open meadow, 8.5 in. of water equivalent; semi-open pine forest, 4.8 in.; fir stand, 2.4 in. In inches/day the respective amounts were 0.057, 0.032, and 0.016. Houk (1921, cited by Kittredge 1948) determined the rate of evaporation from snow from December, 1917, to February, 1918, in Ohio, to be 0.023 in./day.

Measurements of evaporation were made for several years under a range of conditions from open meadow to dense forest on the Stanislaus National Forest in California. Median evaporation for all stations and

years was 0.007 in./24 hours. For 1936 the median was 0.013 and in 1938, -0.002 in./24 hours (the negative value indicating that condensation exceeded evaporation). For individual forest types the medians ranged from a maximum of 0.12 in./day under a mature, open stand of ponderosa pine, to -0.002 in./day in dense stands of white fir, red fir, and ponderosa pine. Records taken morning and evening at a limited number of stations showed that evaporation exceeded condensation in 83 per cent of the day periods, and condensation exceeded evaporation in 72 per cent of night periods (Kittredge 1948). Apparently evaporation from snow on Pacific slopes of the western mountains is much less than that in the interior, the difference presumably being associated with more humid winds from the Pacific Ocean.

In large, exposed openings in California, evaporation minus condensation totaled 2.1 in. during the winter of 1957-1958; in small forest openings gains by condensation essentially balanced losses; and under forest canopies a net gain of 2.3 in. was measured. Only during a dry spell in late February to April, 1958, did significant evaporation from snow surfaces occur (Anderson 1958). Similar results were obtained at the Central Sierra Snow Laboratory. February to June loss in a small forest opening was 0.8 in. while under the canopy the loss was 0.3 in. (Anderson 1958).

Hutchison (1966) compared evaporation from snow and soil surfaces in the central Rocky Mountains, Colorado, during the spring of 1961. Measurements were made in forest openings at 9,000 feet elevation using

evaporation pans set in the soil or snow. Evaporation losses from wet soil surfaces were much greater than from adjacent melting snow surfaces, averaging 0.1705 in. for soil and 0.0361 in. for snow, from April 21 to May 9. This may be explained by increased atmospheric vapour pressure during spring due to increases in area of exposed wet soil and available energy. Vapour pressure gradients between both surfaces and the air will then decrease but the gradient between soil and air will decrease least because the soil temperature can rise under a given level of energy input and the vapour pressure of the soil water will rise correspondingly. The vapour pressure of the melting snow surface is fixed at a value corresponding to 32°F.

Bergen and Swanson (1964) studied evaporation from snow at 9,000 ft. elevation in Colorado using the energy budget method. Measurements were made of snow temperature and density, soil heat flux, incident radiation and the difference between this flux and reflected or emitted radiation from the snow, wind speed, shear, and air temperatures at intervals above the surface, and air humidity. Daytime evaporation losses ranged from 0.02 to 0.07 in. and averaged 0.04 in. for the five measurements made from February 13 to March 23. Nighttime condensation ranged from 0.00059 to 0.012 in., averaging 0.0076 in. for four measurements.

At the Central Sierra Snow Laboratory evaporation was greater in the open than in the forest during the day, and less in the open than in the forest at night (West 1959).

In summary, the evaporation rate ranges from a high of slightly over 0.1 in./day to a low of -0.002 in./day, the most common rate reported being approximately 0.02. The rate is higher in the open than in the forest, decreasing with increasing density to the point where condensation exceeds evaporation.

Melting of Snow

The influence of the forest on snow melt depends on its influence on those sources of energy involved in snow melting. Those sources are solar (short wave) radiation, terrestrial (long wave) radiation, convection heat transfer from the air, latent heat of vaporization by condensation from the air, conduction of heat from the ground, and the heat content of rain.

Equations have been constructed to predict melt using data on the sources of energy involved (Rantz 1964). All the hydrometeorological data are seldom available, however, and approximations based on empirical evidence are necessary. Recorded melt rates under various conditions are therefore of value in estimating approximate rates for other areas.

In Utah for the period April 22 - May 9 the average melt rate per degree-day was 0.054 in. water equivalent (Clyde 1931; cited by Kittredge 1948). A degree-day is a departure of one degree per day in the daily mean temperature from an adopted reference temperature, in this case from 32°F. Horton (1915) reported 0.05 in. water equivalent/degree-day as the melt rate in the sun in New York state.

Examples of the effect of forest cover on snow melt in three areas of the Cascade Range in Washington were provided by Griffen (1918) for Douglas fir, mountain hemlock (Tsuga mertensiana (Bong.) Carr.), and lodgepole pine. Measurements taken after the snow had just disappeared in the open show a greater depth of snow with greater crown density, as well as a longer-lasting melt period.

Hart (1963), working in New Hampshire, reported melt rates in inches water equivalent per degree-day for the period March 29 - April 12 as follows:

0.16 -- open field
0.10 -- hardwood stand of crown closure 24 per cent, basal area 87 sq. ft./acre
0.05 -- white pine stand of crown closure 90 per cent, basal area 199 sq. ft./acre
0.04 -- red pine stand of crown closure 83 per cent, basal area 229 sq. ft./acre.

Lull and Rushmore (1961) reported melt rates of 0.06 in. water equivalent/degree-day for hardwoods and 0.03 for spruce-fir in the Adirondacks.

Sozykin (1959) reported on observations made at the Moskva-Volga watershed, north-west of Moscow. Accumulation averaged 15 mm. (0.59 in.) less in forest than in open and the melt season lasted eight days longer with the rate averaging 16.7 mm./day (0.66 in./day) in the forest and 32.6 mm./day (1.28 in./day) in the open.

Anderson (1963) reported that maximum shade results in least melt but 85 per cent shade is nearly as effective. Trees to the south of the snowpack have a marked influence on melt but trees to the north are only

12 per cent as effective in preventing melt. Trees to the north do intercept sky radiation and protect snow because of this, but they also absorb direct solar radiation and radiate long-wave radiation, some of which reaches the snowpack. Forests reduce the amount of long-wave radiation from clouds and atmosphere that reaches the snowpack at night, however.

The trapping of cold air at the down-hill margin of forest openings may be an important mechanism in delaying winter snowmelt. The down-hill sides of such openings always contain more snow than the uphill sides (Anderson, Rice, and West 1958).

The longer the snowpack persists the greater is the likelihood of rapid melt rate, and consequent rapid runoff, as the transition from cold winter proceeds into the warmer conditions of spring; greater too is the likelihood of heavy rainfall swelling runoff from the ripe snowpack. The timing of high temperature or heavy rain may change the forest's influence from favorable to unfavorable. When the critical warm period comes early with large snowpack accumulations in both field and forest, forests probably contribute less runoff and slower runoff than open areas; when warm weather comes late, with an appreciable snowpack only in forests, the reverse is likely to be true. Consequently, a mix of forest and open may be the best land use pattern to ameliorate high runoff conditions.

In summary, snow-melt rates vary between 0.04 in. water equivalent/degree-day in dense pine stands to 0.16 in. in the open, with values as high as 1.28 in./day being recorded.

3. EVAPOTRANSPIRATION

Many studies have been made to determine the amount of water evapotranspired by different crops. Investigations of water use by forests have been carried out, using various methods, for the past 50 years, but due to the limitations of experimental techniques, results do not show a high degree of agreement. Ideally, data would be available on transpiration in inches of water for each species, age, and size-class, but the problem is very difficult for anything larger than a seedling (Kittredge 1962).

Methods of Measurement

Swanson and Lee (1966) discussed three techniques for estimating evapotranspiration: (1) measuring the rate of vapor production of a plant enclosed in a plastic greenhouse, (2) weighing excised portions of plants to determine the rate of water loss, and (3) measurement of sap velocity by detecting the movement of heat, dye, or radioactive tracers.

Tent method. In the plastic greenhouse, or tent, method, a pump is used to inflate the tent which encloses the plant. The difference in moisture content of outgoing air and ingoing air, combined with the rate of air exchange, gives a measure of the water loss from within the enclosure. Because the water loss includes not only transpiration from the sample plant but also evapotranspiration from the soil surface and low-growing shrubs, the same parameters are measured for a tent without an enclosed plant. This value is deducted from the first measurement to

obtain an estimate of transpiration from the sample tree.

However, the value obtained by this method is not likely to be the same for a naturally-exposed plant because of the effect of the tent on the environment within it. The greatest effect is restricted air movement in the tent causing air temperatures to rise by 10 to 15 degrees when combined with the radiant energy trapped by the plastic tent. The plastic, being more transparent to short-wave radiation than to long-wave radiation, admits the short-wave radiation from the sun or sky but traps much of the heat radiation from the ground and plant foliage within the tent.

A variation of this method requires the ground and all vegetation within the tent, except the test plant, to be covered, so that the only evapotranspiration is by the test plant (U.S. Dept. Agr. 1937).

The tent method may be more useful in measuring the relative rates of waterloss by different plants on adjacent plots. Even here, however, an assumption must be made, i.e., although the plants differ in form and physiology, enclosure effects are the same at each site.

Quick-weighing method. In this method, a part of the plant is cut off, weighed immediately, and weighed again after a short time interval. An attempt is made to keep the plant in its natural position and environment by suspending it before excising. Cutting the plant part also cuts off its water supply so that transpiration would soon stop. The cutting also releases the tension by which the water is held back from the transpiring parts of the plant. This may cause a transpiration increase.

Rutter (1959) found that severed Scotch pine branches underwent a transpiration decrease of 12 per cent in the first 10 minutes after cutting, but that the transpiration rate of detached needles was not reduced during the same period. He reported that evapotranspiration rates determined by the weighing method agreed closely with those estimated by soil moisture measurements. However, as Swanson and Lee (1966) conclude, extrapolation from the part to the whole plant is the most difficult problem with this method.

Sap velocity method. Estimating evapotranspiration with this method depends on the relation of sap velocity and rate of evapotranspiration. Skau and Swanson (1963) reported that field tests showed that sap velocity is closely correlated with the rate of transpiration from entire trees as determined by the tent method.

Two factors complicate the use of sap velocity to estimate transpiration: (1) The area through which the sap moves may vary with time. If this area decreases, for example, less water would be available for transpiration even though the sap velocity remained the same. (2) The amount of water within the sapwood may change, i.e., even if the conducting area remains the same, the moisture content of a given unit within that area may change. The result is the same as in (1). These problems could be resolved by making simultaneous measurements of the velocity profile across the sapwood and radial moisture content across the same area. The sap velocity profiles can be obtained but Swanson and Lee (1966) pointed out that a non-destructive method of obtaining the moisture content is lacking.

Although each of the three methods described above has severe limitations, a combination of methods may prove more useful than any single method. For example, the sap velocity method may be used in conjunction with the weighing method. This would provide information on the change in transpiration rate immediately after cutting.

Energy budget method. Evapotranspiration can be estimated indirectly by the energy budget method. Munn (1961) discussed the theory of evaporation determination by the energy budget and Fowler (1964) and Goodell (1965) described its use in estimating evapotranspiration. This method is an accounting of the energy gain, loss, and storage at a particular location and period of time. If the energy loss due to radiation and reflection from the earth's surface is deducted from the energy input, the difference may be attributed to heat stored in crops and soil and the energy used in heating the air and transforming water from the liquid to the vapor state. To obtain a value for the last mentioned term, evapotranspiration, all other energy inputs, outputs, and use must be measured.

The development of the net radiometer has simplified the measurements required and permits the measurement of that part of the energy budget that is processed at the earth's surface, i.e., net radiation. Net radiation may be described by the equation (Gray et al. 1965):

$$NR = S + V + K + E$$

where NR = net radiation
S = heat flux into the soil
V = heat storage in vegetation
K = heat used in heating the air
E = latent heat flux of evapotranspiration

The above equation assumes that photosynthetic use of energy is small, although the value may be higher than generally supposed (Tanner and Lemon 1962). It also assumes a zero value for the energy released by condensation. Heat storage in agricultural crops is not usually an important part of the heat balance (Gray et al. 1965), but in forest stands may be considerably greater (Jeffrey 1964). On a daily basis, the flux of heat into the soil surface is relatively small during most of the year (Gray et al. 1965), especially under forest.

A linear relation has been shown to exist between net radiation and potential evapotranspiration on a daily basis when soil moisture availability is not limited (Fowler 1964, Tanner and Pelton 1960). However, estimates of actual evapotranspiration where moisture is periodically limiting cannot be expected to be as reliable as estimates of potential evapotranspiration, but as Fowler (1964) pointed out, such estimates may be invaluable where other information is not available.

Eddy fluctuation method. This method combines data on fluctuations in vertical air motion and humidity with net radiation to estimate evapotranspiration. Main problems are associated with instrument difficulties concerning response times of wind and humidity sensors. However, with improved instrumentation, this method is likely to prove valuable in estimating evapotranspiration where moisture availability is limited (Bruce and Clark 1966).

Soil moisture budget. Changes in soil moisture storage have been used in conjunction with moisture input by precipitation and outgo by

runoff, to evaluate evapotranspiration. In such evaluation, seepage into and leakage out of the area being studied are usually ignored (Burroughs and Shultz 1964). Except in those rare cases where seepage and leakage are equal, omitting these terms introduces an error. Willardson and Pope (1963) suggested a method by which the amount of moisture lost due to deep seepage may be separated from the evapotranspiration estimate. This involves the measurement of deep seepage at the same site but on plots stripped of vegetation and covered to prevent evapotranspiration. However, as Jeffrey (1964) pointed out, this assumes that percolation on the denuded plot will be the same as that on the vegetated plot, which is not necessarily true.

If percolation losses are ignored in the estimation of evapotranspiration, irrigation water, when used, must be added sparingly to minimize percolation loss. Water table levels must be deep enough that plants derive no water from this source.

The main advantage of this method is that evapotranspiration is determined under field conditions.

Gravimetric sampling of soil moisture at periodic intervals has been used for many years in estimating evapotranspiration. Electrical resistance blocks permit soil moisture measurement with less site disturbance than does gravimetric measurement. Access tubes for moisture determination with the neutron probe, which has become widely used in the past 10 years, usually cause little site disturbance. However, problems are encountered in installing access tubes in stony soils where

access with tractor-mounted equipment is not practical. With hand-bored access holes, problems include trampling of soil and vegetation at the site and maintaining close contact of the access tube with the adjacent soil.

Potted plant method. A simple method which has been used widely in the past to estimate transpiration is weighing a potted plant, allowing it to transpire for a period, and reweighing it. The difference in weight is due to loss of water and change in weight of the plant. The plant weight changes are so small relative to the loss in weight by transpiration that they may be ignored and the total weight change attributed to transpiration (Bonner and Galston 1959).

Lysimeters. The use of lysimeters to measure evapotranspiration is described comprehensively by Pelton (1961). With this method plants are grown in tanks, and water loss from the tanks is determined periodically. Metal or plastic tanks are used having surface areas of several hundreds of square feet and depths of eight feet or more.

Lysimeters were in use in the 17th century for water percolation studies, but it was not until the 18th century that they were used for measuring evapotranspiration (Gray et al. 1966). In 1906 the first lysimeters with weighing devices were installed in Germany, and in 1923 the first self-recording weighing lysimeters were constructed in the United States (Pelton 1961). More recently, lysimeters have been equipped to record rates and amounts of runoff and percolation automatically (Dreibelbis 1963).

Lysimeters are of three main types, classified according to the principles of construction: (1) Ebermayer, (2) filled-in, and (3) monolith, or undisturbed soil block. Pelton (1961) described the types as follows.

In the Ebermayer type, a percolate funnel is placed under a block of soil left in situ. The lysimeter has no side walls and cannot, in itself, be used to determine evapotranspiration.

The filled-in lysimeter consists of a container with vertical side walls, an open top, and a bottom that provides for percolation. These lysimeters are usually filled with soil that has been stripped from the area in structural layers. They are filled in such a manner that they approach natural conditions as nearly as possible.

The monolith lysimeter is composed of a casing built around a natural block of soil and provided with a partly open bottom.

Measurements of water applied, outflow, and changes in soil moisture are used to determine evapotranspiration. Soil moisture may be measured by direct moisture sampling (e.g., gravimetric samples or neutron probe), or by using weighing or hydraulic methods. In the hydraulic method, the tank is floated and changes in weight are recorded as pressure changes on a manometer (Gray et al. 1966).

The chief argument against the use of the lysimetric method of evapotranspiration determination is that there may be differences between the lysimeter and natural conditions. The scope for such differences is large, e.g., soil profile and moisture regimen, plant rooting

characteristics, methods of water application, and the net energy exchange. However, if the installations satisfy certain minimum standards, they will provide reasonably reliable estimates of evapotranspiration over short time periods (Linsley et al. 1949, Pelton 1961).

The minimum standards that should pertain are: (1) the lysimeter should contain soil that has been disturbed as little as practicable, (2) uniform conditions around the lysimeter should be maintained, and (3) the ratio of the area of surface occupied by lysimeter walls to the enclosed area should be made small.

Results of Investigations

The Tennessee Valley Authority determined that total transpiration from a forest of pine, oak, and other shrubs, from May 19 to October 1, was 420 mm. (16.5 in.) (Rothacher 1949). The method used was the placing against the growing leaf strips of filter paper that had been soaked in a solution of cobalt chloride. The time required for colour changes to take place as moisture was absorbed by the filter paper was compared to a standard to obtain an estimate of transpiration.

Oelkers (1940, cited by Penman 1963), in Germany, used lysimeters to determine transpiration for a growing season of 153 days on a medium pine site. He reported the following values: pine, 80 mm. (3.2 in.); fir, 66 mm. (2.6 in.); birch, 74 mm. (2.9 in.); larch (Larix sp.), 147 mm. (5.79 in.); and spruce, 323 mm. (12.7 in.).

Using a set of large lysimeters at Castricum, Holland, Deij (1954, cited in Penman 1963) determined that conifers had a mean annual

evapotranspiration for the period 1948-1953 of 538 mm. (21.2 in.) compared to 417 mm. (16.4 in.) for deciduous, and 448 mm. (17.6 in.) for low vegetation.

Smirnov and Odinovkova (1954), working on aspen in the Tellerman Forest in Russia, reported transpiration of 203 mm. (7.99 in.) for eight-year old aspen; 230 mm. (9.06 in.) for 25-year old aspen; 201 mm. (7.91 in.) for 36-year old aspen; and 185 mm. (7.28 in.) for 63-year old aspen. These figures were arrived at by calculating a water balance using evaporimeter measurements, throughfall, soil moisture, runoff, and infiltration. Straight-line relations were found between the amount of transpiration and the current annual volume increment of the stand.

Holstener-Jorgensen (1959) reported water use by 65-year old beech and 45-year old spruce on the Danish Forest Experiment Station. The author used ground-water levels, which, if they reach the zone of root activity, may be used to give a measure of water use. For the period April 19 - December 14, 1956, beech transpired 481mm. (18.94 in.); spruce transpired 471 mm. (18.54 in.) for the period April 15 - December 13, 1956; and for April 10 - December 28, 1957, beech 417 mm. (16.42 in.) and spruce, February 28 - December 28, 1957, 469 mm. (18.46 in.). The order is reversed for the two years which might be accounted for by a difference in response of the two species to changed availability of water in the two years, but more likely it is that because of the mild spring or late winter the spruce began transpiration several weeks before the beech in 1957.

Molchanov (1955, cited by Penman 1963) used soil moisture determination to estimate water use in an area where mean annual rainfall was 500 mm. (19.7 in.). The maximum values of evapotranspiration were as follows:

Scotch pine (Pinus sylvestris L.), 40-80 years, 420-467 mm. (16.5-18.4 in.)
oak, 40-100 years, 443-469 mm. (17.4-18.5 in.)
ash, 40 years, 416 mm. (16.4 in.)
aspen, 20 years, 392 mm. (15.4 in.)

Molchanov (1960) concluded that evapotranspiration was greatest in larch, followed by fir, pine, oak, aspen, ash, and birch stands. Wtihin a given species the water use varied with age, the highest use being observed in the period of culmination of current annual volume increment.

Kittredge (1948) also indicated that there is evidence that transpiration is greatest for dense stands on the best sites at the culmination of current annual increment.

Brown and Thomson (1965) measured soil moisture in spring and fall of 1955, 1957, 1958, in Colorado to determine water use. The study indicated that water use per day was greatest on aspen sites, intermediate on Engelmann spruce sites, and least on grassland sites. There is reason to believe that in aspen and spruce types the water use would be similar under conditions of similar soil moisture, since the moisture withdrawn by aspen exceeded that of spruce by almost the same amount as the differences in spring soil moisture under the two types.

The evapotranspiration from spruce-subalpine fir forest in the eastern Rocky Mountains of Alberta, was estimated by the eddy-flux method (Munn and Storr 1967). Measurements of net radiation above the canopy and of gradients of wind and temperature from an 80-foot tower were taken. Fast-speed runs of the fluctuations of temperature, humidity, and vertical wind were taken using dry and wet bulb thermocouples and a vertical anemometer. Evapotranspiration was estimated to be about 0.3 grams/cm.^{2} or 0.13 inches/day.

Rutter (1959) related evapotranspiration to solar radiation. The trends over time of both variables were quite similar.

In 1928, Meyer constructed a graph from which the depth of transpiration could be read directly from mean monthly air temperature. Although factors other than air temperature were neglected, the results were not dissimilar to those obtained by other methods.

Considering the important influences of meteorology and soil moisture as well as the influence of vegetative factors such as the type, colour, density, and shape of the plant on evapotranspiration, few detailed conclusions seem warranted regarding the amount of water use by trees. There is evidence, however, which seems to indicate that in both conifer and deciduous stands there is an increase in water use until about age 60, with a gradual dropping off after that age. The range of evapotranspiration for most species is about 300 to 500 mm./year (roughly 10 to 20 in./year).

4. STREAMFLOW

Annual Discharge

Investigation of the hydrologic role of forests has often been directed toward streamflow measurements. Of the elements of the hydrologic cycle, surface runoff in channels is the easiest to measure. This, along with the importance of quantity and timing of runoff, has been responsible for the accent on stream gauging. Streamflow is the integrator of all the variables on a watershed. Because of this, watershed treatment has been assessed by its influence on streamflow.

Of the factors of the water balance that might be amenable to influence by man, evapotranspiration seems to be the most readily altered. Rakhmanov (1959), reviewing the literature of the past 100 years, concluded that forest cover does not accelerate evapotranspiration, and that there is no substantial difference between forest and other cultivated land areas in similar environments. However, this view is not widely accepted, as a review of the literature will indicate.

In Japan, clearing of broad-leaved trees, 30-feet tall, caused greater streamflow surges immediately after rain, and a reduction in annual water use, the increase in quantity of runoff being similar to the estimated interception before cutting (Hirata 1929).

One watershed of a paired-watershed experiment in Kamabuchi, Japan, containing mixed conifer and broad-leaved deciduous trees, was clear cut, grass and brush regrowth being removed in each subsequent year. Runoff during the succeeding three years averaged 1790 mm. (70.47 in.) from the

forested watershed and 1955 mm. (76.97 in.) from the bare one. The difference, 165 mm. (6.50 in.) was attributed to reduced evapotranspiration on the bare site (Maruyama and Inose 1956).

In the Sperbelgraben and Rappengraben watershed studies in Switzerland, Burger (1954) reported greater runoff from the least forested watershed and that evapotranspiration was greater from woodland than grassland. Penman (1963) suggested that the data from this study must be approached with caution because of doubts about the accuracy of the raingauging and streamgauging.

Delfs et al. (1958) reported 10 per cent greater evapotranspiration from the heavily-forested Wintertal watershed than the clear-cut, grass-covered Lange Bramke watershed in Germany. Precipitation and runoff from the forested watershed for the period 1948-1953 were 49 and 23 in. respectively, and 48 and 28 in. respectively for the grass-covered watershed.

At Wagon Wheel Gap in Colorado, one of two similar watersheds was cleared and slash-burned, with aspen quickly invading the area. Annual precipitation was about 21 in. and runoff was about 6 in. annually. For the first three years after cutting, the treated watershed had 23 per cent greater runoff than the untreated watershed; for the second three-year period runoff was only 18 per cent greater. The assumption is that the decreasing difference in runoff, from 23 to 18 per cent, was due to the vegetative recovery of the treated area (Bates and Henry 1928).

At the Coweeta Experimental Forest in North Carolina, the cutting of one watershed resulted in a runoff increase of 16 in. where pre-treatment

yield averaged about 30 in. (Hoover 1944).

Removal of vegetation from 30 per cent of a 250-acre watershed on the H.J. Andrews Experimental Forest, in Oregon, caused a 12-28 per cent increase in minimum streamflow. Removal of timber on 40 per cent of another watershed increased low flows by 45 per cent, and by 85 per cent after 80 per cent of the watershed had been logged. Annual water yields before treatment were from 50 to 60 in. and annual precipitation averaged 94 in. (Rothacher 1965a).

Twenty years of before-and-after records on the Pine Tree Branch watershed in Tennessee indicated that total runoff decreased from three to six inches per year while ground-water runoff volumes remained unchanged after reforestation. Mean annual runoff for the 20-year period was 10 in. Peak discharges in both summer and winter floods were reduced by 70 to 90 per cent for moderate to large storms (T.V.A. 1962). Up to five inches of increased runoff (increasing the annual yield to 26 in.) resulted from clear cutting watersheds in the Fernow Experimental Forest. Evidence indicated that fully-stocked stands were a benefit to flood control during the growing season (Reinhart et al. 1963).

Evidence reported by Rich (1965) indicated that the type of cut, not just the basal area removed, influenced the runoff from Workman Creek watersheds in Arizona. No significant increase in water yield resulted from a riparian cut on the North Fork, but only 0.6 per cent of the total basal area was removed. A later clear cut of moist-site vegetation along the streams, amounting to 32 per cent of the area, did result in increased water yields. However, removal of 24 per cent of total basal area by

single-tree selection and another 21 per cent by road construction and fire on the South Fork watershed, has not significantly increased water yield during the 11 years since the cut.

Schneider and Ayer (1961) reported that increasing forest cover from 26 to 84 per cent on Shackham Brook watershed, in central New York state, significantly reduced its mean flow over the 26 years following treatment.

Hewlett and Hibbert (1961) reviewed the watershed studies carried out over the past 30 years at the Coweeta Hydrologic Laboratory, North Carolina. Following are some of the conclusions that have been reached at Coweeta:

(1) Five to 16 in. of increased runoff have been measured in the first year after clear-cutting.

(2) South slopes have yielded only half the first year increases obtained on north slopes after treatment.

(3) When treatment effects have been large, there has been considerable delay in the timing of part of the increased runoff. When effects have been small, the increase tends to be during that season in which the actual savings in terms of reduced evapotranspiration would be expected.

(4) When increases are large, they extend over a period of 35-40 years, but most of the increase comes during the winter (high-flow) season.

(5) First-year increases in yield seem to be related to the per cent of the fully-developed stand that is removed. The pattern of cutting at Coweeta showed little relation to the yield increase.

(6) A riparian-strip cut, removing 12 per cent of the basal area of one watershed did not produce a significant increase in annual yield.

An interesting point is that the ratio of first-year increase to per cent basal area cut is approximately the same for the four northerly slopes, i.e., 0.15 (ranging from 0.13 to 0.17), excluding the riparian-strip cut which was also conducted on a northerly slope. The ratio for south slope cuts range from 0.00 to 0.07.

Some Russian investigators report smaller annual runoff from forested watersheds than from non-forested watersheds. The following examples are from Sokolovsky (1959): Tajeshny watershed, 98 per cent forested, had a runoff coefficient of 0.27, (i.e., 27 per cent of the precipitation was runoff) while the nearest field watershed, Usadjevsky, had a coefficient of 0.54; Vorony watershed, 90 per cent forested, had a coefficient of spring runoff of 0.29 compared to 0.56 for the field watershed, Petrushino.

The reason generally accepted for less runoff from forested watersheds is the loss of moisture due to transpiration of the trees. However, observations on medium and large watersheds (116 to 77,000 sq. mi.) in Russia seem to indicate that runoff <u>increases</u> as the forested proportion of the watershed <u>increases</u> (Sokolovsky 1959). The reason for this seeming contradiction of most watershed results may be that the increase in proportion forested is directly related to elevation, precipitation, or some other factors. Whatever factors may explain the conclusion reached

by Sokolovosky, much evidence indicates the opposite to be true.

In summary, runoff is greater from grassland than forest, and annual runoff has usually increased after clear cutting, increases commonly being about 25 per cent with extremes of nine and 85 per cent being recorded.

Flow Regime

The effect of cover changes on streamflow would not be expected to be constant throughout the year but to vary with season as other factors vary (e.g., transpiration). Studies have shown that cover changes do alter the regime as well as total flow of streams.

Wagon Wheel Gap, Colorado. At Wagon Wheel Gap in Colorado, partial cutting of a 200-acre watershed resulted in spring runoff beginning earlier and higher peak flows (Bates and Henry 1928).

San Gabriel River, California. On the San Gabriel River in southern California fire burned over the Fish Creek watershed but missed the adjacent, and similar, Santa Anita Creek watershed. Peak discharges from the Fish Creek watershed were much greater in the first year after the fire, but fell progressively in succeeding years (335, 292, 145, 15, 11, and 11 c.f.s./sq. mile) as vegetation regrew on the watershed. Within six years, runoff from the watershed was back to normal (Hoyt and Troxell 1934).

Coweeta, North Carolina. At Coweeta, North Carolina, a 33-acre watershed was cut over in 1941. The average monthly streamflows for the following 15 years was higher than predicted, with the September-December

period (normally the period of lowest flow) being increased by over 90 per cent (Meginnis 1959).

Pine Tree Branch, Tennessee. On the Pine Tree Branch watershed in Tennessee, reforestation resulted in markedly reduced winter and summer peak discharges (T.V.A. 1962).

H.J. Andrews Experimental Forest, Oregon. Rothacher (1965a) reported on watershed studies at the H.J. Andrews Experimental Forest, on the western slopes of the Cascade Range in western Oregon. After seven years of calibration with an adjacent watershed, a 250-acre watershed in the Douglas fir region, between 1,500 and 3,500 ft. elevation, was treated. In 1959, eight per cent of the watershed was cleared in the process of road construction. The effect on streamflow was studied for three years, then 25 per cent of the area was clear cut. The next year the clear-cut area was broadcast burned. No increase in maximum flows from the treated watershed was recorded, but for the first six years after the beginning of the treatment there was a 12 to 28 per cent increase in minimum flows.

On a second watershed in the H.J. Andrews Experimental Forest cutting began in 1963 when 40 per cent of the area was cut, and continued in 1964 until 80 per cent of the area was cut. In 1963, low flows increased 45 per cent and in 1964, 85 per cent. The increases were small in absolute terms but the high percentages are due to the extremely low flows normal for the late summer months.

Fernow Experimental Forest, West Virginia. On the Fernow Experimental Forest in West Virginia, studies were carried out on watersheds supporting stands of deciduous species, viz., oak, maple (Acer sp.) beech, cherry (Prunus sp.), and poplar. Significant increases in streamflow during the growing season were recorded for three watersheds, one clear cut, one cut to diameter limit, and one cut on an extensive selection basis (harvesting and killing of culls larger than 11 in. d.b.h.). The increase in discharge appeared to be greater with the more severe cut. Large increases in flow were not recorded during the dormant season (November-April). Instantaneous peaks on the clearcut watershed were increased, on the average, by 21 per cent in the growing season and reduced by four per cent in the dormant season (Reinhart et al. 1963).

Fraser Experimental Forest, Colorado. At the Fraser Experimental Forest in Colorado, streamflow records were kept for 12 years before cutting the 714-acre Fool Creek watershed in 1954 (Goodell 1958). The 250- to 300-year-old stands of lodgepole pine and Engelmann spruce-subalpine fir were logged in clear-cut strips so that 278 of the 550 forested acres were cleared (Love 1960). In the eight years since the cut, average annual streamflow has increased by 2.7 area-inches, or 25 per cent (Goodell 1964). However, nearly all of the increased flow occurred during the spring runoff period and low flows were increased little (Hoover and Shaw 1962). It is estimated that increased yield will continue for 35 to 50 years before regrowth reduces it to zero (Goodell 1964).

Spring flood peak was greater the first year and 23 per cent less the second year than predicted values. The author suggested that the effect of clearing may be to decrease or increase peak flow depending on weather conditions (Goodell 1958).

Shackham Brook, Central New York. Reforestation of three watersheds in central New York state resulted in dormant-season runoff being reduced 0.17 to 0.29 in. per year, averaged over the 26 years since treatment. For Shackham Brook watershed, runoff was reduced by 0.14 in. for the growing season, 0.23 in. for the dormant season, and 0.36 in. for the year, and peak discharges by 41 per cent for the dormant season. No significant change in peak flows for the growing season nor annual low flows were recorded for any of the watersheds (Schneider and Ayer 1961).

In summary, the effects of clear cutting on flow regime vary with climate, soils, etc. The literature reviewed indicates that peak flows increased little to as much as 21 per cent and low flows little to as much as 90 per cent.

Snowmelt and Water Yield

Snow accumulation and melt have an important influence on water yield and regime but less attention has been paid to this aspect than to accumulation itself.

In 1935, Connaughton concluded from a study carried out in ponderosa pine in southern Idaho that forest-cover conditions affected snowmelt and that retarding the rate of melt by forest management could increase the

duration of runoff and distribute the peak flow over a longer time.

In the White River drainage basin in Colorado, 226 sq. mi. of Engelmann spruce and lodgepole pine were killed by the Engelmann spruce beetle. The resulting increase in snow accumulation increased streamflow by 22 per cent with peak flows coming in June instead of May as they had before (Love 1955).

Other studies on snow accumulation and melt have been reported in a preceding section on snow, and Colman (1953) has summarized the literature on the subject to 1953. The results of most of these studies indicate that forest-cover reduction usually increases snow accumulation as well as melt rate. This, in turn, produces greater water yield and higher peak flows.

Reinhart et al. (1963), however, reported from limited observations that daily snowmelt runoff from a clear-cut watershed in West Virginia was for one 14-day period more uniform than from the forested, control watershed. The period was March 18-30, 1960, during which flow from the clear-cut watershed was only 92 per cent of the control. On March 30, peak flows were recorded on each watershed and the flow from the clear-cut watershed was 71 per cent of control. The explanation suggested by the authors is that snow cover disappeared near the end of the 14-day period and that it was gone on the clear-cut watershed before the control. Apparently, exposure of the snow cover resulted in a much lower peak.

Eschner and Satterlund (1963) stated that timber harvesting may increase or decrease, depending on weather conditions, not only peak flows,

as suggested by Goodell (1958), but the entire period of high winter-spring runoff.

A study by Satterlund and Eschner (1965) indicated that the average rate of concentrated runoff during snowmelt appeared to be faster after reforestation of Shackham Brook watershed in New York state. The reason given is that runoff from the forested watershed, though reduced in quantity was even more concentrated in time. "If we accept the well-demonstrated fact that the rate of snowmelt per degree day is less in the forest than in the open" (Satterlund and Eschner 1965, p. 404), the concentration in time can be explained.

As spring days pass the number of degree-days increases rapidly. Before this rapid increase, snowmelt has been slower, i.e., the snow in the open, which melts before that in the forest, has melted at a slow rate due to the slow increase in degree-days. The snow in the forest is then subjected to the greater amount of heat per day causing faster melt rates than occurred in the open. Along with this is the greater possibility of a rain on snow event the longer the snow remains.

The authors suggested that the relation between forest and snowmelt under the climatic conditions of the north-eastern United States may be different where a uniformly cold winter climate prevails.

5. EROSION

The terms normal and geological erosion refer to natural erosion which includes the processes of soil formation and soil erosion, and

which occurs through the action of water, wind, gravity, and glaciers. Soil loss in excess of geological erosion, termed accelerated erosion, is usually considered the result of changes in natural cover or soil conditions and is caused by water and wind (Frevert et al. 1955). The erosion of interest here is accelerated erosion because it is this type that is amenable to man's control efforts.

The desire to control erosion is the result of the losses incurred by man because of erosion. These losses include, first of all, productive land that has eroded or upon which eroded material has been deposited. Eroded material also causes damage, as it moves, to engineering structures and homes. Secondly are the losses caused by sediment, which is the product of erosion. These losses take the form of lower water quality, damage to aquatic habitat, silting up of reservoirs and irrigation canals, damage to pumps, turbines, and pipelines, and raised stream bottoms which often cause increased flood damage. Losses also include the plant nutrients and the finer soil particles washed off the soil.

Falling rain imparts tremendous energy to the surface on which it lands. For example, a two-inch rain falling in one hour imparts sufficient energy to lift the seven-inch top-soil layer two feet (Robins and Neff 1963), the drops reaching speeds of up to 20 miles per hour (Laws 1940). The foliage and branches of the vegetation offer the first obstacle to falling rain. Rain which is not held and evaporated by this cover reaches the ground with considerably less driving force. Leaf litter further reduces the force of impact and absorbs water.

Roots and the biological activity associated with vegetation increase soil porosity allowing faster infiltration. Litter, twigs, and plant stems reduce the velocity and cutting action of that water that does not infiltrate the soil but flows overland. This is an important part of the influence of vegetation on erosion because flowing water is a prerequisite to significant soil erosion (Robins and Neff 1963).

Blame for the decline of Near Eastern and North African civilizations has often been laid to deforestation of the hillsides by cutting and grazing, although climatic changes have often been suggested as the cause. Lowdermilk (1953) cited evidence that the climate has not become noticeably drier in those regions since the existence of those civilizations, and that human activity was responsible for the denudation of the hillsides. The resulting erosion certainly played a part in the decadence of those civilizations, but to suggest this as the cause is probably not warranted.

Erosion Studies

The first soil-erosion study in which data were obtained with which to compare vegetational influences on erosion was carried out in China in the 1920's. Runoff and erosion rates were many times greater on cultivated land than on forest land (Lowdermilk 1953). In the Swiss watershed study in Emmental, average sediment load from the almost wholly-forested watershed was 85 $m.^3/km.^2$/year (12.1 cu. ft./acre/year) and 145 $m.^3/km.^2$/year (20.7 cu. ft./acre/year) from the watershed of one-third forest and two-thirds pasture (Burger 1943; cited in Penman 1963).

The sediment production from the pasture watershed was almost double that from the forested watershed but the absolute amount was still very small.

In Michigan, Smith and Crabbe (1952) found that erosion from arable land was from 500 to 1,000 times that from forest. In another Michigan study the following sediment discharge rates were measured (Striffler 1964):

Forest	360	lb./day/sq. mi.	
Wild land	741	"	"
Pasture	1,800	"	"
Cultivated	2,200	"	"

Lowdermilk (1953) reported the results of a study at the Statesville, North Carolina, Erosion Experiment Station in terms of the number of years it would take to erode a seven-inch layer of topsoil under different crops. Land in fallow without cropping would take 18 years; under continuous cropping of cotton, 44 years; natural cover of trees burned over annually, 1,800 years; grassland, 96,000 years; and under unburned forest, 500,000 years.

The conversion of forest land to range land in northern California has resulted in badly gullied and slumping grass lands (Wallis 1965). Watershed activities that decrease the soil-holding influence of vegetation result in accelerated erosion to some degree. Gleason et al. (1955) included among the causes of such erosion, careless logging, fire, over-grazing, and poor road construction methods.

Sixteen watersheds were selected in northern Mississippi to represent prevailing conditions of soils, slopes, erosion, land use, and plant cover in a study of sediment and surface water yields (Ursic and Dendy 1965). Mean annual precipitation varied between 51 and 54 in. for the

different watersheds but average annual runoff in inches was: cultivated land, 16; pasture, 15; abandoned fields, 7; depleted hardwoods, 5; pine plantation, 1; mature pine-hardwood on shallow soils, 9. Sediment yields averaged in tons per year: cultivated land, 21.75; pasture, 1.61; abandoned fields, 0.13; depleted hardwoods, 0.10; pine plantation, 0.02; mature pine-hardwood on shallow soils, 0.02. The data are averages for the three years 1959-1961, except for the mature pine-hardwoods which was for the two years 1960-1961.

The results of many studies have shown the relationship between erosion and forest cover: as forest stand density decreases, erosion increases (Anderson 1949, Anderson and Trobitz 1949, Anderson 1954, T.V.A. 1962).

Erosion Hazard Ratings

Erosion results from the influence of climate on soil, modified by the factors of topography and vegetation. A change in any of these factors will change the erosion hazard and, unless compensating changes occur in the other factors, the amount of sediment produced. Means of estimating the erosion hazard have been the objectives of many studies. The hope has been that such a hazard rating would be helpful in managing land to minimize erosion.

Soils differ in their propensity to erode, i.e., their erodibility. A method by which soil characteristics as they relate to erodibility might be evaluated was proposed by Middleton (1930). He developed two indices of erosion, the dispersion ratio and the erosion ratio.

The dispersion ratio is the ratio of the amount of silt plus clay in the soil, determined without chemical or mechanical dispersion, to the amount of silt and clay determined after standard dispersion. The erosion ratio is the dispersion ratio divided by the ratio of colloid percent to moisture equivalent. Middleton classified erodible soils as those whose dispersion ratios were greater than 10 and whose erosion ratios were greater than 15. Non-erodible soils had ratios below these values.

Anderson (1951) used the erosion ratio and the dispersion ratio in conjunction with other soil characteristics and forest cover density to estimate sediment in streams. He reported that both ratios were useful indices of soil erodibility, but that the dispersion ratio was the better index. His study also showed that forest cover density had a highly significant influence on erosion.

Andrē and Anderson (1961) related the surface-aggregation ratio and dispersion ratio, as indices of erodibility, to geology, vegetation, and elevation. The surface-aggregation ratio is (the amount of surface in square cm./gm. on particles larger than silt) divided by (the total percentage of silt and clay in dispersed soil minus the percentage of silt and clay in an undispersed soil), i.e., the ratio of the amount of surface in the non-binding fraction to the amount of clay in the soil. The study indicated that the surface-aggregation ratio was more significantly related to soil erodibility than was the dispersion ratio. Also shown by the study were: (1) soils developed from acid igneous

rock were about 2½ times as erodible as soil developed on basalt, (2) erodibility was highest for soils under brush, next under trees, and least under grass, and (3) no definite relation of erodibility to elevation was shown.

Analyses of texture and potential erodibility were made on samples of forest soils from 6,500 to 8,000 feet in the southern Sierra Nevada, in California (Willen 1965). Texture and erodibility were related by regression analysis, to rock type, cover type, elevation, aspect, and slope. Soil texture was found to vary widely with rock type, as did aggregated silt and clay. Soil texture was less significantly related to vegetative cover but aggregated silt and clay was highly significantly related to cover type.

Middleton's dispersion ratio and Anderson's surface aggregation ratio were used as indices of potential erodibility in Willen's study. The dispersion ratio was significantly related only to parent rock type. Soils developed from granodiorite were, based on the dispersion ratio, more erodible than those from basalt, and those developed from quartzite were least erodible. Based on the surface-aggregate ratio, the sequence was granodiorite with the highest potential erodibility, followed by quartzite and basalt.

Potential soil erodibility was greatest for soils under grass, followed by brush, pine, and fir. West slopes were more erodible than south slopes, followed by north and east slopes. Soils at high elevations were more erodible than soils of the same derivation at low elevations.

Wooldridge (1965) used mean aggregate size as an index of erosion on basaltic soils. He found this index a good guide in assessing erosion hazard, due to its sensitivity to changes in vegetative cover and its strong relation to organic matter content, bulk density, and porosity, soil properties known to be related to soil tilth and structure.

Anderson (1949) derived an equation to predict annual erosion from California watersheds, in which erosion was related to the maximum yearly peak discharge, the area of the main channel of the watershed, and the cover density of the watershed. In a later study, he reported a more comprehensive equation which included as independent variables, information on the slope of the channel, the soils, roads, land-use pattern, and the character of the hydrograph (Anderson 1960, 1965).

The estimating of sediment production on the basis of soils, topography, and forest cover is a form of erosion hazard rating. The equations constructed by Anderson (1949, 1960, 1965) estimated the volume of sediment from watersheds given the values of the above variables. A proposed change in land management, e.g., clear cutting part of the watershed or building roads, could be used in the equation to predict the sediment production likely to result; in reality, an erosion hazard rating.

Bullard (1962) carried out a study to estimate sediment production on the Umpqua River basin in Oregon. Two watersheds were chosen as standards, one given a very high rating with regard to erosion and

sediment production, the other given a low rating. Other watersheds were rated by comparison to these standards according to observations on channel, slope, and road conditions checked against available sediment sampling data. Geologic maps and aerial photos were used to extend the rating to areas not visited.

The author stated that though the sediment production ratings were guided to some extent by sediment sampling data, good correlation did not exist between them. The total sediment of all the rated watersheds was calculated on a per square mile basis. However, as sediment sampling data did not exist for the whole basin, a comparison of actual and calculated sediment production could not be made. The author concluded that the calculated production should not be considered as within less than $\pm$ 30 per cent. The rating method was highly subjective and does not seem capable of producing figures on sediment production in which confidence could be justified.

Regression theory states that predicted values will be more precise when derived from independent variables than when derived directly from correlated variables. Because of this, estimates of erosion hazard based on independent variables are more precise than those based on related variables such as soil topography, climate, and vegetation, according to Alvis (1961). He presented a theory to attempt "to reduce soil erosion into its fundamental forces" (p. 32), stability capacity of soil and moving capacity of an external agent. The first expresses the capacity of the soil to resist movement, its components being cohesion

of the individual soil aggregates, friction between the surface aggregates, and the mass of the average surface aggregate. The second concerns the erosive agent, and its components are mass and velocity.

Stability capacity and moving capacity are independent of each other and their relation to erosion is fixed. Alvis stated that this method of rating erosion hazard has advantages in addition to its being based on regression theory. If each of the two parts is reduced to its components, factors affecting erosion could then be related to the individual components on a rational rather than empirical basis. An example of the type of equation derived from this theory is one for water erosion hazard during the most intense probable rainfall period:

$$Eea = 1/2\ MV^2 = 1/2\ (Mr \times Vr^2) + 1/2\ (Mp \times Vp^2)$$

where Eea = the kinetic energy of the erosive agent
M = mass
V = velocity
Mr = peak resultant runoff mass
Vr = peak resultant runoff velocity
Mp = peak rainfall mass
Vp = rainfall velocity

The author concluded that equations such as this could be refined as knowledge of erosion grows, and that at any stage of knowledge, hazard ratings based on the fundamental elements of erosion will theoretically be the most accurate.

Erosion Control

As shown by many studies of erosion and streamflow, a strong relationship exists between plant cover, streamflow, and soil stability.

Control of vegetation is a natural and usually very efficient way to maintain or restore soil stability. In some cases, however, revegetation is not sufficient by itself to re-establish the hydrologic norm of a watershed but must be supplemented by engineering structures.

The rehabilitation of damaged watersheds is often an expensive job. On forest areas it will require reforesting understocked areas, protecting against fire, and improving roads that are in unsatisfactory condition. Soil disturbance that has resulted in a concentration of overland flow must be stabilized by vegetation, aided where necessary, by mechanical structures.

In 1960, wildfire burned over part of the San Dimas experimental forest. Rice et al. (1965) conducted studies on the areas burned to obtain a quantitative evaluation of several mechanical and vegetative land treatments. Watersheds seeded to low density perennials had higher sediment production than did watersheds treated in other ways. Planting annual grasses, the report stated, may be justified as an emergency erosion control measure because of its low cost and the speed with which it can be applied.

Of the mechanical treatments to reduce erosion, side-slope stabilization and contour trenching were found to be superior to channel stabilization. This supports the view that measures that prevent the concentration of water are more effective than those aimed at reducing the erosive effect of channel flow.

In June, 1959, the Three Bar experimental watersheds in Arizona were swept by fire. Pase and Ingebo (1965) described the early results

on sediment and water yields of seeding by helicopter to grasses and sweet-clover. The control area was allowed to return to the natural shrub cover of chaparral, live oak (Quercus turbinella Greene), and birch-leaf mountain mahogany (Cerocarpus betuloides Nutt.). The seeded area was sprayed for four successive years, beginning in 1960, to destroy the resprouting natural shrubs. Spray was applied only to the shrub area so that little damage was done to the stand of grass.

Runoff was highest from both watersheds in the first year after the fire. Runoff from the control watershed had decreased to pre-fire rates by the end of the fourth year. Runoff from the seeded watershed has been significantly increased for the last three years, compared to the control. Sediment yields from both watersheds increased greatly immediately after the fire, but have since declined to about pre-fire levels. Sediment production is greater at present, however, from the watershed in natural cover than from the seeded watershed.

In Michigan, 115 areas were treated to stabilize streambanks and the effect was compared to 113 untreated areas (Striffler 1960). Bank treatment consisted of rock riprap, seeding, and fertilization. The study showed that treatment reduced bank erosion by 40 per cent and stabilized waterlines. The key to success appeared to be stabilization of the waterline by rock riprap or other mechanical means.

The mechanical measures which may be used to supplement vegetative measures are outlined by Bailey and Copeland (1961). Debris basins reduce the velocity of channel flow allowing debris and sediment to settle out. Contour terracing retains rainfall on the land where

it falls, thus preventing overland flow and erosion, and creates favorable moisture conditions for the re-establishment of vegetation. Small check dams are sometimes constructed across the trenches.

A modification of contour terracing is pitting the soil surface with short, V-shaped trenches, at regular intervals. Seeding with grasses or legumes must follow pitting or terracing, otherwise the trenches would soon fill with sediment and lose their value.

In disturbed stream channels, check dams or precast cribbing are often used to control channel flow. Sections of interlocking cribbing are placed across the channels and because of their open structure permit water flow but retain sediment. Design and construction of prefabricated concrete were described by Heede (1965) and of rock check dams by the same author (1966).

Bailey and Copeland (1961) discussed vegetation and engineering structures in erosion control and concluded that three kinds of action were needed: (1) wider public understanding of the importance of forested watersheds, (2) a speeded up and more vigorous application of known and tested measures of watershed protection and rehabilitation, and (3) more basic and applied research to fill the gaps in our knowledge.

6. WATER QUALITY

Eschner and Larmoyeux (1963) defined water quality as the sum of the measurable characteristics of the water. By this definition any change in the character of water which is not measurable does not affect

the quality. The characteristics of water that are usually measured are color, turbidity, temperature, pH, and specific conductance. As interest in other characteristics develop, because of new uses for the water for example, techniques will be developed to measure these characteristics. That is, the standards by which water quality is measured change as uses and techniques develop.

Perhaps a better definition of water quality for the purpose of this discussion is the sum of the characteristics of water that describe its usefulness for a specific purpose (Bullard 1963). Consider the example of muddy water. Its value is reduced because some industries cannot use it, people will not drink it, reservoirs fill up with sediment as the result of it, and it has a detrimental effect on fish. (The fishery aspect will be discussed in the next section).

Bullard attempted to define quality as the degree of excellence the water possesses. However, the sum of the measurable characteristics is generally accepted as defining water quality, and is the more useful definition.

The influence of the forest on water quality can be summarized by four statements:

(1) The amount of sediment in streamflow is affected by forest cover,

(2) The color and taste of water is affected by logging debris in stream channels,

(3) Water temperature is affected by the removal of trees along

streambanks and by forest-cover changes that alter the proportion of water that reaches stream channels by surface flow,

(4) Timing of runoff is affected by forest-cover changes. Timing is included in water quality by the second definition given above.

Changes in water temperatures brought about by logging are not likely to affect the quality of water for human use but are important in fisheries, and will be discussed in the section on forests and fish. Timing has been discussed in the section on streamflow and will be considered further in the section on forests and fish.

The influence of vegetation on erosion was discussed in the previous section. Conversion of forests to other land uses generally favors faster erosion rates, higher sediment loads in streams, and impairment of water quality.

The turbidity of water is its capacity for absorbing or scattering light and is measured by the concentration of fine silica which produces an equivalent effect (Camp 1963). Another method of determining turbidity is the Jackson candle method by which the depth of water through which the flame of a candle disappears is converted to an index number. For example, if the flame disappears when viewed through 72.9 cm. of the sampled water, the turbidity is 25; through 10.8 cm. the turbidity is 200. These units were originally intended to be equivalent to p.p.m. (parts per million) of standard silica suspensions, and therefore turbidities are often expressed in p.p.m. Numerically these are the same as turbidity units (Nordell 1961).

Turbidity may result from living or dead algae or other organisms, but it is generally caused by silt or clay. The amount and character of turbidity depend on the type of soil over which the water has run and the velocity of the water (Steel 1960). As the velocity decreases, the heavier particles settle out, but the finest clay particles may require months to settle out of still water.

For drinking water, the United States Public Health Service standards are widely used. These specify that the turbidity shall not exceed 10 units for culinary and drinking purposes (Nordell 1961). Turbidity tolerances for industrial purposes run from as low as two for carbonated beverages to 50 for paper produced from groundwood pulp. A turbidity of 20,000 or more can be tolerated for fish propagation. The effect is an indirect one in that turbidity reduces light penetration and this limits photosynthesis and algal growth, the lower links in the food chain on which the fish depend (Camp 1963).

Some rivers have turbidities as high as 60,000, and extremes of over 100,000 have been measured (Nordell 1961).

Effect of Logging on Water Quality

Logging. Logging greatly affects water quality not so much because of the conversion of forested areas but because of the methods employed. The use of heavy machinery in areas formerly inaccessible because of steep slopes and rugged terrain disturbs some of the soil surface to varying depths and degree. The result is greatly increased sediment discharge. Studies in Oregon have shown that 10 years of

logging in one watershed produced 80 per cent greater sediment discharge than an unlogged adjacent watershed (Anderson and Wallis 1965). In the Sierra Nevada the sediment discharge one year after logging was 17 times the pre-logging rate; two years after, 5 times (Rice and Wallis 1962).

Soil disturbance and the resulting erosion vary considerably for different logging methods. Garrison and Rummell (1951), in eastern Oregon, found that exposure of mineral soil averaged 20.9 per cent of areas logged with tractor, 15.2 per cent of areas logged with cables, and 11.8 per cent of areas logged with horses. In the California pine zone 22 per cent of the area was bare ground after logging by crawler tractor (Fowells and Schubert 1951). Wooldridge (1960) reported a comparison of logging by tractor and by the Wyssen Skyline Crane in Washington. Mineral soil was exposed on 22.2 per cent of the area logged by tractor and only 5.4 per cent of the area logged by Skyline Crane.

Dyrness (1965) reported a study which was carried out in the H.J. Andrews Experimental Forest in Oregon to assess the effects of high-lead and tractor logging on soils with similar undisturbed surface conditions. Surface area of four clearcut units was classified by four degrees of disturbance: undisturbed, slightly disturbed, deeply disturbed, and compacted. The tractor logged area had about three times more area within the compacted class than did the high lead area (27 per cent against nine per cent), and a corresponding decrease in the amount in the undisturbed class. Deeply disturbed and compacted classes

had higher bulk densities, i.e., decreased soil porosity. The author concluded that tractor use results in increased runoff and erosion, but this is minimized if slopes do not exceed 20-30 per cent.

A study in Russia showed that after a shower of 63 mm. (2.5 in.), lasting two days, erosion was 5.3 kg./ha. (4.7 lbs./acre) in forest stands of 60-70 per cent density, 15.1 kg./ha. (13.5 lbs./acre) in stands of 20-30 per cent density, and 32.1 kg./ha. (28.7 lbs./acre) in cut-over area (Molchanov 1963).

In the northern Caucasus and in the Urals, hauling with horses caused soil erosion of 200 cu.m./ha. (106 cu. yd./acre) on slopes of 10° or less, but as much as 550 cu. m./ha. (291 cu. yd./acre) on slopes of 10° - 20°; and with tractors the values were 550 cu.m./ha. (291 cu. yd./acre) and 780 cu. m./ha. (413 cu. yd./acre) (Molchanov 1963).

The cutting of timber in itself does not seem to affect water quality, although there is some evidence that increased streamflow resulting from timber cutting may cause stream-bank erosion and thus increase sediment production (Packer 1965). Log skidding, particularly where equipment is used that deeply disturbs the soil mantle, often increases sediment production, however. The degree of increase depends on many factors such as the location of skidways in relation to stream courses, the adequacy of drainage facilities, the size of storms, and the nature of the terrain and soil.

Logging, even when carried out on steep terrain, does not necessarily reduce water quality as was shown by experiments carried

out on the Fernow Experimental Forest in the mountains of West Virginia (Hornbeck and Reinhart 1964). It was pointed out in these studies that most of the damage to water quality occurs during and immediately after logging. Where skidways become revegetated slowly, however, impairment of water quality can continue for many years.

Stream channels. Logging debris in stream channels can discolour water and cause a disagreeable taste. This is relatively unimportant where the proportion of the watershed that has been logged is small, and where the dilution effect of large reservoirs occurs. Where the opposite is the case, usually confined to small communities where the water supply is taken directly from the stream, the quality of water for drinking purposes is definitely impaired.

The hazard associated with debris in stream channels is the log jam that sometimes occurs during runoff. During high water the jams often break up sending a mass of logs, rocks, mud, and water downstream causing damage to property and changing channel alignment.

The question arises as to the size of stream from which it is necessary to remove logging debris. Rothacher (1959) pointed out that to answer the question information is needed on maximum flow from the stream and the size of stream that can move logs. He suggested that any stream fed by a watershed greater than 40 acres should have logging debris removed.

Roads. Road-building associated with logging is largely responsible for the increased sediment discharge of logged areas. Modern equipment has made road building easy enough that often roads are built piece-meal

without an overall plan. This may result in more miles of road than otherwise needed, and often the location is poor.

Silen and Gratkowski (1953) reported that 12.4 per cent of the total area logged in a study conducted in Oregon was disturbed by road building and landing construction. Building of 1.65 miles of logging road on one of the watersheds of the H.J. Andrews Experimental Forest in Oregon caused sediment discharge from the first rainstorms after construction 250 times that of an adjacent undisturbed watershed. Discharge during the following two years was about twice that before road construction (Frederickson 1965).

The reasons for increased sediment after road building include: (1) roads often intercept seepage and concentrate the flow, and (2) road surfaces often have lower infiltration rates due to the disturbance and compaction of the soil.

A logging system requiring fewer miles of road would be expected to contribute a smaller amount to stream sediment. In the comparison of tractor and Skyline Crane logging it was shown that the truck road system needed for logging by Crane was about 10 per cent of that needed by standard methods (Wooldridge 1960). In the same study it was reported that transporting logs across a stream channel caused little disturbance with Skyline Crane but even well-planned crossings produced silt and debris during runoff periods after tractor logging.

Eight 1/100 ac. plots were set up on the fill slope of a newly-constructed highway in Idaho to determine the effect of various treatments on erosion from side slopes (Bethlahmy and Kidd 1966). Those

plots that were seeded and fertilized produced the greatest amount of erosion, an average of 97 lbs. during the 322 days in which the research was in progress. This figure is larger by 13 lbs. than that for the control plot on which no control measures were taken. The addition of straw mulch to the seeded and fertilized plots was responsible for a reduction of erosion to 24 lbs. Seeding, fertilizing, straw mulching, and netting reduced erosion to 0.5 lbs.

In many parts of North America, especially in mountainous regions, secondary roads are "put-to-bed" after harvesting of timber has been completed. This usually involves removing temporary culverts, out-sloping the road surface, installing earthen cross drains at prescribed intervals, and perhaps seeding the road surface and cut banks.

In recent years, the outsloping of road surfaces and removal of berms or curbs have been questioned, especially on "incurved" sections of road in steep terrain. In such locations surplus road material is usually castover and comes to rest in long unstable fills extending for 100 ft. or more down the ravine. Such fills are usually shorter on side slopes below "outcurved" sections of road.

In a study carried out on a newly-built, secondary logging road in Idaho, both concepts were evaluated (Haupt et al. 1963). Observations indicated that insloping the road surface was more desirable than outsloping as an erosion-control measure. The inslope should be designed

to lead away as much water as possible from the long fill on the incurve of the road.

In West Virginia, on a clearcut watershed with unplanned skid roads and no provision for drainage, turbidity was 56,000 p.p.m. (parts per million). Partial cutting of an adjacent watershed with well planned skidroads resulted in turbidity of only 25 p.p.m. (Reinhart et al. 1963).

A study in central Idaho relating sedimentation to logging indicated that haul roads were the major contributors of sediment (Haupt and Kidd 1965). The amount of sedimentation was not related to total area bared by roads but to the severity of disturbance. Sedimentation reaching streams originated primarily on haul roads and not skidroads, and the proximity of the road to the stream affected the frequency with which sediment reached that stream. Where buffer strips between roads and streams were greater than 30 ft. wide, sedimentation did not reach the stream.

Trimble and Sartz (1957) studied the width of strip between stream and road in New Hampshire by measuring the distance that sediment travelled from the road and relating this to slope. They devised a rule-of-thumb for the general situation where it is accepted that some sediment will occasionally reach the stream: the width of strip should be 2(slope per cent) + 25 ft. For municipal watersheds the strip should be 4(slope per cent) + 50.

A study was conducted in Idaho relating sediment-flow distance to the four significant road and downslope characteristics: slope obstruction index (a function of sediment flow distance, slope obstructions, and plant cover), cross-ditch interval, embankment slope length, and road gradient (Haupt 1959). A multiple regression equation was developed which, with substitution for the dependent variables, would estimate the width of protective strip needed to dissipate sediment movement that may occur from a proposed road.

Guides were developed from the prediction equation giving: (1) The minimum slope distance to the centre line of the proposed road, given road and side slope gradient and aspect. This should prove useful in locating roads far enough away from streams so that sediment flowing from the road does not reach the channel, (2) the maximum permissible cross-ditch interval for roads having protective strips narrower than 200 ft., given slope exposure, embankment slope length, width of protective strip, and road gradient, (3) the minimum number of slope obstructions needed below cross ditches spaced 30 ft. apart, given road gradient, embankment slope length, and width of protective strip.

Kidd (1963), working in Idaho, conducted a study to determine the optimum spacing of water bars on skidtrails and the most effective structures for controlled disposal of sediment-laden water that originates on skidtrails. The results of his study indicated that erosion was greater from skidtrails located in ravines than from those on sidehills. Optimum spacing of control structures, such as log water bars and cross ditching, depends on the slope and location of the skidtrail

as well as soil parent material. Structures that divert water off the skidtrail onto undisturbed forest floors are superior to those that only retard water movement and filter out sediment along the skidtrail.

Wallis (1963), in prescribing logging methods to protect water quality, cautioned that each area is different and that many variables besides logging method influence sediment discharge. His warning can be applied to all aspects of erosion control. The results of studies conducted in a particular location cannot be assumed to apply in every situation. However, such studies should be considered and methods of erosion control suggested by those studies should be applied where they seem applicable. For example, the study by Haupt et al. (1963), concerning insloped road surfaces, warrants consideration in road construction even though it cannot be assumed that the method applies in all situations.

Actual prescriptions for road building, as well as for other aspects of logging, will be covered in Chapter V which deals with watershed management in British Columbia.

Fire. Slash is often burned after logging to reduce fire hazard, to facilitate regeneration, or to make the area amenable to planting. The degree to which these objectives are met by slash burning will not be discussed in this section, but the effect on erosion will be considered. (For a comprehensive discussion of the effects of forest fires see Ahlgren and Ahlgren 1960, Davis 1959, and Jablanczy 1963).

Evidence that burning decreases the infiltration capacity of the soil was reported by Rowe (1941). An increase in infiltration rate was reported by Scott (1956) and Burgy and Scott (1952) who attributed this to formation of larger-sized aggregates in the soil surface. Differences in the severity of the burn are probably largely responsible for what appears to be conflicting evidence. Other variables influencing the evidence may be differences in the characteristics of the soils under investigation and the moisture content of the soils and the surface fuels at the time of burning (Dyrness 1963).

Austin and Baisinger (1955) reported that moisture-holding capacity of the top one-half inch of soil significantly affected by the fire was reduced by 33.7 per cent after slash burning. Dyrness et al. (1957) reported similar evidence and concluded that it was due to less organic matter in the soil after burning.

Tarrant (1956) reported that severe burns reduced percolation rates by over 70 per cent whereas light burns increased the rates. In the areas examined in Tarrant's study less than five per cent of the burned area was severely burned. Dyrness et al. (1957) reported only eight per cent of a slash-burned area severely burned. Bethlahmy (1960) pointed out, however, that the effect on erosion of these severely burned areas may be far in excess of their insignificant areal extent.

Croft (1946) reported that extreme floods in Utah were traced to severe fires and overgrazing on only 2 to 10 per cent of the headwater area.

Most of the evidence indicates that light burning has little effect on water movement through the soil profile. If the litter has been burned, however, infiltration capacity can be expected to decrease with time as the surface structure of the mineral soil is broken down by rain drops and the pores clogged by sediment. The result may be increased peak flows as reported by Rich (1965) for a wildfire in ponderosa pine on Workman Creek, Arizona.

Erosion would be expected to increase after fire due to greater surface runoff caused by reduced infiltration rates and due to the looseness of soil particles caused by decreased clay (Dyrness and Youngberg 1957, Sreenivasan and Aurangabadkar 1940) and organic matter content (Austin and Baisinger 1955, Dyrness and Youngberg 1957, Youngberg 1953). Accelerated erosion after burning has been reported by many investigators among whom are Anderson (1955), Anderson and Trobitz (1949), Connaughton (1935), Hendricks and Johnson (1944), Pillsbury (1953), and Sartz (1953). The increased sediment in water supplies resulting from fires, then, affects water quality, and often to an extreme degree.

7. FORESTS AND FISH

The value of the fisheries must include the recreational benefit derived by man as well as the economic benefits and costs. Important in British Columbia are salmon (sockeye, pink, coho, spring, and chum) and steelhead trout (Fraser River Board 1958). These migrate from stream to sea, returning to spawn in stream gravels after one or more years in the ocean. After emergence from the gravel as fry the fish spend

different lengths of time in fresh water depending on the species, so that the freshwater environment has greater importance for some species.

Water Yield and Regime

Discussion of the forest and fish mainly concerns the influence of logging on the yield, regime, and water quality of streamflow. The effect of logging on water yield was discussed in the section on streamflow. Most studies have shown that clear cutting increases yields by four to eight inches, but the effect on regime is not as well defined (Jeffrey 1965).

Some studies indicate that cutting causes greater low flows (Eschner and Larmoyeux 1963, Kittredge 1948, Meginnis 1959, Rothacher 1965a, and Shirai et al. 1954). This may be explained by precipitation being well distributed through the year so that low flows are probably due not to a lack of precipitation but to high evapotranspiration drain (Eschner and Larmoyeux 1963). Greater minimum flows, where low flows are critical, would improve the survival of fish during this period and favor higher fish populations. Greater flows in summer would provide greater water surface for catching terrestrial insects, greater algae and insect-producing bottom area, and more room for the fish (Chapman 1963).

The results of some studies indicate that removal of the forest causes higher peak flows (Bates and Henry 1928, Hirata 1929, Hoyt and Troxell 1934, and Tennessee Valley Authority 1962). Higher flows may

result in channel scour and cutting, movement of stream-bottom gravels, and higher sediment loads. Erosion and sediment discharge caused by logging and road building was discussed in the sections on erosion and water quality.

Channel scour and cutting can remove established spawning beds, isolate others, and add to the debris transported by the stream and dumped in other locations. Gravel deposition on incubating embryos may be so deep that the hatched fry suffer high mortality in emerging from the gravel (Chapman 1963). Gravel movement may kill fish embryos, algae, and aquatic insects, thus decreasing future populations of fish while reducing present food supplies.

Sediment may cover stream-bottom fauna and fish eggs, reduce the size and number of gravel interstices in which small fish hide, and lower the depth, i.e., decrease the living space, for large fish. High sediment loads may cause inflammation of the gill membranes of young fish and their eventual death. The growth of green plants decreases as sunlight is filtered out of the water by sediment.

Fish embryos in spawning gravels need dissolved oxygen and a velocity of intra-gravel water sufficient to maintain the oxygen supply and to carry away metabolic waste products. Sediments reduce the velocity of intra-gravel water thus reducing the oxygen available (Peters 1962). The decomposition of organic sediments decreases the oxygen content even more.

Debris in Channels

Logging debris left in stream channels was discussed in the section on stream channels. Such debris, whether it be normal debris or the result of logging, often results in log jams. These often act as barriers to migration but can also provide pools for resident fish. When log jams break, the stored up water and debris rushing downstream often change the channel alignment. The effects of this action are discussed in the previous section. Probably the main hazard to fish resulting from organic matter in stream channels is the reduction of dissolved oxygen caused by its decomposition.

Water Temperatures

High water temperatures in summer are often the factor limiting distribution and survival of trout. Limiting high temperatures of from 75° to 83° F. for brook, brown, and rainbow trout are cited by Eschner and Larmoyeux (1963) but these vary with the pH, dissolved oxygen, and condition of the fish.

Clear cutting on the Fernow Experimental Forest increased maximum summer water temperatures by 8° F. and decreased minimum winter water temperatures by 3.5° F. (Eschner and Larmoyeux 1963). Removal of riparian vegetation may also cause increased maximum summer water temperatures (Chapman 1962). Lower winter temperature minima may result from the loss of insulation provided by streamside vegetation (Green 1950). This could extend the incubation period for fall- and winter-spawning species, thus increasing the period of vulnerability of embryos to unfavorable conditions.

Chapman (1963) suggested the possibility of increased spring and summer temperatures causing accelerated algal production and fish metabolism. Where streams are cold the effect of increased temperature might be advantageous, but an increase in the temperature of already warm streams would likely prove detrimental in net effect (Jeffrey 1965).

Removal of riparian vegetation also cuts down on the food supply of aquatic insects provided by terrestrial plants. It would also tend to reduce the number of terrestrial insects reaching the water surface. Chapman (1963) estimated that over 60 per cent of the energy reaching coho salmon originated with terrestrial plants. This is estimated in the following manner. Thirty per cent of the cohos' diet is terrestrial insects. The other 70 per cent is aquatic insects, 50 per cent of whose diet is terrestrial plant material. On the other hand, however, vegetation removal should stimulate algal production by increasing the light reaching the stream.

CHAPTER III. ADMINISTRATION OF WATER RESOURCES

1. JURISDICTION

British North America Act

An act for the union of Canada, Nova Scotia, and New Brunswick, and the government thereof; and for purposes connected therewith; otherwise known as the British North America Act, 1867, is often blamed for many of the problems involving the federal and provincial governments (Information about the B.N.A. act is from Sirois 1940).

With specific regard to the water resource, "the British North America Act is the root of today's dilemma" (C.A.A.E. 1966, p. 10). This statement brings forth the following questions:

(1) Are there jurisdictional problems with the water resource?

(2) If so, how do they manifest themselves?

(3) Is the B.N.A. act responsible?

(4) What solutions can be proposed?

Relevant sections of the act. The sections of the B.N.A. act relevant to the water resource are Sections 91, 92, and 95. Section 91 lists the classes of subject that are the exclusive legislative responsibility of the parliament of Canada. Provincial legislative responsibility is listed in section 92, as well as section 95 which includes laws related to agriculture.

Section 91 of the B.N.A. act includes navigation and shipping (para. 10), sea-coast and inland fisheries (para. 12), and peace, order, and good

government in Canada. Section 92 includes as provincial powers, legislation regarding the management and sale of public lands belonging to the province and the timber on them (para. 5), local works and undertakings other than transportation lines connecting provinces or between the province and another country (para. 10), and generally all matters of a local or private nature in the province (para. 16) (Sirois 1940).

Interpretation. The administration of water resources in Canada has been the result of the provisions of the B.N.A. act and their subsequent interpretation. The administration, control, and development of water resources within a province are the responsibility of the province. However, the federal parliament has jurisdiction over water where navigation and fisheries are concerned, as well as water in national parks, Indian reserves, along or crossing the international boundary, and, in some cases, over inter-provincial waters.

Obviously the expression of the powers of the two levels of government is in general terms even yet open to interpretation in many cases. This was considered necessary in a federation to allow flexibility to the constitution (Lederman 1962). The price of this flexibility is sometimes duplication and omission, as well as conflict between the levels of government.

2. EVOLUTION OF WATER POLICY

Canada

Evolution of water policy in Canada came about by restatement of policy objectives as the need became apparent. The needs were often brought to light by forestry and conservation conferences which had great influence on

water policy at the federal level.

Early conferences. The first Canadian Forestry Convention was held in 1906, presided over by the Prime Minister, Sir Wilfrid Laurier. Among the topics discussed was the relation of forests and water. The recommendations made by the conference included:

(1) Forests should remain under crown ownership.

(2) Greater emphasis should be placed on protection of the forest from fire, disease, and insects.

Representatives from Canada attended the North American Conservation Conference held in Washington in February, 1909. From this conference came a declaration of principles which were an important influence on agencies later established in Canada to deal with natural resources. One of the recommendations was that a study of multiple use of the water resource be undertaken. Another was that a conservation commission similar to those in the United States be set up in each of the countries represented.

Conservation Commission. In May, 1909, three months after the North American Conservation Conference, the Canadian cabinet approved the principle of establishing a commission of representatives from federal and provincial governments and universities. The commission had six main committees: forestry, lands, fish and wildlife, water, minerals and fuel, and public health. The committee on forestry included land use and watershed studies in their program. The water committee dealt mainly with water power and domestic water supplies.

During the period 1909-1921 the Conservation Commission stimulated interest in natural resource topics and provided a public forum for discussion.

The commission gradually became more oriented toward research, a function not intended by its charter. This created friction with federal agencies set up to carry out research responsibilities and was one of the reasons for abolishing the commission in 1921.

Reconstruction Conference. Much of the work which had been carried out by the Conservation Commission became the responsibility of federal agencies. The coordinating function was neglected, however, and the effect on Canadian water policy is still apparent.

Natural resource studies on the scale carried out by the Conservation Commission were not revived until the Reconstruction Conference of 1945. In 1943, the federal government, aware of the great changes in Canada's economy brought about by the war, set up the Advisory Committee on Reconstruction to study economic and social life of the country. Among the recommendations made by this committee to the National Reconstruction Conference were:

(1) Develop conservation measures to protect renewable resources.

(2) Carry out surveys of resources.

(3) Enact a dominion forest act to divide forestry work between the federal and provincial governments.

(4) Carry out studies of water resources.

The National Conference adopted in large part the recommendations of the advisory committee. This led to a statement of policy on the part of the federal government accepting as its responsibility the basic surveys and research essential for the development and management of natural resources and for the development and conservation of resources that are interprovincial in nature (e.g., the protection of regional watersheds). The federal

government would provide assistance, by specific agreement, to provinces for resource development (Thorpe 1962).

Resources for Tomorrow Conference. The most ambitious of resource conferences held in Canada was the Resources for Tomorrow Conference of 1961. The Prime Minister, the Rt. Hon. John G. Diefenbaker, announced in February, 1958, that a national conference on conservation would be called. The steering committee met in the same year to plan for the conference whose objectives evolved during the next three years ending up with the following:

(1) Identification of the major problems requiring attention in the renewable resources field.

(2) Examination of what is being done to solve these problems.

(3) Clarification of the impediments to further progress and possible courses to achieving solutions to these problems (Kristjanson 1962).

The water resource was examined in detail at this conference. Problems in the management of the resource were isolated and recommendations designed to alleviate these were set out. The conference agreed that a regular exchange of views on resource management was necessary.

Canadian Council of Resource Ministers. To meet this need the Canadian Council of Resource Ministers was formed in February, 1962, to allow the resource ministers of the 11 senior governments to meet several times a year to discuss resource policy. The council is not an executive agency but provides a forum within which the resource policies of member governments are examined and coordinated. The 11 governments agreed also to establish the necessary coordinating machinery to allow cooperation between

the various departments involved in resource management (Can. Coun. Res. Ministers 1965).

The first project of the council was a study of 69 federal-provincial shared-cost resource agreements. Deficiencies were examined and a set of guidelines drawn up for use in future resource agreements.

Concerning water, the council believed that a serious study of this resource required, first, an understanding of present management. The council sponsored the national conference "Pollution and our Environment", held in Montreal in October-November, 1966. The aim of this conference was to assist governmental and industrial agencies in establishing coordinated programs for pollution control.

The council was instrumental in having the UNESCO-sponsored International Hydrologic Decade (IHD) backed by the federal and provincial governments. The object of this decade, 1965-1974, is "to accelerate the study of water resources and the regimen of waters with a view to their rational management in the interest of mankind; and to improve our ability to evaluate resources and to use them to the best advantage" (IHD 1965a, p.3).

Federal-Provincial Premiers' Conference. The federal government's gradually-evolved water program was set out at the Federal-Provincial Premiers' Conference in Ottawa, July, 1965. The statement, acknowledging that water is vital to Canada's development and that there are regional differences in water endowment, described the policy as endeavoring "to foster both a wise management and optimum use of water throughout all of Canada and on behalf of all Canada's people" (Federal-Prov. Premiers' Conf. 1965, as quoted by C.A.A.E. 1966).

At the Federal-Provincial Premiers' Conference of 1965, the federal government's water program was described as consisting of inventory, basic and applied research, development of protective regulations (e.g., pollution control measures), development of specific projects (e.g., water diversion for irrigation), consultation with the provinces and the United States, and publication of scientific and technical material.

British Columbia

British Columbia became the sixth province of the Dominion of Canada in 1871, Manitoba having joined the original four in 1870. Five years previous to entering the confederation the crown colony of British Columbia had been established by union of Vancouver Island, Queen Charlotte Islands, mainland British Columbia, and Stickeen Territory.

Water policy in British Columbia did not evolve as at the federal level but because the provinces administer the water resource, evolution took the form of a series of additions and amendments to water legislation.

Gold Fields Act. Legislation regarding water administration in British Columbia began with the Gold Fields Act of 1859. This act gave power to the Gold Commissioner to grant exclusive rights to the use of defined quantities of water, not necessarily to a riparian owner. This denial of riparian rights is an important feature of British Columbia law. The act stipulated that the water user pay rental to the crown, and that cancellation of his right would result from non-use or waste of water. The act allowed the sale of water by the holder of the right, as long as fair and non-discriminatory prices were charged.

The Water Privileges Act of 1892 dealt with water uses not covered by the Gold Fields Act nor the Land Ordinance of 1865 which concerned irrigation. The importance of this act is the declaration that all water in streams belonged to the province.

The objective of the Water Clauses Consolidation Act of 1897 was to consolidate the various laws dealing with water. It also stated what had been implied in earlier legislation, that water rights were conditional on reasonable use of the purposes for which the rights had been granted. This provision did not apply, however, to municipalities for water works systems.

Water acts. The first Water Act by that name was enacted in 1909. It created the Board of Investigation to hear claims of all persons holding water rights and to prescribe the terms for new licences. Amendments to the Water Act, in 1913, divided the province into eight water districts each supervised by an engineer. The amendments of 1914 further clarified the principles established by earlier legislation, and definitely ended any riparian rights for which licences had not been granted before June, 1916.

The Board of Investigation, established in 1909, was abolished by the Water Act of 1939, and most of its functions were vested in the Comptroller of Water Rights. This act has changed little since 1939, one of the most important changes being an amendment in 1960 to include ground water in the act. In the past few years studies have been carried out on ground licencing and procedures and recommendations have been drawn up. No ground water licences have yet been issued.

Water Resources Service. In 1962, the Department of Lands and Forests Amendment Act created the Water Resources Service responsible for the administration of the Water Act and all matters pertaining to the water resources

of the province. In 1963 the South Okanagan Lands Project was transferred from the Department of Agriculture to the Water Resources Service. This irrigation project, developed and administered by the province, serves about 5,000 acres of irrigated land and provides the domestic water supply for Oliver, B.C.

In 1964 the Water Resources Service began work on some of the problems of flooding and erosion. Increased responsibilities were taken on by the Water Resources Service in 1965 when the Pollution-Control Board was transferred from the Department of Municipal Affairs, and the Office of Inspector of Dykes from the Department of Agriculture (B.C. Nat. Res. Conf. 1964; B.C. Water Res. Serv. 1964, 1965, 1966; Shelley 1957).

3. AGENCIES ADMINISTERING THE WATER RESOURCE

Knowledge of the various responsibilities of federal, provincial, and other agencies regarding water is necessary for an appreciation of the complexities of water resource administration and the problems associated with this administration. The number of agencies involved is remarkable. The B.N.A. act has certainly influenced the number of agencies because of its division of responsibility between federal and provincial governments, but it can hardly be blamed for the many agencies at both levels of government.

The number of agencies dealing with water is indicative of the implications of water in our daily lives. Water is used for such diverse purposes as domestic supplies, irrigation, and hydro power, and to suggest that one agency should administer the resource for all three uses would be

extreme. This is not to suggest that the present administrative set-up is the most efficient, nor that overlapping and omission do not occur.

Federal Agencies

The main source for this and the following section is the background paper for the Resources for Tomorrow Conference by Patterson (1962). Until recently, ten separate federal departments were directly involved with the water resource. These included Agriculture, Fisheries, Forestry, Mines and Technical Surveys, National Health and Welfare, Public Works, Northern Affairs and National Resources, Transport, Trade and Commerce, and External Affairs. In addition, eight other federal agencies were involved: Atomic Energy Control Board, Canadian Maritime Commission, National Research Council, National Harbours Board, Central Mortgage and Housing Corporation, Saint Lawrence Seaway Authority, Northern Canada Power Commission, and the International Joint Commission.

These agencies carried out work involving surveys and mapping of the water resource, research, administration and regulation, engineering, liaison, negotiation of agreements, and advisory functions. Of all federal agencies, the Water Resources Branch of the Department of Northern Affairs and National Resources has been involved with the water resource to the greatest degree. Its chief duty has been the collection of data as well as administering the Dominion Water Power Act and regulations dealing with water resources of the Yukon and Northwest Territories, national parks, and Indian reserves.

A brief summary will be given to indicate the agencies involved with various aspects of the water resource. There is considerable overlapping of responsibility even between agencies at one level of government.

Five federal departments are involved with the water resource under the topic of navigation, but only two of these, Public Works and Transport, have responsibilities which go beyond basic data collection. Concerning flood control, six departments are involved, five of these with basic data collection and five (Northern Affairs and National Resources, Agriculture, Public Works, Transport, and Mines and Technical Surveys) with further responsibilities. Agriculture is the only department concerned with irrigation, other than basic data collection in which five other departments are also involved.

Five departments are involved in power development, only one of which deals solely with data collection. Seven departments deal with domestic and industrial water supplies of which the responsibilities of three (Northern Affairs and National Resources, Health and Welfare, and Agriculture) go beyond data collection. The Fisheries department alone has responsibilities concerning fisheries beyond data collection, for which five other departments are also involved.

In pollution control, seven departments are involved, four (Public Works, Fisheries, Health and Welfare, and Trade and Commerce) to an extent greater than data collection. Three of the five departments concerned with watershed treatment deal with the water resource in ways other than as data collection agencies. The departments are Northern Affairs and National Resources, Agriculture, and Forestry, and their responsibilities include erosion control, soil programs, and reforestation. Two of these departments, Northern Affairs and National Resources and Agriculture, with the Department of Fisheries have responsibilities in recreation and wildlife in which three other departments are also involved in data collection.

In 1965, five separate units in the Department of Mines and Technical Surveys united to form the Water Research Branch. Later in the same year a Resource Development Branch of the Department of Northern Affairs and National Resources was created and then transferred, along with the Water Resources Branch, to the Department of Mines and Technical Surveys.

It was announced in December, 1965, that a new department, that of Energy and Resources, was to be created to coordinate all national activity in the energy field. The Prime Minister, in his announcement, made the following explanation:

> Different forms of energy and different energy sources have been the responsibility of a number of departments and ministers. One focus of federal responsibility is needed, in order both to make possible closer cooperation with the provinces and with industry and more effective coordination of policy is needed in relation to resources generally. The new importance of water policy is particularly notable (C.A.A.E. 1966, p. 12).

Legislation following the announcement created the Department of Energy and Resources out of the Mines and Technical Surveys, and Northern Affairs and National Resources became the Department of Indian Affairs and Northern Development (Prince 1966).

These changes reflect the concern of the federal government with the administration of water resources. The effect on coordination of water resource activities in Canada remains to be seen, but the least that will result is a decrease of one in the number of federal departments involved in administration of the resource.

Provincial Agencies

In the province of British Columbia administration of the water resource

is primarily the responsibility of the Water Resources Service of the Department of Lands, Forests, and Water Resources. This service administers the Water Act which governs the issuing of water licences, required of all water users in the province. There are, however, five other departments, two boards, and two commissions also concerned with administration of the resource. Following is a brief summary indicating the provincial agencies involved with the water resources of the province.

Two departments are involved in flood control, Lands, Forests, and Water Resources, and Highways. Irrigation is the responsibility of four departments: Lands, Forests, and Water Resources, Highways, Agriculture, and Finance. Domestic and industrial water supply concerns the departments of Lands, Forests, and Water Resources, and Finance, as well as the Public Utilities Commission. The departments of Lands, Forests, and Water Resources, Finance, and Health have responsibilities dealing with pollution control.

Fisheries are administered by the departments of Lands, Forests, and Water Resources, and Recreation and Conservation. Watershed treatment, which includes erosion control and soil conservation programs, is administered by a single department, Agriculture. Power development is the responsibility of the Department of Lands, Forests, and Water Resources, and the B.C. Hydro and Public Utilities commissions. The departments of Lands, Forests, and Water Resources, and Recreation and Conservation administer the water resource under the heading recreation and wildlife.

Federal-Provincial and International Agencies

As well as the distinctly federal or provincial agencies active in the water resource field there are the federal-provincial agencies, inter-provincial

agencies, and provincial agencies receiving program assistance from the federal government. Of the 69 federal-provincial resource agreements in effect in 1964, 23 concerned the water resource (Can. Coun. Res. Ministers 1964).

Federal-provincial cooperative activities in water management have been undertaken under various types of arrangement. Some agencies have been established to perform a particular function on a continuous basis, e.g., the Lake of the Woods Control Board (the first joint program involving water, resulting from the 1921 Canadian Lake of the Woods agreement), the Prairie Provinces Water Board, and the Eastern Rockies Forest Conservation Board. Other agencies have been established to deal with emergency situations such as floods, e.g., the Fraser Valley Dyking Board. The South Saskatchewan River Development Board is an example of the type of agreement under which the federal government finances and constructs part of a water-development project.

About 2,000 miles of the Canada-United States border are marked by navigable and non-navigable rivers, and the remaining 3,000 miles are crossed by many rivers. To avoid controversy regarding the use of these waters and to arbitrate those problems that do arise, the Boundary Waters Treaty of 1909 provided for the establishment of the International Joint Commission. To facilitate the carrying out of the functions of the commission a number of boards of control have been established including the St. Lawrence River Board of Control, the Rainy Lake Board of Control, and the Kootenay Lake Board of Control. Engineering boards have also been established such as the Columbia River Engineering Board and the Saint John River Engineering Board.

Other Agencies

Many agencies other than those of the provincial or federal governments are interested in, and involved with the water resource. Some of these have administrative responsibilities which they derive from the higher levels of government, especially provincial; some function as advisory boards; and some are involved only to the extent of data collection for their own use.

Municipal public utilities with provincial charters derive their authority over the resource from the provincial government. Examples are the water districts of Greater Vancouver and Greater Victoria. These corporations have the authority to own land and to purchase, construct, and operate water works, and they are required to furnish an adequate supply of water to the municipalities within their district. Whether the district owns outright the complete municipal watershed, as does the Greater Victoria Water District, or leases the area from the Crown in the right of the province, as in the case of the Greater Vancouver Water District, it must obtain water licences from the British Columbia Water Resources Service.

Data collection, both hydrometric and meteorological, is carried out by such organizations for their own use.

Some agencies, although comprised of representatives from government, have no governmental responsibilities. The Canadian Council of Resource Ministers, described in an earlier section, is an example. It is neither a policy-making nor executive agency, but is made up of the resource ministers of the 11 senior governments. The council concerns itself with the promotion of orderly development of Canada's renewable resources. Water has received much of the attention of the council, one of whose major projects was the

collection of basic data concerning the administration of the water resource in Canada.

The Canadian National Committee of the International Hydrologic Decade is another example. Made up of members from provincial and federal governments and universities it is not a governmental agency but its objectives include the promotion and supervision of Canada's IHD program.

In addition there are many agencies whose concern with the water resource is limited to data collection with a minimum of analysis. Some of these are interested in hydrometric as well as meteorological data, e.g., power companies operate gauging stations and assist in snow surveys; conservation groups are interested in water levels and precipitation, as are irrigation districts. Most groups in this category, however, limit their activities with regard to the water resource to meteorological observations, e.g., prairie grain companies use the data for crop forecasting; resort owners and private individuals do so simply out of interest.

4. DISCUSSION

It is probable that in the future much more emphasis will be placed on the intangible values of many of the nations resources, especially water. As standards of living rise resulting in higher incomes and more leisure time the value of natural resources, from the point of view of recreation and aesthetics, will increase. To achieve the objectives of this aspect of water development and management, as well as the more familiar aspects such as industrial, power, and domestic uses of water, government will be relied on more heavily than in the past. Even if Canada's water resource administration

is adequate for the present, and there is evidence to the contrary, it will not satisfy the needs of the future unless it is substantially improved.

Problems

B.N.A. Act. The provinces of Canada have been given the right and responsibility to develop and manage their own resources by the B.N.A. act. In most enterprises, money inputs greatly exceed revenues when the enterprise is in the developmental stage. This is true in the natural resource field, also. But, even after development, the return from many natural resource enterprises does not accrue to the government as revenue. The B.N.A. act and succeeding federal-provincial agreements have given to the federal government the right to a large part of the revenues raised by taxation. This has contributed to a large extent to the difficulty of managing the water resource. One attempt at overcoming this difficulty is the shared-cost agreements between the federal and provincial governments. An example is the Canada Water Conservation Assistance Act under which the provinces receive financial assistance to develop the water resource.

The writers of the B.N.A. act could not foresee all of its implications and problems have arisen from the need to interpret the act. Doubt as to the interpretation has occasionally resulted in unresolved situations being allowed to continue. The jurisdiction of off-shore oil rights is a current example.

Provincial attitudes. Another factor contributing to the difficulty of managing water is the zeal with which some of the provinces guard their rights. The federal-provincial shared-cost programs also mean shared responsibility in that the federal government has had a hand in framing the

terms of the agreement. The demands by the provinces that federal money be made available without stipulations as to its use is perhaps legitimate if the resources are to be managed efficiently. Divided responsibility may lead to compromises by which resource management suffers, although in some cases, benefits may be derived from such division of responsibility.

Federal attitudes. The federal government has long taken a passive role in the management of the water resource. The reasons, real or imagined, but often stated, are the provinces' rights to administer its own resources and its unwillingness to allow any encroachment on these rights. However, the reasons may also be the belief that this was the will of the people, or just lack of leadership.

Administration. Coordination is sometimes lacking between the many agencies involved in administering water resources. This is due to the number of agencies involved and to the overlapping nature of their responsibilities. Duplication of effort is one result of the overlapping; effort directed to the opposite ends is another; and complete omission is a third.

Data collection. Duplication and gaps are probably more apparent in data collection than in any other phase of water management. Many of the data-collecting agencies described in a preceding section are collecting data for their own particular use or, especially in the case of government departments, to satisfy the particular needs of another user. This often means that data collection has been designed to fill one need, that of the immediate user, and does not satisfy future needs. Hydrometric and meteorological data must cover a period sufficiently long that the user is confident that extreme values have been sampled and that averages are representative of

long-term averages. The collection of data often begins when data are needed. The result is a waiting period before the data are available.

Another problem resulting from the number of data-collecting agencies is that potential users are often unaware that data do exist. There is no clearing house for data of this nature, and numerous data are unpublished.

Recommendations

Recommendations to improve some of the situations in which problems exist in administering Canada's water resources can be based on either of two views. One view is that a strong federal role is necessary; the other is that a strong federal role is unacceptable in view of the provinces' jurisdiction over the resource.

In the last few years there has been much discussion in Canada about a national water policy. This has probably resulted from the proposal of an American engineering firm by which water from Canada's northwest would be diverted to the United States. This scheme as well as Canada's water-export policy will be discussed in a subsequent section.

Supporters of a strong federal role in water resource administration have expressed their views on the subject. General A.G.L. McNaughton, former chairman of the Canadian section of the International Joint Commission, in calling for a national water policy stated that federal guidance and co-ordination were essential to proper management of the resource (McNaughton 1965). The Honorable John Turner, federal minister without portfolio, stated his belief that the federal government must act not only as a referee, "it must now act as a coordinator and must, on behalf of the people of Canada,

bring provincial governments together by initiative and persuasion into coordinated national policies" (Turner 1965).

On the other hand, voices have been raised in support of the opposite view. In 1965, the Canadian Council of Resource Ministers recommended a set of guidelines to govern joint federal-provincial programs. Included was the recommendation that the responsibilities of the cooperating governments should be consistent with their responsibilities under the B.N.A. act. Since the council is composed of resource ministers from the 11 senior governments, 10 of which are the provinces, this recommendation is consistent with the provincial-rights attitude (C.A.A.E. 1966).

The Hon. R.G. Williston, minister of the British Columbia Department of Lands, Forests, and Water Resources, stated his view of the federal role in a speech in Vancouver: "A national policy with regard to water pollution, then, can only be concerned with the broadest statement of objectives and criteria, leaving full scope for careful investigation and sound judgement to the responsible provincial agencies" (Williston 1966).

However, this is exactly the situation that has been in existence for many years. The federal government has made broad statements of policy and the provincial governments have administered the resource. It does not appear that this will be adequate for the future administration of the water resources.

Federal level. The proper administration of Canada's water resources for the national good requires a strong federal role. The passive role of the past must be given up and responsibility for initiating action must be accepted by the federal government.

To secure the proper foundation for a national water policy in which the federal government would assume a leadership role, a high-level committee reporting directly to the cabinet should be formed. It should work closely with, but be independent of, government departments. The size of the committee should be kept small, the individual members being chosen not so much for their knowledge of a single phase of the water resource but for their wide knowledge and experience in the field of water resources.

At the next level an interdepartmental committee composed of specialists in all fields of water resources should be formed. Reorganization of the federal departments involved in water resource management should be accomplished first. This has already begun with the establishment of the Department of Energy and Mines containing the Water Research, Water Resources, and Resource Development branches. Consolidation to an even greater extent is probably necessary.

The interdepartmental committee should act as an advisory board and provide liaison between federal agencies.

The federal government should then apply its resources to existing water problems. An example of such a problem is water pollution. The provinces should be persuaded of the necessity for uniform legislation for pollution control. The B.N.A. act should not limit federal action in such fields because provincial rights and responsibilities in particular areas can be assigned to the federal government by mutual agreement.

Provincial level. At the provincial level the need is for increased awareness of the water resource and a willingness to cooperate with the federal government, even to the extent of foregoing some degree of provincial

rights in the interest of comprehensive development and management of the water resource. There is no valid reason for considering the water resources of the Canadian provinces as continental resources but it should be possible, and in fact seems necessary, to manage these resources as national resources.

In British Columbia, responsibility for administration of the water resource rests mainly with the Water Resources Service of the Department of Lands, Forests, and Water Resources. Its function includes administration of the Water Act (mainly through water licensing), water supply investigations, basin planning, supervision of improvement districts, and pollution control.

The Water Resources Service is not yet adequately staffed to handle the overall planning of the water resources of the province especially with increased industrial growth and proposed water diversion schemes demanding study. The service has only recently assumed responsibility for certain aspects of the resource, e.g., pollution control. But this agency is the logical one in which to vest greater authority for management and development of the provincial water resource.

A commission similar to that proposed for the federal level should be established having overall responsibility for water resource planning and development and reporting directly to the premier. The members of the commission should be drawn from non-government agencies as well as government departments. Ontario was the first Canadian province to establish a water resources commission responsible for all aspects of water resources (C.A.A.E. 1966). In 1964 Saskatchewan created a similar commission and named as members were the deputy ministers of Natural Resources, Agriculture, and Health departments, and representatives from the South Saskatchewan River

Development Commission, Saskatchewan Power Corporation, and the provincial Economic Advisory and Planning Board (Regina Leader Post 1964). Members of the British Columbia commission should be from similar agencies.

The British Columbia Water Resources Service should be responsible to a much greater degree for the management and development of the water resource and for coordination of the activities of the various agencies concerned with the water resource. To carry out this task, specialists should be employed from fields other than just the engineering and hydrology fields, e.g., economics, forestry, and regional planning.

Data collection. If, instead of many government agencies being responsible for data collection, one agency were responsible for hydrometric data and another for meteorological data the system would be much more efficient. The future needs for data on the water resource could be anticipated to a greater degree than at present and the type of data and the method of collection could better serve potential users.

Once observations of a particular phenomenon are begun they should not be dropped without careful consideration. Streamflow records are available for some streams for very short periods interspersed with many years for which there is no record. The original observations were probably begun with a single need in view and when data were collected to satisfy the need the observations ceased. However, the short period of record has made even more valuable any subsequent record.

One agency should have the responsibility of collection and publication of hydrometric data, and another for meteorological data. This task should logically fall to the federal government, two of whose agencies, the

Meteorological and Water Resources branches, do the greater part of basic data collection. Data should be published more often and receive wider distribution so that current information is readily available.

The need for more extensive coverage for hydrometric and meteorological observation is especially true of British Columbia. Observations at higher elevations are important because a large proportion of streamflow originates there as precipitation. More research on long-term recording instruments for use in remote locations would be well repaid.

A good start has been made in extending the climatological network as an A.R.D.A. (Agricultural Rehabilitation Development Act) project. In 1965, temperature and precipitation stations were established (many along altitudinal transects) in the Prince George and East Kootenay areas. In 1966 effort was concentrated in the East Kootenay area and measurements of soil temperature and evaporation were begun. Additional altitudinal transects for precipitation were established near Nelson, Kamloops, Smithers, and north of Prince George. In 1967, the climatological network will be extended to the Peace River area, Fort Nelson, and between Vanderhoof and Terrace (Schmidt 1967).

The Research Division of the B.C. Forest Service has been working on long-term recording instruments and a prototype constructed by Sperry Gyrascope is presently being tested on the campus of the University of British Columbia (Schmidt 1967). However, in view of the need for hydrometric and meteorologic data more resources should be devoted to such research.

CHAPTER IV. WATER RESOURCES OF BRITISH COLUMBIA

1. CLIMATIC REGIONS

The difficulty encountered in delineating climatic regions in British Columbia is that, because of the mountainous terrain, variations in climate are greater with elevation than with horizontal distance. For example, in an area south of the Crowsnest Pass, winter (October-May) precipitation averages 20 in. at 4,400 ft. and 40 in. at the 5,200 ft. elevation (Gray et al. 1965).

Some division of the province is necessary for discussion of climatic regions. Kendrew and Kerr (1955) established the following climatic regions for British Columbia: Littoral, Southern Interior (eastern and western), and Northern. This classification is based on observed differences in climate as well as physiographic divisions which help to explain the climatic differences. But the classification is not based on defined limits of such climatic factors as precipitation and temperature.

Another system of delineating climatic regions is by enclosing those areas having approximately the same values for a particular climatic parameter such as precipitation, temperature, and length of growing season. The ARDA classification of climates for agriculture (Can. Dept. For. and Rural Devel. 1966) produced maps of (1) temperature zones (seven classes) based on the number of degree-days above 42°F. per year, (2) moisture zones (nine classes) based on a combination of water deficiency and summer precipitation, and (3) climatic regions for agriculture based on a combination of (1) and (2).

The division of British Columbia into climatic regions according to the classification developed by Köppen distinguishes eight regions based on temperature and the amount and distribution throughout the year of precipitation (Can. Dept. Mines and Tech. Surveys 1957).

These classifications satisfy to a greater or lesser degree the needs for which they were devised, but they are not very useful for consideration of water resource management. Nor is any one classification likely to present a complete picture of the water resources in British Columbia. The information presented in Maps 1-5 on the following pages does provide to a greater degree the means of assessing the water resources of the province.

Precipitation

Amount. Map 1 contains the isohyets of mean annual precipitation for British Columbia. An estimate of the mean annual precipitation falling on the whole province was obtained by planimetering the area within each isohyet and applying the indicated precipitation to this area. The average precipitation is about 45 in. annually, or 880,000,000 acre-feet.

The limitations of the precipitation calculation, as well as the following calculations based on Maps 1-5, must be mentioned. Aside from the accuracy of the meteorological observations involved there is the problem of forming isolines of various parameters where large areas have not been sampled, as is the case in British Columbia. Potential and actual evapotranspiration and moisture deficit were estimated by Thornthwaite's (Thornthwaite and Mather 1955) method and are another possible source of error. Some obvious discrepancies are noted in following sections and may be due to these factors. Even with the possible inaccuracies in the

RESOURCES MAP NO.

BRITISH COLUMBIA

MAP I.

MEAN ANNUAL PRECIPITATION

(INCHES)

(SOURCE: MAP PRODUCED BY THE DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF BRITISH COLUMBIA)

Scale

40 30 20 10 0 40 80 120 160 MILES

estimates they do provide some insight into the water resources of the province.

Annual precipitation varies greatly across British Columbia, from lows of 7.55 in. (30-year average) at Ashcroft in the Thompson River basin, 8.94 in. (15-year average) at Alexis Creek in the Upper Fraser River basin, and 9.07 in. (34-year average) at Merritt in the Nicola River basin, to 145.69 in. (30-year average) at Seymour Falls near Vancouver, 167.52 in. (six-year average) at Holberg on western Vancouver Island, and 174.32 in. (30-year average) at Ocean Falls on the North Coast (B.C. Dept. Agric. 1964).

Of the total of 880,000,000 acre-feet of precipitation falling annually in British Columbia, half of it is received by only 20 per cent of the land surface. At the extremes are the 39 per cent of the province which receives 20 in. and less precipitation, or 15 per cent of the total, and the five per cent of the province receiving more than 150 in., or 16 per cent of the total, as shown in Table 2.

Table 2. Ratio of class area to area of British Columbia and class precipitation to total precipitation by mean annual precipitation classes

Mean annual precipitation in inches	Ratio of class area to area of province in per cent	Ratio of class precipitation to total precipitation in per cent
Less than 20	39	15
20 - 60	41	35
60 - 100	8	14
100 - 150	7	20
Greater than 150	5	16

Rainfall regions may be described as follows. Least rainfall (12-20 in. annually) is received in the Southern Interior of the province, with most of the Northern Interior receiving 20 in. annually. Along the mountains on the eastern border of the province, mean annual precipitation ranges from 40 to 60 in., mainly, with small areas receiving up to 80 in. Highest rainfall is received on the west coast, a 50-mile-wide strip from Vancouver to Alaska receiving over 100 in. Within this coastal strip is a discontinuous strip 40 miles wide which has a mean annual precipitation of over 150 in. Most of Vancouver Island receives more than 100 in. of precipitation annually.

Seasonal distribution. The data used in the analyses of precipitation and actual and potential evapotranspiration are mainly long term averages of annual values. Of more importance in many cases is the distribution of precipitation throughout the year. Regions of high annual precipitation may suffer summer drought, whereas regions of low total rainfall may support crops because of the distribution of precipitation.

Data on seasonal precipitation show that most of British Columbia receives less rain during the spring and summer than the amount of potential evapotranspiration. Combining seasonal precipitation data (Can. Dept. Mines and Tech. Surveys 1957) with annual data (from Map 1) provided the information presented in Table 3. Potential evapotranspiration, which will be discussed in the following section, is also shown in Table 3 and has been derived from Map 2.

Table 3. Spring-summer precipitation in inches and as a percentage of annual precipitation, and potential evapotranspiration in British Columbia

Location	Spring-summer precipitation in inches[1]	Mean annual potential evapotranspiration in inches	Spring-summer precipitation as a percentage of annual precipitation
Southern Columbia Mts.	12-14	18-20	30
Northern Columbia Mts.	14-16	16-18	35
Southern Interior	6-10	20-24	50
Northern Interior	8-10	18-20	45
Coast			
52°N. - 54°N.	14-20	18-20	17
49°N. - 52°N. 54°N. - 57°N.	20-30	18-20	20

[1]Source: Atlas of Canada (Can. Dept. Mines and Tech. Surveys 1957).

The proportion of annual precipitation falling in spring and summer is lowest for the coastal region (17-20 per cent), followed by the Columbia Mountains region (30-35 per cent), and highest for the Interior (45-50 per cent) (Table 3). However, only in the coastal region does spring-summer precipitation equal or exceed the potential evapotranspiration, and generally only this region and the Peace River region do not require irrigation to support agricultural crops (B.C. Nat. Res. Conf. 1964).

Extremes. Another important aspect of precipitation is the extreme amounts which may occur. In planning for the use of the water resource, whether it be for irrigation or hydro power for example, the probabilities of precipitation greater or less than specified amounts must be considered.

As an indication of precipitation extremes in British Columbia, Kendrew and Kerr (1955) expressed the range between the maximum and minimum annual precipitation as a percentage of the mean annual precipitation. These percentages range from 58 to 96 for selected coastal stations, 60 to 119 for the Southern Interior, and 68 to 88 for the Northern Interior.

As an indication of the extremes that have been recorded in the province the following are taken from Kendrew and Kerr (1955). From 1915 to 1950, the lowest May-September precipitation recorded at Victoria was less than 0.3 in. and the greatest was 4.9 in.; at Prince Rupert, 4.7 in. and 60.3 in.; at Kelowna, 0.9 in. and 13.8 in.; and at Prince George, 2.9 in. and 22.0 in.

Kendrew and Kerr (1955) tabulated the percentage of years in which annual precipitation of specified amounts had occurred in British Columbia. O'Riordan (1966) gave the probability of monthly (for the months of April to September) precipitation amounts for Southern Interior stations. For example, at Penticton there is a 50 per cent probability of receiving 4.45 in. of precipitation, or less, from May to September, a 10 per cent probability of receiving 1.14 in. or less during that period, and a 90 per cent probability of receiving 9.76 in. or less.

Intensity. Murray (1964) presented rainfall intensity maps of British Columbia for six and 24 hour durations, and 2, 5, 10, and 25-year return periods. (The return period is that period within which a storm of given intensity may be expected to occur). Because of the very sparse recording precipitation-gauge network and the great areal variability of rainfall in British Columbia, rainfall intensity-duration-frequency maps

were not presented for durations less than six hours.

Most of British Columbia may expect a 24-hour rainfall of 1.00-3.00 in. within a two-year period, but up to 5.00 in. may occur in the Coast Mountains between 51°N. and 53°N. latitude, and 6.00 in. on south-western Vancouver Island and Pitt Lake near Vancouver. For a return period of 25 years, the intensity of a 24-hour rain increases to 2.00-4.00 in. for most of the province, 8.00 in. on south-western Vancouver Island, and 12.00 in. in the Coast Mountains.

For a six-hour rain and a return period of 25 years, 1.25-3.00 in. may be expected over much of the province, up to 4.00 in. on Vancouver Island, and 6.00 in. in two small areas, near Brittania Beach in the south Coastal Mountains and between Ocean Falls and Kemano.

The areas of highest rainfall intensity are also those having the greatest annual precipitation. This would be expected, especially for durations as long as six and 24 hours.

Relation to watershed management. Precipitation data must be supplemented by other information for effective watershed management. Flooding can occur anywhere in the province in spite of the low annual precipitation received in the particular location. Erosion, too, can occur in those areas having low annual precipitation and low-intensity rains due to other factors that are also related to flooding and erosion, such as topography, soil type, and vegetation. The amount of water needed for irrigation depends not only upon the amount of precipitation, but on its distribution throughout the summer, on temperatures during the growing season, and on the type of crop.

Potential Evapotranspiration

Potential evapotranspiration (PE) is the combined water loss from the earth's surface to the atmosphere that would take place if soil moisture were not limited but available as needed for evaporation from soil and water surfaces and transpiration by vegetation. PE is controlled solely by available energy, and its calculation by the Thornthwaite method is based on air temperature and length of day (Mather 1961).

Estimates of total PE for British Columbia were obtained from Map 2 in the same manner as that described for precipitation, and amount to 19 in. or 379,000,000 acre-feet annually.

Isolines of PE (Map 2) indicate its dependence on temperature. For the northern half of the province annual PE is about 16-18 in. No part of the south half of the province has values as low as 16 in. and those areas having 18 in. PE are at the top of the Coast Mountains on the west and the Columbia Mountains on the east. The highest PE values, 26 in., is found in the Okanagan Valley. About 22 in. are indicated for the remainder of the Southern Interior, 24 in. for Vancouver Island, 20 in. for the coast below 51°N. latitude, and about 18 in. north of 51°N. The higher values for the coast and Vancouver Island reflect the mild winters, not high summer temperatures.

Actual Evapotranspiration

Actual evapotranspiration (AE) is the actual water loss from evaporation and transpiration and is calculated in the Thornthwaite method by using PE, precipitation, and moisture storage capacity of the soil

RESOURCES MAP NO.

BRITISH COLUMBIA

MAP 2.

MEAN ANNUAL POTENTIAL EVAPO-TRANSPIRATION AFTER THORNTHWAITE

(INCHES)

(SOURCE: MAP PRODUCED BY THE DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF BRITISH COLUMBIA)

Scale

40 30 20 10 0 40 80 120 160 MILES

(Mather 1961). The value of AE obtained from Map 5 for the whole province is 15 in. annually, or 287,000,000 acre-feet.

It might be expected that isolines of AE would be similar in trend to those of PE, with highest values in the Southern Interior where summer temperatures are high. The opposite is the case, with most of the province (80 per cent) having annual AE values of 12-16 in., and the lowest values (8-12 in.) in the Thompson and Okanagan Valleys. A narrow strip along the coast and south-western Vancouver Island (eight per cent of the province) exceeds 20 in. of AE, because water availability and length of season of evaporation (the Thornthwaite method assumes no evaporation when temperature is $0^{\circ}C$. or lower) more than compensate for cool summers.

Moisture Deficit

The difference between PE and AE is a measure of the moisture deficit, the amount by which the available moisture fails to satisfy the demand for water at a particular location. The difference between PE and AE as obtained from Maps 2 and 5 is four inches (92,000,000 acre-feet), whereas the moisture deficit obtained from Map 3 is 2.6 in. (51,000,000 acre-feet). The previously described possible inaccuracies may be responsible for a large part of this discrepancy.

Because of the high PE and low AE in the Southern Interior, the moisture deficit is greatest in this area. Sections of the Okanagan Valley, Thompson River basin, and Fraser Valley between Williams Lake and Boston Bar (four per cent of the area of the province) have a moisture deficit of 8-16 in. (17 per cent of the total moisture deficit of the

RESOURCES MAP NO.

BRITISH COLUMBIA

MAP 3.

MEAN ANNUAL MOISTURE DEFICIT AFTER THORNTHWAITE

(INCHES)

(SOURCE: MAP PRODUCED BY THE DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF BRITISH COLUMBIA)

Scale

0 10 20 30 40 60 80 120 160 MILES

RESOURCES MAP NO.

BRITISH COLUMBIA

MAP 4.

BRITISH COLUMBIA'S

MAJOR RIVER BASINS

	BASINS	AREA		AV. FLOW c. f. s.	
		SQ. MI.	%	PER SQ. MI.	TOTAL
1.	FRASER	90,000	24.6	1.28	115,000
2.	LIARD	55,500	15.1	0.92	60,000
3.	PEACE	49,500	13.6	1.33	66,000
4.	COLUMBIA	39,500	10.8	1.59	90,000
5.	SKEENA	21,000	5.7	2.00	42,000
6.	STIKINE	19,500	5.3	1.95	38,000
7.	YUKON	9,500	2.6	1.89	18,000
8.	NASS	8,000	2.2	4.13	33,000
9.	TAKU	6,500	1.8	2.00	13,000
10.	HAY	3,000	0.8	1.00	3,000
11.	ALSEK	2,500	0.7	2.00	5,000
12.	COAST	61,500	16.8	7.32	450,000

(SOURCE: RESOURCES MAP NO. 8, BRITISH COLUMBIA ATLAS OF RESOURCES)

Scale 40 30 20 10 0 40 80 120 160 MILES

province). Seventeen per cent of the province has no moisture deficit. This region is an 80-mile-wide strip running the length of the west coast, most of Vancouver Island, and the Columbia Mountains on the east side of the province. Over 80 per cent of the province has a moisture deficit of four inches or less.

The moisture deficit is a measure of the irrigation needs of a region. O'Riordan (1966) estimated irrigation requirements for five stations in the B.C. Southern Interior using Penman's method of calculating PE and deducting from this the amount of water available to the crop from soil moisture storage and rainfall. The following are the seasonal irrigation requirements in inches with those derived from Map 3, Mean Annual Moisture Deficit, in brackets: Hope, 6.7 (6), Lytton, 25.8 (14), Penticton, 19.1 (12), Princeton, 15.1 (10), and Kamloops, 24.6 (14). O'Riordan's values are higher than those derived in this thesis, but lower than the average water duty in the Southern Interior which averages about 32 in. (B.C. Nat. Res. Conf. 1964).

The PE values for the Okanagan Valley average only 24-26 in. (Map 2) or only 50-75 per cent of the amount actually applied by irrigationists. This seems to indicate that a considerable amount of irrigation water is lost by percolation beyond the root zone.

2. RUNOFF REGIONS

The major river basins of British Columbia are delineated on Map 4, and the legend box gives the average flow per square mile for each basin. The basins themselves cannot be considered distinct runoff regions, nor

RESOURCES MAP NO.

BRITISH COLUMBIA

MAP 5.

MEAN ANNUAL ACTUAL EVAPO-TRANSPIRATION AFTER THORNTHWAITE (4" STORAGE)

(INCHES)

(SOURCE: CANADA DEPT. OF FORESTRY AND RURAL DEVELOPMENT. 1966. THE CLIMATES OF CANADA FOR AGRICULTURE. THE CANADA LAND INVENTORY, REPORT NO. 3, FIG. 20.)

Scale

40 30 20 10 0 40 80 120 160 MILES

can several basins be combined on the basis of similar average flows per square mile to obtain runoff regions. The rivers flow through regions differing greatly in precipitation, PE, and AE, and the flow that originates at different parts within a basin varies greatly. For example, in the Fraser River basin, runoff at Ashcroft is four inches annually (12 in. precipitation minus eight inches AE) and at Stave Lake near Vancouver, 132 in. (150 in. precipitation minus 18 in. AE).

Because runoff is mainly the difference between precipitation and AE, and because AE is fairly consistent across the province at 12-16 in. (80 per cent of the province has AE values in this range), the isohyetal map (Map 1) may be used to indicate runoff patterns. Runoff values may be obtained by reducing the value of the isohyets of Map 1 by about 14 in.

Runoff regions may be described as follows. For most of the province, runoff ranges from two to four inches. Runoff is very close to zero in a small area in the Thompson River Valley between Spences Bridge and Kamloops, ranges between 30 and 50 in. in the Columbia Mountains, and from 100 to 120 in. in the Coast Mountains.

The average flow of all B.C. rivers is about 898,500 cfs (B.C. Nat. Res. Conf. 1964), which amounts to 651,000,000 acre-feet or 33 in. Another estimate of runoff is the difference between annual precipitation (45 in.) and AE (15 in.) which is 30 in. The discrepancy of three inches is surprisingly small, considering the method of obtaining the estimates.

3. WATER NEEDS

In 1956, 438,650 acre-feet of water were used to irrigate 200,440 acres of land in British Columbia. An estimated 400,000 acres were considered potentially irrigable, requiring an additional 1,025,000 acre-feet of water (B.C. Nat. Res. Conf. 1964). The breakdown of irrigated and potentially irrigable land is presented in Table 4. In 1965, more than 300,000 acres were irrigated and licenced water use was 769,100 acre-feet (B.C. Water Res. Serv. 1966). It appears that between 1956 and 1965, 100,000 acres of the potentially irrigable land had become irrigated land. In 1965, then, 300,000 acres were being irrigated and 300,000 additional acres were potentially irrigable, suggesting that the present licenced water use for irrigation of 769,100 acre-feet would likely double if all potentially irrigable land were developed. Table 4 indicates a total water requirement for irrigated and potentially irrigable land of 1,463,650 acre-feet.

The annual runoff from B.C. rivers is 651,000,000 acre-feet, so that it appears that the province has adequate water not only for all potential irrigation requirements but for other potential uses. Not all the water is economically available for irrigation, however. Many of the major rivers are so deeply entrenched that their water requires too great a pumping lift to economically supply adjacent irrigable land. Because of this, little use has been made of major streams in British Columbia for irrigation. On the other hand, small streams are commonly used to irrigate nearby land, many such streams being so fully utilized for irrigation that water rarely

Table 4. Irrigated and potentially irrigable land in British Columbia, and water requirements (from B.C. Nat. Res. Conf. 1964, Tables 3 and 4)

Region	Irrigated land, 1956		Potentially irrigable land		Total requirement in acre-feet
	Area in acres	Water use in acre-feet	Area in acres	Water required in acre-feet	
East Kootenay	13,720	31,000	120,000	360,000	391,000
West Kootenay	12,130	15,160	75,000	150,000	165,160
Okanagan, Similkameen, Kettle Valley	70,400	193,600	100,000	300,000	493,600
Lower Mainland	5,210	5,210	10,000	10,000	15,210
Vancouver Island	4,280	4,280	15,000	15,000	19,280
Kamloops-Lillooet	77,300	154,600	60,000	150,000	304,600
Central B.C.	17,400	34,800	20,000	40,000	74,800
Total	200,440	438,650	400,000	1,025,000	1,463,650

flows in these streams below the irrigation intakes. There are about 600 dams on these streams under licence to store spring freshet and other water in excess of irrigation requirements (B.C. Nat. Res. Conf. 1964).

The following list of the major licenced water uses indicates the requirements of these uses in relation to one another. The list is derived from an analysis as of April, 1965, presented by the B.C. Water Res. Serv. (1966).

Domestic	-	13,664	acre-feet/year
Irrigation	-	769,100	" " "
Industrial	-	1,381,965	" " "
Processing ore	-	670	" " "
Power	-	156,755,412	" " "
Waterworks	-	534,719	" " "

There has been some apprehension that development of B.C.'s hydro power will result in most of the province's water being appropriated for that purpose (B.C. Nat. Res. Conf. 1964), leaving little for future irrigation needs. In view of the very small percentage of the total water resource that will be required for any foreseeable consumptive use (e.g., irrigation), such fears seem groundless. Those water licences that have been issued for the Peace and Columbia River projects have included a clause to the effect that the licencee's rights shall be considered subsequent to any rights granted under any licences that may be granted, at any time, for the consumptive use of water. Consumptive use in this case includes domestic, municipal, stock-water, irrigation, mining, and industrial use. The clause establishes a permanent priority for these uses over power use in these major river developments (B.C. Nat. Res. Conf. 1964).

4. WATERSHED MANAGEMENT REGIONS

Ideally, the province should be divided into watershed-management regions, within which the problems of watershed management would be similar. However, few areas of the province have unique problems and the degree of any problem varies little across the province. Several regions may be delineated on the basis of water scarcity, flood and erosion control.

Coastal Region

Irrigation is not needed for crops in the Coastal region (except in the south-west of the province, e.g., Fraser Valley and Saanich), and the rivers do not supply water to other regions. Therefore, increasing the water supply is not necessary. Forest management should be directed to reducing peak flows and minimizing erosion, and at maintaining spawning habitat for anadromous fish where these are of importance.

Peace River Region

The Peace River region of British Columbia does not require irrigation for agricultural crops (B.C. Nat. Res. Conf. 1964), industrial water needs are limited, and the rivers flow to the Arctic Ocean through an area of very little water demand. Therefore, in this region, watershed management should be directed to reducing peak flows and minimizing erosion.

Columbia Mountain Region

The Columbia Mountain region is similar to the previous two regions in that the annual moisture deficit is zero. This region includes only a small area at the higher elevations of this range of mountains. The

rivers rising in the region do flow through areas of moisture deficit as well as areas in which there are water uses other than irrigation. Therefore, forest management should be directed not only to flood and erosion control, but also to increasing water supplies.

Interior Region

The B.C. Interior from the southern to the northern boundary of the province has an annual moisture deficit, but the deficit is much greater in the south where farming is much more important. One objective of forest management having high priority in the Southern Interior should be increasing water supplies and prolonging spring runoff. Erosion and flood control should receive considerable attention in forest management as well.

5. WATER DIVERSION SCHEMES

In the early 1960's a proposal to divert Canadian waters to the United States, called the North American Water and Power Alliance, or the NAWAPA, was put forth by the Ralph M. Parsons Company, an engineering firm of Los Angeles. The proposal touched off a lively debate on Canadian water policy, mostly by elected representatives of federal and provincial governments.

The timing of the NAWAPA proposal was termed unfortunate by the British Columbia Minister of Lands, Forests and Water Resources, because of the danger of formulating water diversion policy without adequate information (Williston 1966). However, from this standpoint the proposal

was worthwhile in that Canada's water resources began to receive much-needed attention, inventory of the resource and prediction of national needs being foremost among the suggestions.

Other diversion schemes have been proposed in recent years to make water available to water-short areas of Canada and even to international waters (e.g., the Great Lakes), but none have proposed diversion to the United States, nor have been of the size of NAWAPA.

This section will describe some of these diversion schemes, their relation to the water resources of British Columbia, and their implications with respect to a national water policy.

NAWAPA

According to its planners, the North American Water and Power Alliance will provide direct benefit to seven Canadian provinces, 33 American states, and three Mexican states, and the beneficial economic effects of the scheme will be felt by the whole continent. It has been estimated that the U.S. national income from agriculture, livestock, mining and manufacturing would increase by $30 billion annually (Moore 1965). The project would add $2 billion per year to the B.C. economy (Vancouver Sun 1965c).

NAWAPA would generate its own power for pumping and would have a saleable excess. It would provide a navigable waterway from Vancouver to Lake Superior, deliver irrigation water to the northern plains from Alberta to South Dakota, and would increase flow through the Great Lakes-St. Lawrence system. The project would provide storage for 4.3 billion acre-feet of water, 2.8 of which would be in Canada. It would irrigate 36

million acres, nine million in Canada, six million in Mexico, and 20 million in United States. An installed capacity of 99,700 kilowatt-hours of electric power would be part of the scheme, 56,000 of which would be in Canada (U.S. Senate 1964).

The NAWAPA project would cost about $80 billion of which construction in Canada would account for $31 billion, and Mexico $2 billion, and it would take about 30 years to complete (U.S. Senate 1964).

Location. The project would begin in the headwaters of the Yukon River in the Yukon and the Tanana River in Alaska, where reservoirs would be created by a series of dams. From here, water would be pumped 300 feet to the Peace River reservoir. Several streams in northern British Columbia would be dammed to form a chain of reservoirs above the Peace River reservoir. A portion of the outflow from the Peace River reservoir would be directed into the Alberta-Great Lakes canal. Diverted flows from several streams on the east slopes of the Rockies would be added to this system also, providing inflow to Lake Superior in excess of 40 million acre-feet per year. A diversion from the South Saskatchewan River in Saskatchewan would take water into the plains states of United States.

By damming the Columbia, Fraser, and Kootenay rivers, which have their upper reaches in the Rocky Mountain trench, a 500-mile-long reservoir would be created 3,000 feet above sea level, extending southward into Montana. The annual yield into the trench would average 74 million acre-feet and would provide the major supply for the NAWAPA system (C.A.A.E. 1966, Can. Coun. Res. Ministers 1964, U.S. Senate 1964).

Conception. In March, 1964, the Parson's Plan, or NAWAPA, was released for public examination and appraisal. According to A.W. Moore, vice-president of the Ralph M. Parsons Company, the concept was brought to the attention of the company by its foreign operations division which has been engaged in water development projects in Taiwan, India, Iran, and Kuwait. It was this knowledge of water and mankind's needs for water which led the company to begin development of the project (Moore 1965).

Other reasons for the development of the plan have been given which do not attribute such an altruistic motive to the Parson company. One is that the firm, "looking far into the future when its current heavy missile program for the U.S. government is phased out, conceived of the North American Water and Power Alliance" (C.A.A.E. 1966, p. 23). A similar view is that the scheme is nothing more than an attempt by "a private engineering firm, to drum up business for themselves" (McNaughton as quoted by MacDonald 1966, p. 6).

Another reason is that "its immediate objective appears to be . . . 'to maximize' the amount of engineering construction during the next 30 years, a period when the industry may be less active than it has during the last quarter century" (Lloyd 1966, p. 14).

These are the views of some Canadians, and the plan has not been as strongly supported in Canada as in the United States where "acceptance of the concept by the general public, elected officials and the engineering profession has been heartening" according to a Parson's company vice-president (Moore 1965, p. 30).

Perhaps there has been wide acceptance of the NAWAPA plan in the United States, although no government agency has yet commissioned any technical study of the project. The U.S. government has not acted on a congressional resolution to refer the project to the International Joint Commission for study (McNaughton, as quoted by MacDonald 1966). The reason that the study has not been referred to the commission may be that the plan does not have the support of the U.S. government.

It may also be that because a joint reference by both the U.S. and Canadian governments to the commission is required, the U.S. government has refrained, recognizing that Canada has vetoed past attempts at international study of a purely Canadian resource. In 1964, Canada turned down the suggestion by the U.S. State Department that a study be made of regulating Great Lakes' water levels by partial diversions from rivers in northern Ontario and Quebec (O'Leary 1966).

The NAWAPA project has been studied by the Western Water Development subcommittee of the U.S. Senate Committee on Public Works. Some of its views are expressed in the following section.

Engineering. The NAWAPA project has been studied by a U.S. Senate subcommittee and some of its shortcomings have been pointed out in the committee report (U.S. Senate 1964, p. 1-2):

> It is not an engineering study, it is not definitive in the sense of location, in the height of dams, or in the water impoundments.
>
> Nor are its water availability figures or hydropower projects definitive.

> But it does apply hydrologic and engineering standards to the concept. And it was a serious enough attempt to warrant a serious analysis.

Lloyd (1966, p. 14), a geography professor at McGill University, described the project as an "exercise in sophomore civil engineering which has received far greater attention than it ever deserved." The NAWAPA plan includes a seaway to James Bay where ". . . the off-shore waters are so shallow that even a canoe cannot be assured of getting within sight of land at low tide" (Lloyd 1966, p. 14).

The federal Water Resources Branch studied NAWAPA in 1965 and concluded that there was a lack of definite information on engineering problems and costs. From the Canadian viewpoint there are closer and more economic sources of water for the Canadian prairies than the NAWAPA-proposed trans-Canada canal (O'Leary 1966).

National water policy. The engineering and economic feasibility of NAWAPA is not the main consideration at this point in the development of Canada's water resources. Presumably these aspects would be proven before any commitments were made. One important factor is the economic feasibility of Canada's participation in the project, i.e., the relation of the benefits and costs accruing to Canada. But the most important factor from the Canadian standpoint is the long-term effect of water export on the welfare of the nation. Will water export limit industrialization? Will water export doom particular regions to future water shortages? And, if so, what are the implications?

When NAWAPA first became a popular topic some of the views expressed by Canadian elected representatives were quite extreme, but gradually these

have moderated. In the beginning, Canadian views were, generally, that no diversion to the United States should be permitted. Since that time the benefits which could accrue to Canada from water export have been considered, the result being a more tolerant attitude toward such export.

A no-diversion policy was held by Diefenbaker, leader of the Progressive Conservative party in the federal House of Commons (Vancouver Sun 1965a). Hamilton, a Progressive Conservative member of the House of Commons, held that Canada should consider water export provided the country benefits in such ways as guaranteed access to U.S. markets for steel and wood products, along with tariff reductions (Vancouver Sun 1965b).

Prime Minister Pearson stated that export of water would be beneficial to Canada as long as only that amount would be diverted which was surplus to Canada's future needs.(Vancouver Sun 1965a). Laing, federal minister of Northern Affairs and National Resources, said that diversion of water to the United States was not negotiable. "It is our water and we're going to keep it" (Vancouver Sun 1965a). In January, 1966, Laing's views were that Canada's water was not negotiable until it had been surveyed and the nation's needs provided for (O'Leary 1966). Laing's executive assistant, Austin, said that the Liberals do not agree with sharing Canadian water (Vancouver Sun 1965a).

The views in the previous two paragraphs are those of politicians who expressed their views in the heat of an election campaign. The lack of agreement on a water-export policy within either of the two political parties is indicative of how meaningful election speeches are. It is also indicative of how little thought had been given to a national water policy until then.

McNaughton, former chairman of the Canadian section of the International Joint Commission, stated that there must be no sale of water to the United States in the foreseeable future (C.A.A.E. 1966), although he did allow that diversion could be considered after studies have been carried out (MacDonald 1966). This view was also held by New, of the Canadian Natural Resources Council, who urged the formation of a Canadian committee on water, weather, and vegetation, to carry out studies amounting to an inventory of resources and a forecast of needs (MacDonald 1966).

The local view on water export has been expressed by B.C.'s premier Bennet and Yukon commissioner Cameron who are opposed to NAWAPA (MacAlpine 1965). Williston, minister of Lands, Forests, and Water Resources for British Columbia, said that any policy at this time would have to be a policy of no diversion, although he indicated that future policy would have to be the result of study (C.A.A.E. 1966). Paget, deputy-minister of B.C.'s Water Resources, stated that British Columbia has a huge water resource, but needs to reserve all of it for potential development (MacAlpine 1965).

The majority of opinions stated by Canadian government officials towards NAWAPA, or to any diversion of Canadian water to the United States, seems to be that the first requirement is to make certain that enough water to satisfy Canada's future needs is safeguarded. After that has been seen to, diversion schemes may be considered. This view was stated by Moss, chairman of the U.S. Senate committee studying NAWAPA (MacDonald 1966), and by McFarland of the Ralph M. Parsons Company (Vancouver Sun 1965c).

The view that Canada must first study its resources and needs before entertaining any plan to export water has resulted in demands for

a national water policy (C.A.A.E. 1966, Lloyd 1966). Williston (1966) said that it might seem inconceivable for Canada to be without a national water policy, but it may be impossible to state such a policy because of the differences in the value of water between regions. He said that federal-provincial relations at this time are such that an over-riding federal authority affecting provincially-controlled water rights would not be readily accepted.

Laing, then minister of Northern Affairs and National Resources, said that the federal government, while taking steps to see that Canada's national interest is protected in the development of water resources, does not intend to infringe on provincial ownership and responsibility (MacAlpine 1965).

McNaughton, in calling for a national water policy, recognized that it would require an unusual degree of federal-provincial cooperation, but that federal guidance and coordination are essential (C.A.A.E. 1966).

The difficulty of resolving the problem of federal-provincial relationships and producing a national policy to guide development of Canada's water resource is apparent. The statements by both federal and provincial officials do not suggest that a national water policy is imminent.

However, the question of what Canada's policy toward water export should be, is a valid one. The following are alternatives:

(1) No water export at any time.

(2) Water export only after a study of the resource and forecasts of Canada's needs.

(3) Water export even before any study has been made.

There are several reasons why a no-export water policy may be established. One is the belief that water is unique, a national heritage which should be reserved solely for the use of Canadians. Another reason is the desire not to export the raw material to sustain industry outside Canada. Tied in with this is the view that by refusing to export water, industry will have to come to the water.

As for the first reason, water is not unique as a resource but can be considered as a combination stock and flow resource. It is a stock resource in lakes and aquifers, which can be depleted like an ore deposit. It is a flow resource as part of the hydrologic cycle and renewable like the forest. Therefore water should be treated like other natural resources, as part of the nation's capital.

The second reason has some validity, but would, at best, result in very slow growth. But water is only one of the requirements of particular industries, and the attraction of water may not be enough to outweigh the advantages of other regions. The water-rich area may be no better off than if it had exported the water. In fact, selling the resource would have provided capital for the growth of the region.

Export of water only after inventory of the resource and forecast of future Canadian needs is probably the policy which would be most popular in Canada. But even this is not necessarily the best choice. Why should only that amount of water be exported that is surplus to Canada's needs? If the return from exported water is greater than its value locally, it may

be advantageous to forego local use in favour of the revenue from sale of the resource.

Considering the preceding paragraph the best policy might be to begin exporting water now, or at least as soon as the engineering can be completed for the diversion. Canada could then take advantage of the revenue brought in by that part of the resource not presently being used in Canada, and not likely to be completely used at any time in the future.

The problem is that at this stage in Canada's water resource development information is lacking on both the extent of the resource, its present and probable future use, and its value to the nation. Therefore it would be pure chance if the export of a specific amount of water based on the present state of knowledge of the resource proved to be optimum from the standpoint of the future welfare of the country.

Another factor is that any export of water becomes an export in perpetuity. The supply cannot be decreased easily if later it is decided that Canada needs to retain more. It has been pointed out by both Canadians and Americans that once water is diverted into the United States, regardless of stipulations about Canada's future needs, the water is not, in fact, reclaimable (MacDonald 1966).

Other Diversion Schemes

Kootenai River diversion. The Saskatchewan Power Commission proposed that water from the Kootenai River be pumped through the Crowsnest Pass to the Old Man River, and water from the Columbia River be diverted over the mountains into the Bow River near Banff. The Old Man and Bow rivers feed

the South Saskatchewan River which flows across the provinces of Alberta and Saskatchewan. The Commission further proposed that water from the Peace River be diverted into the Athabasca and North Saskatchewan rivers via Lesser Slave Lake, then southerly via the Qu'Appelle Valley, to service southern Saskatchewan (Can. Counc. Res. Min. 1964).

This proposal created considerable discussion, especially in British Columbia where the Kootenai and Columbia diversions would occur and where downstream diversions on the Peace River would affect future use of that part of the Peace River in British Columbia.

Nothing has come of the Kootenai River diversion scheme, nor is anything likely to, but it has focused attention on the water needs of the prairies. The provinces of Alberta, Saskatchewan, and Manitoba have begun a study of the Saskatchewan-Nelson River basin. This basin is within the three provinces, the Saskatchewan River flowing east from Alberta into the northern end of Lake Winnipeg, in Manitoba, and the Nelson draining Lake Winnipeg northeast to Hudson Bay.

Clearwater-Red Deer River diversion. A project being considered by the Alberta Water Resources department is the diversion of water from the Clearwater River to the Red Deer River for irrigation in eastern Alberta and western Saskatchewan (Can. Counc. Res. Min. 1964). This scheme does not affect any British Columbia river - the Clearwater River rises in the mountains east of the B.C.-Alberta border. The plan is to divert the Clearwater River from the North Saskatchewan River to the South Saskatchewan River, via the Red Deer River.

The GRAND canal. The Great Replenishment and Northern Development, or GRAND, canal, proposed by Sudbury engineer, T.W. Kierans, would divert the Harricanaw River, which now flows through Ontario and Quebec into James Bay, into the Great Lakes. It would also create by dredging and lock-construction, a shipping route running the length of the Ottawa River (Canadian House of Commons 1960). The scheme was described to the House of Commons mines, forests, and water committee in 1960, but it was not considered economically feasible. During discussion on Great Lakes' water levels in 1964, the plan was revived and the federal government proposed to Ontario and Quebec that feasibility studies be carried out (Can. Counc. Res. Min. 1964).

The GRAND canal does not affect the waters of British Columbia but it indicates that river diversions are being considered as solutions to water problems in eastern Canada, also. A further implication is that the Great Lakes are part Canadian, part American, and some of the Great Lakes water is diverted into the United States, e.g., Chicago uses water from Lake Michigan to flush its waste water into the Mississippi River system.

The conclusion to be drawn from this discussion of international and interprovincial diversion schemes is that whatever policy is adopted it must be based on a thorough study of the resource, its present and future use, and the value of the resource to the nation. This study must be undertaken soon and completed quickly so that a national water policy may be established to guide Canada's use of this resource.

CHAPTER V. FOREST MANAGEMENT AND THE WATER RESOURCE IN BRITISH COLUMBIA

Legislation dealing with water rights in British Columbia was discussed in a previous section. This chapter will deal with watershed management in British Columbia with regard to erosion and water yield, timing, and quality.

1. WATERSHED MANAGEMENT AND LEGISLATION

Establishing the Forest Service

The forest lands of British Columbia were administered from 1871 to 1908 by the Chief Commissioner of Lands and Works, and from 1908 to 1912 by the Chief Commissioner of Lands. During this period, forest administration was under three independent branches (Griffith 1965):

(1) Timber Inspection Branch, responsible for the collection of royalties and other dues, as well as the control of trespass.

(2) Scaling Branch, responsible for the scaling of timber cut.

(3) Forest Protection Branch, responsible for the protection of forests from fire.

In 1910, the final report of the Royal Commission of Inquiry on timber and forestry in British Columbia was published. It recommended the enactment of a forestry bill to create a department of forests to be headed by a chief forester. The duties of the chief forester would include direction of the department in the care and maintenance of forest cover and the prevention of soil erosion (Fulton *et al.* 1910).

In 1912, the provincial legislature passed the Forest Act establishing the Forest Branch, and appointed H.R. MacMillan as Chief Forester. By early 1913, organization of the Forest Branch along the lines of the United States Forest Service was completed.

Forest Reserves

The Royal Commission of 1910 recognized the dependence of future development in British Columbia on water, either for irrigation or power, which "in turn will depend upon the maintenance of forest cover upon the mountain slopes, - the cover that holds up the snow and holds back the floods, sustaining a spongy soil for the storage of the water supply and the regulation of the flow of rivers" (Fulton et al. 1910, p. D66).

The commissioners agreed with the government's consideration of permanent forest reserves on headwaters. They expressed the view that one of the main duties of the department of forests should be the protection from fire of those reserves, as well as all high altitude forests, not only for water supply but also for "the prevention of soil erosion and catastrophes by land and snow slides" (Fulton et al. 1910, p. D66).

The creation of forest reserves was suggested by others about that time, also, as the following quotation attests:

> B.C. has been very dilatory in the matter of establishing forest reserves. Extensive reserves should be placed over the gathering grounds or water sheds of our larger streams and the forest cover held inviolate for all time. . . . The imperative necessity of creating forest reserves has been a burning question for governments all over the world, and in many cases large areas have been bought back again to be created into reserves (Sutton 1910, p. 18).

The strong feeling for forest reserves was based to some extent on an extreme view of the relation of forests to the hydrologic cycle, a view which was especially prevalent about that time. Sutton (1910, p. 18) expressed this view: "It is now well recognized that a forest covering not only greatly lessens evaporation, but also increases the rainfall and checks the rapid descent of water from the higher levels."

The authors of the Royal Commission report and Sutton expressed their views on the need for forest reserves for the protection of watersheds. During the forty years following its beginning in 1912, the Forest Branch maintained a policy of establishing forest reserves and provincial forests. However, a brief review of the history of forest reserves in British Columbia indicates that watershed protection was not the main reason for their establishment.

The Forest Act of 1912 provided for the creation of forest reserves "for the maintenance of the timber growing or which hereafter may grow thereon, for the protection of the water supply" (Prov. of B.C. 1912, p. 90). In 1913, Chief Forester MacMillan advocated the establishment of forest reserves where needed for the protection of streamflow (B.C. Dept. of Lands 1913) but one year later, MacMillan stated that forest reserves were not necessary because legislation existed to safeguard against alienation of timber areas (B.C. Dept. of Lands 1914). On December 31, 1914, notice appeared in the British Columbia Gazette of the establishment of the first forest reserve, the Elk River Valley Forest Reserve. The area was described as being suitable only for growing timber and nothing was said of watershed protection (B.C. Dept. of Lands 1915).

In 1922, four forest reserves were established, covering 1,200,000 acres of the higher elevations of the Okanagan Lake watershed. These were the Okanagan Reserve on the west side of the lake, and Aberdeen Mountain, Grizzly Hills, and Little White Mountain Reserves on the east side (Griffith, undated).

The Inkaneep Forest Reserve in the south-east section of the Okanagan Valley was established in 1923 to serve a double purpose "since it is covered not only with a valuable stand of young timber which will be of future commercial value, but also covers the headwaters of Vaseau, Sawmill, and Inkaneep Creeks, and the conservation of the timber on the reserve is essential for regulating the streamflow therein" (B.C. Dept. of Lands 1924, p. 19). In the same annual report, it was felt necessary to define "reserve".

> It might be well here to reiterate that the word 'reserve' may create a wrong impression. There is no idea of locking these areas up and withholding them from use, but rather the proclamation dedicates them to the purpose for which they are best suited - timber production - with which may be coupled as protection, prevention of floods, game, and aesthetic purposes (B.C. Dept. of Lands 1924, p. 19).

In the period 1924-1929, 13 new forest reserves, or provincial forests as they were called after 1924, were established. In 1930, 14 national forests were transferred to the province (Griffith, undated). Two of these, the Arrowstone Forest and the Hat Creek Forest had been reserved by the dominion government for watershed protection but the province questioned their value as provincial forests. Of Arrowstone, the 1933 annual report of the Department of Lands stated, "it is doubtful if

it is worth the expense of administration as a Provincial Forest," and of Hat Creek Forest, "it is doubtful if this object [watershed protection] justifies its continued administration as a Provincial Forest" (B.C. Dept. of Lands 1934, p. 7). In 1934, the Arrowstone and Hat Creek Forests were cancelled, "having been found to be of little value for the protection of commercial timber" (B.C. Dept. of Lands 1935, p. 4). Other provincial forests were established after 1930, however, and by 1949, 52 had been reserved.

The point of this brief discussion of the history of forest reserves in British Columbia is that at no time was watershed protection the main consideration; in fact it appears as if it were a very minor consideration. Ease of administration of the timber resource seems to have been the prime reason for the establishment of forest reserves and provincial forests.

The Royal Commission of 1955-1956

The terms of reference of the 1955 Royal Commission relating to the forest resources of British Columbia included inquiry into "the maintenance of an adequate forest cover with a view to the regulation of moisture run-off and the maintenance of the levels of lakes and streams" (Sloan 1956, p. 2). Sloan (1956, p. 721) commented that in the 1956 inquiry, watershed management "did not appear to loom as large as it did in 1944-45." Much of what was written on watershed management in his 1956 report was from the 1945 report in which mention was made of the role of forest cover in water-shed protection.

Some of the recommendations made by Sloan in his 1956 report are given below to illustrate their non-specific nature. The nature of the recommendations is understandable in view of the general lack of knowledge of how to achieve particular watershed objectives. However, the value of such general recommendations is questionable and the need for direction concerning how to obtain the necessary knowledge is obvious.

Sloan suggested that thinning to reduce water consumption by the forest may be necessary to improve the watershed. In some cases, most of the non-commercial cover may be removed to increase water supply. Where flood and erosion damage is not anticipated, the cut may be as heavy as a sustained-yield policy would dictate. Where stream-flow regulation is important, the cut must be light enough to maintain a fairly complete forest canopy. He concluded the recommendations section of his report with the following statement (1956, p. 723):

> The practical application of these fundamentals will necessitate considerable research and experimentation . . . .
>
> Methods . . . must be determined by a close study of local conditions by men equipped for this work by training and experience. . . .
>
> Logging methods must also be governed by local conditions and a careful appraisal of conflicting values.
>
> All of these matters must, however, be decided according to the circumstances peculiar to the area under review.

The recommendations would have been of greater value if they had included direction as to the government agency which should accept responsibility for watershed studies. The Forest Service submission to the Royal Commission inquiry indicated that its research division was prepared to

undertake studies on soil and water conservation (Sloan 1956, p. 632). However, such studies have not been carried out, although Stewart (1963) prepared a set of guidelines for watershed protection in British Columbia. The responsibility for erosion studies was assumed in 1964 by the B.C. Water Resources Service (B.C. Water Res. Serv. 1965). As indicated in a preceding section, the Water Resources Service has documented many cases of erosion. Concerning erosion studies, however, this agency has done little more than the Forest Service.

The Forest Act of British Columbia

Another indication of the attitude toward watershed management in British Columbia may be found in the statutes governing forest administration in the province. The B.C. forest act (Prov. of B.C. 1964) makes no reference to soil and water conservation whereas the first forest act passed in 1912 (Prov. of B.C. 1912) referred to the creation of forest reserves for maintenance of timber production and protection of water supplies.

A brief look at forestry laws in the western United States and Alberta will provide a comparison with the B.C. forest act. Colorado forestry laws grant authority to the forest service to "foster and promote the control of soil erosion" on public forest lands (Colo. State For. Serv. 1966, p. 1). Stipulation is also made that no trees needed to conserve the snow, ice, or water of any irrigation district shall be cut from any part of the public domain, except as provided in the statutes (Colo. State For. Serv. 1966).

Forestry laws of the state of Idaho include in the preamble the statement that water resources are among the most important natural resources of the state, and that "forest cover is a vital factor in regulating and conserving streamflow and water supply; forests are effective in conserving soil, preventing its erosion and consequent silting of stream channels and reservoirs" (State of Idaho 1964, p. 20). Section 38-304 of the Idaho forestry laws lists general forest practices to guide logging of public and private lands within sustained-yield districts, in order to protect the site.

Under Utah forestry laws, a board of forestry and fire control was established whose responsibilities included "protecting non-federal forest and watershed areas on conservation principles" (State of Utah 1961, p. 4). In California, the Forest Practice Act requires that private forest lands be managed according to forest practice rules established for each of four districts. For the Redwood District, for example, section 914.8 sets out regulations to control erosion, and deals with runoff from road surfaces as well as stream-bed crossings (State of California 1965).

Section five of the Forest Reserves Act of Alberta states that forest reserves have been created for the conservation of forests and other vegetation, and "for the maintenance of conditions favourable to an optimum water supply" (Prov. of Alberta 1957, p. 1792). Section 10 authorized the Lieutenant Governor in Council to designate areas for the study, experimentation, and demonstration of watershed management (Prov. of Alberta 1957). This act was repealed with the Forest Reserves Act of 1964 taking its place (Prov. of Alberta 1964). However, the new act is

substantially the same as its predecessor.

Of course, reference to watershed management in the forest act does not necessarily indicate the consideration actually given in practice to watershed protection. Nor does lack of reference to a specific aspect necessarily limit its consideration in practice. Forest laws generally contain a rider of the following nature, which is contained in the B.C. forest act (Prov. of B.C. 1964, p. 1537):

> (1) The Lieutenant-Governor in Council may make such regulations not inconsistent with the spirit of this act as he considers necessary or advisable for carrying out the purpose and provisions of this act, including matters in respect of which no express or only partial or imperfect provision has been made.
>
> (2) Without thereby limiting the generality of the provisions contained in subsection (1), the power of the Lieutenant-Governor in Council to make regulations extends to the making of regulations . . . .

An example is the conditions imposed on the successful bidder for a licence to cut crown timber on the Windermere Creek watershed of the East Kootenay region of British Columbia. These include the following conditions dealing with watershed protection (B.C. Dept. Lands, Forests, Water Resources 1964):

(1) Logging and road-building debris shall be kept out of streams and out of reach of high water.

(2) Tractors and logging equipment shall be kept out of streams and away from the banks, except for the minimum number of necessary crossings.

(3) No logging shall take place within two chains of any sink hole.

The above conditions indicate that consideration is given to watershed protection in British Columbia even though the forest act does not specifically refer to watershed protection. However, the omission of references to watershed management in the forest act probably indicates the general unconcern with this problem. Also, although timber-sale contracts contain conditions aimed at protecting the watershed values, the degree to which these conditions are adhered to and enforced is the real test of the consideration given to watershed management.

2. EROSION

Erosion is not generally recognized as a problem in British Columbia. How serious erosion is in this province and whether, in fact, it is a problem will be considered in this chapter.

British Columbia's deputy minister of Water Resources, in charge of the provincial agency whose responsibilities include erosion studies, stated that the Water Resources Service has given a great deal of thought to erosion and has found "remarkably little erosion no matter how serious the situation of denuding a forest area" (B.C. Nat. Res. Conf. 1964, p. 92). Paget, the deputy minister, cited as an example the area burned in Manning Park on the Hope-Princeton highway, in 1945. He stated that there had been little, if any, erosion on the hillsides and the streams were running clear even though reforestation had not been successful because of the severity of the fire (B.C. Nat. Res. Conf. 1964).

However, erosion due to man's activity is apparent in British Columbia. Accelerated erosion is locally severe and may be noted by casual

inspection of logged hillsides or by study of individual watersheds. It does seem, however, that erosion is not as severe, generally, as would be expected from the appearance of some logged areas.

The files of the Water Resources Service provide examples of erosion due to logging and roadbuilding. Some of these will be cited in the following sections.

Examples of Erosion

Brodie Creek flood. The following example is from a report by Pollard (1965).

Brodie Creek is a small stream flowing southwest out of the Slocan Range into the Slocan River, near Nelson. The creek basin is about one-half square mile in area, from 1,500 to 6,700 ft. elevation. The watershed above 2,800 ft. was logged between 1955 and 1964 to a 14-inch diameter limit.

In April, 1965, Brodie Creek flooded, washing out a gravel road and depositing mud, boulders, and brush over an acre of hayfield. Windfalls in the creek as well as trees felled into the channel during logging some years ago and power-line clearing in 1957, were floated downstream forming moving dams. It appears that water piling up behind the obstructions finally broke through on April 13, 1965.

There was no appreciable rain immediately preceding the flood, and the weather was warm. On the day after the flood snow covered about 20 per cent of the logged area. Runoff was from snowmelt, and the rate was not unusual for the time of year. No floods were reported for any other

stream in the Slocan Valley at this time.

Pollard (1965) indicated that the sequence of events leading up to the flood was probably as follows. An unnaturally-heavy spring runoff was conveyed via skid trails to an unlogged hillside of 40° slope. A slide occurred on the slope triggered, apparently, by saturation of the soil. Trees and earth from the slide cut a narrow swath for 1,000 ft. across the unlogged forest (slope 30°). This material piled up just above Brodie Creek. As the creek level rose, water and debris from upstream were impounded behind this material. Finally the dams gave way causing the flood and damage below.

The report stated that no cross-ditching of skid trails was apparent, and perhaps none had ever been constructed. The conclusion was that the flood was due to runoff reaching the slide area via logging skid trails. The owner of the agricultural land on which the debris was deposited laid a claim against the logging company. The claim was settled out of court according to information from the insurance adjusters for the insurer (Leighton 1966).

This would suggest that the insurers of the logging company considered the evidence too strong to refute. However, Leighton (1966) stated that the claim was settled out of court not because the insurer was legally liable, but for reasons communicated to the writer with the stipulation that reference not be made to them in this thesis. A similar settlement was made with the provincial Department of Highways.

The argument put forth by the insurer to support its stand is interesting (Leighton 1966, p. 1-2):

> Those timber licences had been completely abandoned, not less than six months prior to the occurrence of the land slip. The land upon which the timber licenses rested had reverted to the total control of the Crown.
>
> . . . . . .
>
> It was further argued in the alternative that anything which our insured had done on the ground, was with the approval of the Forest Service, as well as being without negligence, insofar as road construction techniques were involved. It was further argued, and this is a principle of law, that even though our insured's road construction might have been the cause of moisture accumulation at any particular point, the likelihood that that moisture accumulation would produce a slide, was not foreseeable by our insured, so that our insured would not be liable therefore.
>
> Again, this is based on a legal principle, we argued that even if our insured should have foreseen the consequences of moisture accumulation so as to produce a slide, there was no reason to foresee that that slide would cause a blockage in the creek, or alternatively that the creek would overcome that blockage and sweep down its valley to do damage to the Department of Highways and Mr. Plotnikoff. It was argued that the damages of the claimant were too remote from the source of the commencement of the incident to be anything for which Pacific Logging could be liable.

An interesting point is the insurance company's claim that even if the damage were the result of the logging, the logging company was not liable because (a) the timber licence had been abandoned six months before the land slip, and (b) whatever the company had done was with the approval of the Forest Service.

It would seem that, if, by acts of commission or omission of the logging company, damage was incurred, the fact that the timber sale had been abandoned should have little bearing on the case. Regarding (b), approval by the Forest Service is usually required for the logging plan, including location of haul and main skid roads. The intent is certainly not to assume responsibility for the action of the licensee, but a protective

clause is probably part of the contract and similar to one on the Notice of Timber Sale (B.C. Dept. Lands, Forests, and Water Resources 1964, p. 2A): "The licensee shall not injure or impede in any way with the rights and privileges of the said holders of the said claims [mineral], and will indemnify and save harmless the licensor from and against all claims for loss and/or damage. . ." . Whether such a clause does, in fact, indemnify the licensor is questionable.

Regarding the further arguments, it is doubtful that because "the damages of the claimant were too remote from the source of the commencement of the incident" (Leighton 1966, p. 2) the logging company could not be held liable if it initiated the first action.

The fact is that a claim was laid aganst the logging company and an out-of-court settlement made. This is not an admission of fault nor does it imply guilt, but simply avoids the costs of defense and any judgement that a court might possibly render.

Giveout Creek slide. On April 3, 1966, a slide deposited about 1,400 cubic yards of debris in Giveout Creek, near Nelson, B.C. Information on the slide is from Pollard (1966a).

Giveout Creek drains an area of six square miles and flows northeast into Cottonwood Creek. The elevation of the watershed is from 2,290 ft. to 7,260 ft. Twenty-one water licences on the creek authorize the use of water for domestic purposes in 23 houses and 18 trailers and for irrigation of 12 acres of land. The slide temporarily destroyed its value as a domestic water supply. The debris which had accumulated in the channel

endangered, for a time, a road bridge and the property below the bridge. The bridge would likely have been taken out and the property covered with debris had the stream flushed itself suddenly.

The slide was caused by the slip failure of a fill on the Athabaska Mining road. The fill appeared to have become saturated by spring runoff flowing down the road. On April 7, four days after the slide occurred, the flow down the road was estimated at one-quarter c.f.s., indicating that the road was intercepting a considerable amount of drainage from the hillside above the road. The road has been in existence for over 40 years, although at the slide location it was relocated in 1953. It is used by a company logging upstream on the Giveout Creek watershed and by a mining company.

When the slip failure occurred, fill material for 150 ft. along the road slid down the steep slope, shearing off the mantle to a depth of two to three feet. About one-half of the slide was stopped about 100 ft. above the creek by a heavy forest growth. The other half continued down into the creek, clearing a 30- to 50-ft. swath through the trees, climbed 20 ft. up the opposite slope and veered off downstream. By April 15, three more slides had occurred in the same location. A fifth slide occured on May 5 or 6 after which a more thorough inspection of the area was carried out by personnel of the Water Rights Branch.

No cross-ditching was evident and erosion had occurred on most of the roads. Skid trails, some going up draws, were carrying a considerable amount of water onto the main haul road. The main haul road had no cross-drains near any of these skid trails except one partially-plugged culvert.

According to the logging company, it did not cross-ditch the main haul road after logging had been completed in the autumn of 1965 because the road was still being used by the mining company. Neither company had an easement to use the road. The Forest Service indicated that this was an oversight on its part and an easement should have been issued with the timber sale. However, no cross-ditching clauses would have been included in the easement, had one been issued, according to the local forest ranger. The road had been cross-ditched regularly until 1965, according to the assistant forest ranger (Nelson Daily News 1966).

Other aspects of the timber sale are of interest. No reserve was placed on the timber adjacent to the creek, nor was the timber sale referred to the Water Rights Branch for comment, as is often done.

The conclusion reached by the Nelson district engineer of the Water Rights Branch was similar to that of the Forest Service forester who inspected the area. The conclusion was that logging by itself did not contribute appreciably to the silting of Giveout Creek, but that poor road location and construction caused the slides. Lack of proper road maintenance should also be included as one of the causes.

Unnamed Creek flood. On May 5, 1966, an unnamed creek near Nelson, B.C., flooded, washing out part of a private road and requiring clearing of the stream channel. Pollard (1966b) reported on this flood. Information in this section is from his report.

The creek is a small mountain stream draining a part of the southwest slope of Slocan Ridge, and flowing into the Slocan River. During

early April, 1966, a slide occurred on a small ephemeral tributary of the creek. The slide began on a skid trail which was bulldozed either in or near a depression which was the channel of the tributary. The material on which the trail was located was probably saturated by spring snow-melt runoff, triggering the slide. This slide was small, probably less than 400 cubic yards, but it appears to have caused a larger slide of about 2,000 cubic yards in the same depression. It was this slide which probably caused the flood on the unnamed creek.

The area was logged in 1964 but the logged area extends only a few hundred feet above the slide, and not all of the skid trails drain toward the slide. Pollard's (1966b) report concluded that the construction of the skid trail in a stream channel may have caused the flood but the evidence is circumstantial.

Certainly, the evidence is far from conclusive but it is another example of poorly-located logging roads and trails.

River Bank Erosion

In 1955, the British Columbia Federation of Agriculture completed a survey of agricultural land lost through river bank erosion (B.C. Fed. Agr. 1955). In only a few of the cases discussed has reference been made to the cause of the erosion, and in those cases little evidence has been presented. The following excerpts from the report are given to indicate the areal extent and the seriousness of the problem.

Salmon River - Falkland area. Two acres of arable land were eroded by high water from one farm in 1955. In addition, the flooding left a

heavy gravel deposit on the cultivated fields. Windfalls in the river were blamed for causing the buildup of gravel bars, which in turn were responsible for raising the flood waters over the banks of the river. The comment is included that the Salmon River "is one of the worst rivers for windfalls, some of which have been caused by logging operations" (B.C. Fed. Agr. 1955, p. 18).

Shuswap River - Mabel Lake area. The Shuswap River in this area is fast flowing with many windfalls in the channel causing the continuous cutting of new channels. This condition did not prevail in the past when logging companies kept the river free of windfalls to allow log-driving. (This is one of the few beneficial effects attributed to log-driving.) The author stated that log jams on the river could be decreased by cutting the taller trees along the river's edge. The remaining root system would protect the bank and there would be no tall trees to windthrow into the channel. (This practice is contrary to good watershed management.)

Stream bank erosion was halted temporarily by cutting straight channels to bypass bends in the river.

Elk River - Fernie area. "This is one of the worst rivers for erosion in British Columbia and I am told that logging in the watersheds has stepped up the suddenness of the high water in the past ten or fifteen years" (B.C. Fed. Agr. 1955, p. 37). Ten acres of farm land, as well as the barn, house, and outbuildings were washed away on one farm during the spring flood of 1954.

The above are the only examples in the report where reference is made to logging, but many other cases of bank erosion are cited. Some bank erosion on the lower Fraser River is attributed to the backwash of the high powered gill-netters which ply the river.

Many areas of the province are included in the report, including: the Skeena River near Terrace, Bulkley River near Houston, Salmon and Fraser River near Prince George, North Thompson River between Barriere and Kamloops, Shuswap River near Mabel Lake, Kicking Horse River near Golden, Elk, Kootenay, and St. Mary Rivers in the Fernie-Fort Steele area, Similkameen River near Princeton and at Keremeos, Kettle River near Westbridge, lower Fraser River near Agassiz, Pitt Meadows, and Albion, and Cowichan River near Duncan.

Some indication of the amount of land lost to bank erosion by single farms is given by the following extreme values reported in the survey: a strip 150 yards wide from one farm on the Skeena River, between 1917 and 1955; 70 acres of uncultivated land in the period 1948-1955 along the same river; a 10 to 20 ft. strip per year along the North Fork River; 50-60 acres of ranchland near Keremeos on the Similkameen River, between 1947 and 1955; and in the same area, 28 acres of ranchland in 1948.

Sedimentation

Associated with erosion is sedimentation. Material eroded from one area accumulates in other areas, often where its presence is detrimental. Where sediment accumulates in stream channels the storage capacity of the channel is decreased, often forcing high flows to overtop their banks and

flood the surrounding country. Sediment deposited on farm land often impairs the quality of the land as in the example cited by the B.C. Federation of Agriculture (1955) in which 80 acres of ranchland had sand, gravel, and logs deposited on it by the Similkameen River from 1947 to 1955.

Another example is that of Lagace Creek near Hatzic Lake, as reported by the B.C. Water Rights Branch (Raudsepp 1953). During heavy rains in fall and winter Lagace Creek was subjected to severe channel sedimentation. The filling of the creek channel resulted in increased frequency and height of over-bank flows, sand deposition on fields along the channel, and obstructed drainage of the bottom lands. The creek washed out bridges and sections of the highway on several occasions. The provincial Public Works Department removed the accumulated sediments several times, the last cleaning previous to the report being in the spring of 1953, and costing $10,000.

The report suggested that flash floods on Pattison Creek, a tributary of Lagace Creek, bypassed its former channel and cut a new channel through the sandy-gravelly fill of the valley. This excavation of a new channel contributed large quantities of sediment to Lagace Creek. The bypassing of the old channel on Pattison Creek was attributed to obstructions left in the channel during logging operations.

The files of the B.C. Water Rights Branch contain many other examples of erosion and sedimentation of the streams of the province.

Large-Scale Earth and Snow Movement

The examples cited of erosion, sedimentation, and floods are typical of those that occur in many regions of the province. Little attention is paid to such occurrences except by those whose property is damaged. At the other extreme are those slides and floods that are of such massive scale that they result in headlines in newspapers across the country. A few examples of these will be cited to indicate their severity and frequency of occurrence in British Columbia and also to point out their relation or lack of relation to land management.

Hope-Princeton slide. On January 9, 1965, a 200-ft. thick section of an unnamed mountain on the Hope-Princeton highway crumbled and slid 2,000 feet down into the valley, 700 feet up the base of Coulter mountain, and back down into the valley. An estimated 15 million cubic yards of material slid off the 6,300 ft. mountain covering a 1.5 mile stretch of the southern trans-provincial highway to a depth of 400 feet in places and filling the basin of Outram Lake. Four people were buried in the slide along with their vehicles.

A popular theory as to the cause of the slide is that snow, which had piled to a depth of several feet on the mountain, began to thaw in a brief but sharp temperature increase the day before the slide. Melt water that had run into the faults in the rock subsequently froze, the consequent expansion forcing fractured surfaces further apart. This triggered small slides which, in turn, were partly responsible for the main slide (Hammond 1965, MacDonald 1965a, Vancouver Sun 1965d). This

or a similar explanation, could very well have been the cause. Dr. K.C. McTaggart, professor of geology at the University of British Columbia stated that it would be some time before the exact cause of the slide would be known, but that slides are frequent where precipitation is heavy in mountainous areas. The accumulation of eroded rock and mud eventually has to come down, whether it is pressed by its own weight or the weight of snow and water (Leiren 1965).

Ocean Falls snow slide. A slide swept down from the 4,000 ft. Caro Marion Mountain on January 13, 1965, killing seven people in the town of Ocean Falls. A 200-ft. swath was cut through one section of the town burying it under 10 to 12 feet of debris. A minor slide preceded the main slide by two hours. Up to 50 in. of snow covered the area before the slide but temperatures well above freezing were experienced during the week preceding January 13, accompanied by heavy rains. This combination is believed to have caused the snow slide. The community has had a history of slides but none before have caused fatalities (Vancouver Sun 1965e, 1965f).

Granduc avalanche. An avalanche of snow and ice hit the Granduc mining camp on February 18, 1965. The camp was situated at the junction of the north and south forks of the one-half mile wide by five-mile long Leduc Glacier. Twenty-six men were killed by the slide which originated on the glacier (MacDonald 1965b, Vancouver Sun 1965g, 1965h, 1965i).

Lillooet slide. On April 10, 1965, a 13-year-old boy was killed when a soft shale and clay bank at the side of the road near Lillooet crumbled and buried the boy along with three companions. The 20-ft. high bank gave

way after the boys had begun to carve their initials in the soft shale at the foot of the cliff which bordered the road. The slide contained only about 10 cubic yards of material (Vancouver Sun 1965j) and would normally have attracted very little attention. It illustrates, however, that the severity of a slide is reckoned mainly by the amount of damage or the loss of life that results, and not simply by the amount of material transported. This has some implication with regard to the general belief that erosion is not severe in British Columbia. Most cases of erosion go unnoticed if loss of life or direct property damage has not resulted from the occurrence.

Ramsay Arm slide. On September 16, 1964, a landslide swept down a mountainside, through a small logging camp, and out into the sea at Ramsay Arm, 28 miles northeast of Campbell River. Three people lost their lives in the mud and rock slide which, according to the newspaper report of the tragedy, was triggered by very heavy rains on the day before the slide. The estimated two inches of rain that fell in the 12 hours before the slide saturated the earth in a logged-off area where the slide originated (Olding 1964).

Indian Arm slide. On October 5, 1965, after two days of heavy rain, a 200-ft. wide strip of earth broke away from the hillside and flowed 1,000 ft. before reaching a logging camp at Indian Arm, 10 miles from Deep Cove. Many of the camp buildings were pushed into the sea; what was not, was buried in mud. The slide caused an estimated $80,000 loss (Ablett 1965).

Revelstoke avalanche. A massive snow slide swept down off the shoulder of Mount MacDonald near the summit of the Rogers Pass highway on January 8, 1966, killing two men. The slide, 1,000 ft. long and up to 18 ft. deep across the highway, was at almost the same spot as the 1910 slide which killed 66 men. At the time of the 1966 slide the highway was closed because of avalanche warnings due to the sudden rise of temperature from 8°F. to 45°F. The area had been subjected to artillery charges on the day before and a slide had been produced (Vancouver Sun 1966b).

Recognition of the Problem of Erosion

The examples of erosion that have been given indicate that erosion problems do exist in British Columbia. The fact that many of the cases cited were in the Nelson region indicates only that examples were better documented there, probably because of greater awareness of the problem and ability to recognize erosion by the Water Resources Service personnel in that region.

If the observer knows what to look for, evidence can be found of watershed damage by erosion in most regions of British Columbia. Rills and gulleys are the most obvious evidence of erosion, but there are many more signs that are less obvious but just as indicative of erosion. Knight (1964) pointed out in his study of erosion after slash burning on the south-west coast of Vancouver Island that erosion in the sense of gullying and mass soil removal is not common in that region. However, there is other evidence that accelerated erosion does occur. Knight reported soil losses of up to 10.8 tons/acre in a 26-day period on a bare slash-burned area.

This amounted to five per cent of the amount estimated by Knight to be potential erosion material, although the average amount eroded was only slightly over one per cent of the potential.

Sartz (1953) found that 1.1 to 2.2 in. of soil had eroded from bare, burned-over slopes in Oregon in one year. He suggested that erosion is much more common in the Douglas fir region than is generally recognized.

Some indicators of erosion are plainly visible but go largely unnoticed, e.g., banks undercut by high water, channels gouged deeper by runoff, and freshly-deposited sand and gravel along stream channels. More noticeable is muddy water in streams, ponds, and reservoirs which shows that soil has been washed from higher elevations. Newly exposed plant roots indicate erosion also.

Sheet erosion is much less noticeable than gully erosion, but can be detected by close examination. Soil particles that have been splashed on the leaves of plants by raindrops are an indicator of this type of erosion, as are pedestals of soil capped by stones or resistant clods. A puddled soil surface that forms a crust upon drying is evidence of soil disturbance by raindrops and sheet erosion. As Gleason et al. (1955) pointed out, sheet erosion goes almost unnoticed except where the topsoil is becoming thin. Thinning topsoil is usually indicated by a change in soil colour from darker to lighter as the subsoil is exposed.

There is no reason to believe that erosion problems related to forest management are confined to particular regions in British Columbia, although there may be a greater incidence of such problems in one area because of greater activity. Therefore the discussion and recommendations

in the following sections on erosion are meant to apply to the whole province.

Administrative Measures

From the administration standpoint, it must be recognized that logging and road construction are erosion-causing agents and that losses do result in British Columbia from such erosion. While erosion problems are often overlooked, irrigationists, for example, indicate that sediment-laden waters from logged areas are causing concern.

In some districts of the province, timber-sale applications are usually referred to the Water Rights Branch for comment. This suggests that the procedure has become established because the need to protect particular watershed values has been recognized. In one district (Kelowna) at least, the Water Rights Branch solicits the comments of water users, such as municipalities and irrigation districts, on timber-sale applications.

Training of Forest Service personnel. The responsibility for watershed management rests to a large degree with the B.C. Forest Service, and decisions as to how watersheds should be logged and roads constructed must be made by Forest Service personnel. However, the opinions of such groups or agencies as municipalities and irrigation districts should certainly be considered. It is, therefore, necessary that Forest Service staff be trained not only in forest mensuration, logging, and utilization, but also in the management of other watershed resources such as water and soil. Not only is the Forest Service entrusted with

management of the forests from a timber supply point of view but also management of the total land resource.

Those attending the B.C. Forest Service Training School should receive training in watershed management to a degree sufficient to enable them to safeguard watershed values during logging and road construction. Both the Advanced, or Ranger, Course and the Basic Course offered by the Training School should include watershed management. As well, there should be special in-service training courses in watershed management given periodically. These courses should be directed mainly to the Forest Ranger, the man in the field responsible for the supervision of logging operations on Crown land.

To supply both the Forest Service and forest industry in British Columbia with men well-trained in watershed management, the University of British Columbia, regional colleges, and technological schools should increase the emphasis placed on watershed management.

Forest Service staffing. Not only must present Forest Service staff be trained in watershed management, staff must also be increased in order to keep up with the increasing burden of forest administration in the province and to permit field men to spend the time required in inspection and enforcement.

During 1964, the permanent Civil Service establishment of the Forest Service was increased by only three, from 860 to 863. However, 82 employees left the Service and only 63 were taken on staff, for a net loss of 19. Of those leaving the Service, 18 were graduate foresters and engineers, whereas of those entering, only 13 were in these classes (B.C.

Dept. Land, Forests, and Water Resources 1965). In 1964, total Forest Service personnel numbered 3,094 (1,956 continuously employed and 1,138 seasonally employed) (B.C. Dept. Lands, Forests, and Water Resources 1965). The comparable figure for 1956 was 3,137 (1,620 continuously and 1,517 seasonally employed) (Sloan 1956). During the period 1956 to 1964, a net decrease of 43 employees was registered in the Forest Service, although there was a net increase in the category of continuously employed.

Sloan (1956, p. 545) stated that "the [Forest] Service generally is understaffed, overworked, and - measured in terms of responsibility - underpaid." He concluded that the Service needed more skilled men and more money. Sloan suggested that salaries would have to be raised in order to attract men to the Service and to reduce the number leaving for industry. The situation in 1967 appears similar to that described by Sloan.

Another indication that the B.C. Forest Service is understaffed is the degree to which Sloan's recommendations have been carried out with regard to forest protection personnel. Sloan recommended that the 140 lookout towers manned in 1956 be increased by 266, to 406 (Sloan 1956). In 1964, the number of manned lookout towers was 160 (B.C. Dept. Lands, Forests, and Water Resources 1965), an increase of only 20 in the past nine years.

The need for lookout towers for fire detection is probably not as great as Sloan foresaw it, because of the greatly increased use of aircraft for fire patrolling. In 1944, protection flying amounted to 210 hours; in 1955, 2,280 hours (Sloan 1956); and in 1964, over 6,000 hours (B.C. Dept. Lands, Forests, and Water Resources 1965).

However, data do not indicate any decrease in the area burned annually over the past decade. The area burned annually during 1930-1954

averaged 287,000 acres (exclusive of grazing or pasture land and non-productive sites burned); for the period 1950-1955, 177,000 acres (Sloan 1956); and for the period 1955-1964, 365,000 acres (B.C. Dept. Lands, Forests, and Water Resources 1965).

A direct comparison of these figures is not a valid judgement of the quality of forest protection, however. The figure for 1930-1954 does not include the area burned in the northern region of the province. This region was later added to the Prince George forest district, and the area burned in that region is included in the figures given above for 1955-1964. Forest fire hazard during the past decade may have been much higher than during the previous period due to short-term climatic trends. A third factor to be considered is the greatly increased use of forest land by those seeking recreation. More fires are attributed to campers and smokers than any other single agent. For the decade 1944-1954, 31.6 per cent of the total number of fires was caused by campers and smokers (Sloan 1956), and for 1955-1964 the per cent was 23.1 (B.C. Dept. Lands, Forests, and Water Resources 1965).

The forest protection aspect was discussed here as an indication of the under-staffed position in which the Forest Service operates. However, it suggests another aspect, and that is the loss of watershed protection caused by damage to forest and ground cover, litter, and soil, by fire. The comparative figures of area burned during two periods is less meaningful in this context. What is important is the tremendous annual loss due to forest fire, and it is obvious that the situation must be

improved. A very important step in improving watershed management in British Columbia is reduction of the area burned annually.

Protective clauses in timber-sale contracts. Another step from the administration point of view concerning watersheds is the inclusion of protective clauses in timber-sale contracts and road easements. The Forest Service does, in many cases, insert conditions in its contracts concerning such things as streamside reservations, logging method, debris in channels, and road construction (Stewart 1963). One example is the timber sale on Windermere Creek watershed. Three of the clauses in the Notice of Sale of Crown Timber preceding the awarding of the timber sale specified:

> Prior to the commencement of operations on the sale area, the licensee shall mark on the ground the location of all haul and main skid roads, landings and millsites, and shall submit a logging plan showing their location as established on the ground (B.C. Dept. Lands, Forests, and Water Resources 1964, clause 2, p. 2D).
>
> Further, it is understood and agreed that following approval of the logging plan, no logging operations shall be carried out until the main haul road has been completed to the satisfaction of the District Forester (B.C. Dept. Lands, Forests, and Water Resources 1964, clause 17, p. 2D).
>
> Temporary or permanent culverts and cross drains shall be of a size and be placed to provide adequate drainage . . . (B.C. Dept. Lands, Forests, and Water Resources 1964, clause 19(e), p. 5).

However, in some cases protective clauses are not included in the contract when they should be. For example, in the previously cited case of the Giveout Creek slide, the local Forest Ranger stated that no cross-ditching clauses would have been included in the road easement, had one been issued (Pollard 1966a). Due to an oversight on the part of the Forest Service, a road easement was not issued with the timber sale. It is apparent from the slide which occurred that cross-ditching should have been a condition of the contract.

Enforcement of contract conditions. In spite of the clauses inserted in the Windermere Creek timber sale, the first two of which required prior approval of the District Forester, a brief inspection in October, 1966, by the writer, of the haul road on the timber sale showed that (1) in several places the road fill encroached upon the stream, and this at a period of comparatively low water, and (2) one of the culverts was being washed out, either because of under capacity or improper installation.

The inclusion of watershed protective clauses in timber-sale contracts and road easements is a necessary but not sufficient step to protect watershed values. Inspection and enforcement must follow. Without these, not only may the watershed of a particular sale incur damage, but the

attitude of timber operators toward adherence to contract conditions in general may be adversely affected, making even more difficult the job of administering Crown lands.

Timber harvest subsidies. If the cost of getting logs from a particular area to the mill is greater than the value of the logs at the mill, the area will not usually be logged. The result is the same if the situation has been brought about by increased logging and hauling costs due to the imposition of watershed protection standards. Generally, this is as it should be. For example, in such areas as exposed ridge tops with shallow soils, the cost of protecting the soil properly during and after logging would be prohibitive as far as logging is concerned. Therefore, the timber harvest must be foregone or subsidized. Often, foregoing the timber harvest is the valid alternative.

However, in some situations where the cost of watershed protection would prohibit logging, the timber should be harvested and the harvest should be subsidized. These situations would include areas where avalanches and earth slides are especially hazardous and where a managed forest offers a greater degree of protection than an unmanaged, uncut forest. A forest left completely unmanaged may have a greater chance of being devastated by insect or disease attack, by fire, or by storms. This is especially true of over-mature stands.

In Switzerland, the protective value of managed forests is recognized, and the forest act allows higher government subsidies for forests that are managed for protection against avalanches, falling rock and ice,

earth slides, erosion, and floods, than for forests not managed primarily for protection (Pfeiffer 1966).

Although in some cases watershed management would be better served by management of the forest, in particular areas the damage done by common logging methods would exceed the benefit derived. Balloon or helicopter logging might be considered in such cases. There are many problems involved in a scheme such as this. For example, would the number of cases warrant a private company's maintaining the necessary equipment? Should the work be subsidized, contracted to private industry, or carried out by the Forest Service?

Even though there are problems involved, helicopter or balloon logging merits consideration where forest management is essential to the protection of the watershed.

Regarding a subsidy, the question naturally arises as to who pays it. The subsidy can take several forms but two suggest themselves as most practical: (a) reduced stumpage price for crown timber and (b) more participation in road construction by the forest service. In the first case, the government would receive revenue from the sale of stumpage from an area that would not have been logged had the stumpage price not been reduced. This may amount to a net dollar gain or loss, depending on whether the stumpage price exceeds the cost of administering the timber sale. The second case is similar to the first as far as it relates to cost to the government.

The costs of subsidizing timber harvest in situations as outlined in the previous paragraph are legitimate costs of managing the natural

resources of the province and of providing desired watershed protection. A subsidy should be paid for timber harvesting only where the benefits derived from a managed forest, e.g., protection from slides, are considered to be worth the costs involved. It is possible, in some cases, that the cost to the government of timber harvest subsidies could be passed on to those who benefit directly. However, in general, the costs should be borne by the province as a whole.

Logging Measures to Reduce Erosion

Failure to apply proper watershed protection measures during logging operations is often due to ignorance of the proper method or the desire to economize by cutting corners. Ignorance of the proper method is not universal, however, - many of the techniques of watershed protection are known - but often those responsible for the actual work on the ground are unaware of either the need for watershed protection or the methods.

The measures necessary to protect watersheds during logging and road building will vary from place to place in the province, depending on such factors as soil, topography, and climate. In many cases, improved watershed protection involves very little cost increase. It should involve better and longer-range planning, which in itself may produce a long-term net gain in spite of an immediate increased cost of operation.

Planning. Timber harvest should not be carried out piece-meal, i.e., only the present season's operation being considered, but each year's operation should be part of an over-all plan for the whole area. This is especially true of road networks, which will be discussed in a following

section, but also applies to cutting areas and landings. These should be located in advance of actual operations and proper consideration given to the protection of soil, water, and fish. Maps and aerial photographs should be used for advance planning followed by fieldwork to confirm the plan.

Cutting method. Certain cutting methods are usually common to a particular region, having been decided by the economics of logging as well as silvicultural requirements. Cutting methods generally used in British Columbia may be classed as clear cut (either strip or block) and selection (either single tree or group). Clear cutting, especially in blocks, is usually considered more damaging to watersheds than selection cutting because of the greater degree of disturbance associated with clear cutting. Timber cutting itself does not seem to affect erosion greatly (Packer 1965), and logging, even on steep slopes, does not necessarily cause erosion (Hornbeck and Reinhart 1964). However, where alternate cutting methods are possible, the one that causes the least watershed disturbance should be chosen.

Logging method. Tractor logging and cable logging are the most common methods employed in British Columbia. The first involves the skidding of logs with the tractor. A variation of tractor logging is the use of devices to reduce the friction of logs being dragged across the ground. One such device, the skidding pan, is a steel pan on which the front ends of the logs rest during skidding. Another anti-friction device, the logging arch, lifts the front ends of the logs off the ground during skidding.

Cable logging lifts the logs partly or wholly off the ground during skidding. Various skyline methods have been developed in which logs are skidded laterally to the skyline, a cable suspended between spar trees or portable spars, then lifted to the carriage and transported along the skyline to a landing at its lower end. Depending on the skyline system used, the logs may or may not be suspended clear of the ground during transportation along the skyline (Binkley 1963, Lysons 1966).

High-lead systems of logging employ either a spar tree or portable spar and drag the logs over the ground with the front ends elevated. In this way the logs can more easily pass over obstructions such as rocks and stumps. This advantage lessens as the length of skid increases, although the distance can be increased with higher spars (U.S. Dept. Agr. 1951).

Balloon logging has received field testing in Canada and the United States and is a promising logging method for very steep slopes and rugged terrain. Tests were carried out in British Columbia by MacMillan, Bloedel & Powell River, Ltd., in 1963 and 1964, and in Oregon by the U.S. Forest Service (Lysons et al. 1966). The mechanical feasibility was established by studies carried out by the Goodyear Aerospace Corporation in 1964 (U.S. Dept. Agr. 1964a, 1964b).

Balloon logging is not in common use at present, one of the reasons being the cost of helium which is used to inflate the balloon. The method might become economically feasible on many areas if the cost of helium were reduced by 50 per cent (Steinbrenner 1966). The use of ammonia gas was suggested by Lysons et al. (1966) and tests have been carried out on

the compatibility of this gas with balloon fabrics (Lysons 1966). The cost of ammonia to fill a 100,000-cubic-foot balloon would be about $150, compared to $6,000 for helium (Lysons et al. 1966).

Helicopter logging has been tested in Canada and the United States (O'Leary 1963), but is not yet in common use for the same reason that balloon logging is not in common use, and that is its high cost (Steinbrenner 1966).

Although tractor logging is often responsible for watershed damage it is an efficient logging method in many situations. Tractors are extremely mobile, require no rigging, and can be shifted from place to place quickly and with little advance planning. The problems of tractor logging that are associated with watershed protection are generally the result of using tractors in the wrong places or at the wrong time. Tractors are usually preferred for skidding because of their assumed economy of operation. Under favorable conditions this economy is often realized. Steep slopes and deep mud are not favorable conditions and under these circumstances other methods are usually more economical.

Skid roads occupy about 25 per cent of areas logged by tractors (Steinbrenner 1966) and are characterized by a particular type of soil disturbance, one that reduces the natural macroscopic pore space, lowering soil permeability. Tractor logging causes greater soil disturbance and compaction than does cable logging (Dyrness 1965, Garrison and Rummell 1951, Wooldridge 1960).

Soil compaction is usually associated with tractor skid roads but Steinbrenner (1966) suggested that other soil disturbances may have greater

impact. The soil displacement occurring when contour skid roads are cut deeply into the side slope results in a situation that is an extreme erosion hazard. Often such roads are unproductive for many generations and are, therefore, the site of erosion for long periods.

Tractor use on very wet or saturated soils results in puddled soils, and frequent trips with a tractor under these conditions disperse the soil into a thin mud, destroying all structure.

The following recommendations are made regarding watershed protection during tractor logging (Steinbrenner 1966).

(1) Tractors should not be used where slopes are so steep that skid roads must be excavated into the side hill on the contour. Slopes in excess of 20 per cent should not be logged with tractors.

(2) Tractors should not be used on very wet soils unless the soils are sandy or gravelly with little clay content.

(3) Where skid roads have become compacted, consideration should be given to scarifying after logging. This should be done only when the soil is dry, with for example, a three-toothed rock ripper.

In skyline operations, soil disturbance occurs when the logs are being skidded laterally to the skyline, directly below the skyline where logs may drag when travelling down the skyline, and in the construction of roads necessary for the operation.

Skyline logging creates very little soil disturbance in the skidding of logs (Wooldridge 1960), and the amount of road required for the operation is much less than for either the high-lead system or tractor logging. In a study by Wooldridge (1960), it was shown that where 10 miles of road

were required to tractor log a 1,000-acre area (6.25 miles/sq. mile), one mile was all that was required using the Wyssen skyline system (0.6 miles/sq. mile). Silen and Gratkowski (1953) reported that about 5.2 miles of road per square mile were needed to log Douglas fir with standard high-lead techniques.

High-lead logging, because it drags the logs over the ground to the landing, disturbs the soil surface over most of the setting. The disturbance does not penetrate the soil very deeply in most cases and is nearly always beneficial to forest regeneration and water infiltration, according to Steinbrenner (1966). This seems to overstate the case and should probably be qualified by adding the conditions that such is the case when high-lead logging is carried out in the best possible manner and not including the effect of roads associated with the operation.

For watershed protection, the high-lead system is generally inferior to the skyline system. However, there are advantages associated with high-lead logging. Compared to the skyline system it is a relatively simple and inexpensive system. It is much easier to move from place to place than the skyline system. Compared to tractor logging the high-lead system can yard on steeper slopes and cause less soil damage, as well as yarding up or downhill and when the soil is too wet for tractors.

Because of the advantages of the system, high-lead logging will be carried out where watershed protection would be better served by the skyline method. A few rules should be followed for all high-lead logging but especially for logging areas such as described in the preceding sentence.

(1) Skidding should be carried out uphill in order to lessen damage to soil, ground cover, and reproduction, as well as allowing runoff to disperse rather than concentrate as it runs downhill.

(2) Yarding across streams, ridges, roads, or benches should be minimized.

(3) Where natural boundaries are absent, cutting boundaries should run perpendicular rather than parallel to the slope.

(4) The spar tree should be positioned at the landing to give the greatest lift to logs being skidded.

(5) Landings should be reasonable in size and kept well drained.

Balloon and helicopter logging offer advantages for watershed protection in that neither method should require more miles of road than skyline logging, in fact fewer miles are more likely. The second point is that logs could be lifted almost vertically off the ground causing little skidding disturbance. Either method might be used to advantage on steep slopes and in rugged terrain but helicopter logging has the further advantages of speed and versatility.

When new methods, such as balloon and helicopter logging have proven feasible from the point of view not only of logging costs but also the costs of other watershed factors such as water pollution, sediment discharge, and erosion, the B.C. Forest Service should provide incentives for industry to overcome inertia and adopt the new methods. In fact, the Forest Service should work closely with industry to develop and test new techniques.

Road Construction Methods to Reduce Erosion

The section on erosion in Chapter II indicated the relation of erosion to roads and their construction. Logging roads are one of the main causes of sediment in forested areas, and on even the best of such roads, culverts and dips discharge sediment (Trimble and Sartz 1957). However, careful design and lay-out will minimize the effects of logging and skid roads on erosion.

About 5,000 miles of road are constructed annually on forest land in British Columbia. The B.C. Forest Service, other government departments, and resource users construct main roads but most of the mileage is built by the forest industry (Dunham 1963). Since most of the road mileage is built by the forest industry, the B.C. Forest Service must establish and enforce standards for these roads. This should be established as one of the priorities of field inspection. This section will recommend practices for minimizing erosion caused by logging roads and skidtrails. Sources for the following recommendations include Arnold (1963), Banta (1963), Enberg (1963), Rothwell (1966), Stewart (1963), Svinth (1963), U.S. Dept. Agr. (1951), and Walters (1966).

Road location and design. The location of any section of road must be considered in the light of the total transportation plan. The standard of road and its location depend on its relation to other roads in the system, its destination, and the kind and amount of traffic which will use the road. The standard of road will influence the soil and water problems to be faced. For example, if the road is to be designed for a speed of 20 miles

per hour the grade and alignment can be much more compatible with mountain terrain than is possible for a road having a design speed of 40 miles per hour. For the faster speed, both horizontal and vertical curves must have a longer radius, requiring deeper cuts and fills.

Road location should be planned well in advance of construction, and final construction should follow the pioneering stage closely. Occasionally, the preliminary stages of road construction are carried out, with the road being pushed through by bulldozer, long before the ditches and culverts are installed and the road surface finished. Erosion rates are much higher during the period between the first and last stages of road construction than after completion. Where erosion hazard is great, the road grade should be outsloped after the first stages of road construction, especially if the final stage is to be postponed.

To minimize erosion, roads should be located as much as possible on benches and ridges, on well-drained soils and horizontal rock strata. Areas should be avoided where severe disturbance would result from road construction, and where large cuts or fills are necessary. Roads should not be located on rock outcrops and ledges, steeply dipping rock strata, seeps, clay beds, and alluvial fans because of the greater possibility of slides in these areas.

Road grades should be less than 10 per cent in general, except for short distances where 15-20 per cent grades may be allowed. Long, steep grades should be avoided as well as long level stretches which are difficult to drain.

Roads should not be located in stream channels but should be located far enough away that most of the sediment originating on the road is filtered out before reaching the channel. Trimble and Sartz (1957) found the following rule-of-thumb useful in the White Mountains of New Hampshire: the width of the filter strip in feet should be equal to 25 + 2 (degree of slope between road and stream).

Road construction. Wet-weather road construction should be kept to a minimum, especially on poorly-drained or erodible soils. Grading and installation of drainage structures should be completed before wet weather occurs. Fills should be built in layers to ensure full compaction and to minimize slumping. Slash, logs, and other organic debris should not be used as fill material. The low point of a grade should not be located on a deep fill or runoff water from both directions will be concentrated at the site of the fill.

Where roads are located on unstable soils and slopes, and slides are indicated, back-slopes should be flattened and road-side ditches deepened to minimize the effects of slides. Cribbing may be used on back-slopes where a safe slope is impractical. The slope of the bank of a road cut is determined by the stability of the soil and should be as steep as possible to reduce the area of exposed soil. The angle of repose of the material should be considered in making the road cut or fill. For recommended side and fill slopes for different soils, see Rothwell (1966).

Where road banks tend to slump, water should be diverted from up-slope areas to prevent saturation of road banks.

Gently rolling dips, or rolled grades, may be built into roads to aid in surface drainage. Such dips must have adverse grades on the downward as well as upward side. The bottom of the dip should slope from the toe of the road cut to the shoulder of the fill.

Stream crossings should be avoided where channels are not well defined. Such areas are often the site of channel relocation especially during high water.

The grade of bridge approaches should be uniform for at least 50 ft. from the end of the bridge and at the same grade as the bridge. Changing the direction of streamflow in bridge construction should be avoided, but where it is necessary, the banks should be rip-rapped to reduce soil movement into the stream. Heavy equipment should be used sparingly near stream banks, e.g., in bridge construction.

Unbridged stream crossings should be avoided. However, where skid trails are permitted to cross drainage channels they should cross at right angles to the channel to minimize bank and channel disturbance. Channel approaches to bridges or fords should be of solid material or solid fill material of shale or rocks should be used to produce a solid approach to prevent washing and soil movement. Adverse grades should be maintained on both sides of the channel so that the road or skid trail does not become the new channel.

Where erosion hazards are high, vegetation should be used to protect cuts and fills. Fast-rooting grasses may quickly stabilize the slopes, but mulching and even wire mesh or an asphalt emulsion may be necessary to hold

the soil long enough for the grass to become established.

Skidroad networks and landings should be included in the preliminary road planning. Skidroad grades should be as low as possible, going obliquely up slope or along the contour rather than perpendicular to the slope. Tractor operators should not skid unrestricted but should use skidroad locations that have been laid out in advance.

Drainage. The drainage system associated with the road network should not receive consideration only after the road location has been planned and construction partly carried out, but should be included in the planning of the road system. Where unstable areas are evident, plans should include means of diverting drainage water to stable areas to avoid saturation and slumping. A good plan is to divert drainage water into areas of undisturbed ground cover where sediment can be filtered out before reaching streams.

Culverts should be installed at all drainages that are crossed by roads except where the amount of water is small enough to be safely diverted into roadside ditches. Culverts must be properly installed to be of maximum value. Improperly installed or inadequate culverts are often more damaging than the omission of culverts. Where pipe culverts are to be used, trenches should be prepared with an even grade and rock-free to prevent damage to the pipe when fill is added. Culverts should have at least a three per cent slope and where large amounts of sediment are expected, up to 20 per cent slope may be needed. The following rule-of-thumb may be used: the slope of the culvert should be the per cent slope of the road grade above the culvert plus two per cent. Slope is not the only consideration, however. The culvert should have a free outfall or be designed for a given tailwater level.

Culverts should have their inlets protected to prevent their being clogged with sediment and debris. Culvert outlets should be protected with permanent aprons to disperse water flow and prevent the formation of gulleys. On large, unstable slopes and fills, downspouts and permanent aprons should be used to prevent erosion and gulley-formation. Downspouts may be open or closed, and aprons should be either concrete or rock that will dissipate the energy of the falling water.

On secondary logging roads, open-topped culverts provide an economical way of obtaining drainage. These may be poles spiked to a wooden crossmember, a plank box culvert, or a steel rail culvert. These culverts should be placed across the road at an angle, rather than perpendicular, so that the two front or two back wheels of a vehicle will not hit the culvert at the same time.

Culverts should be spaced so that water is diverted often enough to prevent erosion of road surfaces and ditches. The spacing depends on the various factors of the particular watershed. The forest truck trail handbook of the U.S. Forest Service (U.S. Dept. Agr. undated) gives maximum cross-drain spacing for different road grades. Another method of spacing determination is the use of the formula, spacing in feet = 1,000/road grade in per cent (Packer undated). Other guides have been presented by Haupt (1959) and Kidd (1963). Local experience used in conjunction with one of these methods would be the best guide currently available in British Columbia.

Culverts should be large enough to handle the maximum runoff expected. To obtain sufficient capacity without resorting to very large

culverts, two or more culverts may be used at the one location.

Berms should be constructed along road shoulders to divert surface water from fills or unstable slopes. They should be about eight inches high with a base width of 30 in. and a top width of six inches. Care should be taken during road maintenance and snow removal not to damage the berm. Berms should be interrupted where drainage is desired and the erosion hazard is slight.

Depth and side slope of roadside ditches should be adequate to carry water without erosion of the ditches. Ditches should be constructed so that water does not pond along the roadside.

Outsloping of roads provides surface drainage and reduces the number of culverts required. The degree of outsloping should be about one-quarter to three-eighth inch per foot. Roads should not be outsloped in steep country or where conditions are often wet and slippery. In such cases, insloped roads are recommended but will require more culverts to provide adequate drainage.

Stream channels. The location and condition of stream channel must be considered in planning logging operations and road location. Channel disturbance can cause erosion right in the stream, whereas soil disturbance adjacent to stream channels can contribute to the sediment that reaches the stream. Therefore, the general rule is that channels should be disturbed as little as possible and that buffer strips should be established between the stream and any soil disturbance.

The following rules apply to channel protection during logging and road construction:

(1) Strips of uncut timber should be left along streams to trap sediment and to reduce the concentration of runoff on slopes. Trees should not be felled into the stream.

(2) Landings should be located far enough upslope that sediment is filtered out of runoff by ground cover before reaching the stream.

(3) Skidding across or down drainage channels should be avoided.

(4) Temporary bridges or log culverts should be constructed at all stream crossings.

(5) Logging and road-building debris should be kept out of channels. Where natural debris exists in amounts that might form debris dams during heavy runoff, it should be removed.

(6) Where stream crossings are necessary they should be at right angles to the channel.

(7) Roads should not encroach on the natural high-water channel of streams.

Road and Drainage Maintenance

Road maintenance. Road maintenance is essential to any road system. Erosion and sediment are the inevitable results of rough, rutted, and pot-holed roads, and clogged culverts and ditches. Road maintenance is a continuing procedure and not a series of steps taken only when road conditions have deteriorated to a certain low level.

The following measures are recommended for watershed protection:

(1) Roads should be graded every season to fill in ruts and holes and to maintain the road crown. The crown is important for adequately draining the road surface. The maximum height of crown at the

centre of a nine-foot wide road is 2½ in. for a road grade of 0-5 per cent; 1 3/4 in. for a road grade of 5-10 per cent; and 1½ in. for a road grade of 10 per cent and over. The appropriate values for a 16-foot wide road are four, two, and two inches.

(2) Roadside ditches should be cleaned and graded periodically. Care must be taken not to undercut back slopes during the ditch grading, nor to damage culverts.

(3) Culverts and stream channels for 50 ft. above the culverts should be kept free of debris.

(4) Screens should be installed above culverts to catch debris and prevent blocking of the culvert.

(5) Inspections should be carried out to spot and repair trouble spots. These should be carried out at regular intervals as well as shortly after construction and during prolonged rainfall.

Post-logging erosion-control measures. For those roads that will be closed to traffic after logging has been completed the following procedures should be followed:

(1) Temporary roads, skidroads and landings must have adequate cross drainage. The spacing interval can be estimated by the methods outlined for culvert spacing. Open-top culverts and similar structures should be removed and replaced with cross drains.

(2) Temporary fills, culverts, and bridges should be removed.

(3) In erodible soils, landings, skidroads, cuts, and fills should be seeded to fast-rooting grass species to temporarily hold soil until natural cover is re-established.

(4) Rocks and slash should be placed on skidroads to retard water flow, to trap sediment, and to hold soil.

(5) Road surfaces should be outsloped to facilitate drainage.

(6) The area should be inspected periodically for signs of erosion, especially prior to the wet season.

For roads that will be open to limited traffic the following recommendations apply:

(1) Immediately after logging, cross drains should be constructed to take the place of temporary drainage structures. These may be constructed with a bulldozer in the following manner: Excavate the roadbed to a minimum depth of six inches next to the cut bank and to eight inches at the other side of the road. Use excavated material to a depth not exceeding three inches to provide an adverse grade along the down-hill edge of the drain. The cross drain should extend the full width of the road, the long axis of the drain forming an angle of not less than 30° to the perpendicular across the road. This provides a slope to the cross drain running down from the cut bank to the opposite edge of the road.

(2) The amount and kind of traffic should be limited, especially during wet weather.

Slash Burning

The effect of wildfire and slash burning on erosion was discussed in Chapter II. The evidence strongly indicates that burning causes

accelerated erosion. Knight's (1964) studies on south-western Vancouver Island showed that the soil was resistant to erosion provided the organic layer remained intact. However, burning reduces the organic matter in the top layer of soil (Austin and Baisinger 1955, Beaton 1959, Dyrness and Youngberg 1957, Knight 1964, Rowles 1957, Youngberg 1953), as well as the clay content (Dyrness and Youngberg 1957, Sreenivasan and Arangabadkar 1940).

Rowles (1957) stated that the organic material in the top layer of soil not only protects the soil but provides important water storage capacity also. Rideout (1949) found in a study of the effects of slash burning on British Columbia forest soils that the water holding capacity was reduced immediately after burning, requiring 18-19 years to completely recover. Other studies have shown similar results (Austin and Baisinger 1955, Dyrness 1963). Beaton (1959) reported that burning in the Lac la Jeune area of British Columbia reduced total porosity of the surface soil and its infiltration capacity. Reduced infiltration and percolation rates after burning were reported in other studies also (Rowe 1941, Tarrant 1956).

Pelishek et al. (1962) reported that fire caused hydrophobic properties in chaparral soils in southern California. Addition of a wetting agent to the hydrophobic soils in laboratory tests resulted in increased infiltration rates. Osborn et al. (1964) sprayed a wetting agent on soils that displayed hydrophobic properties after a fire in the San Dimas Experimental forest, and found that erosion rates were greatly reduced.

It must, then, be accepted that burning does cause erosion in many situations. Burning has also been shown to cause greater surface runoff

(Rich 1965) and decreased site productivity (Knight 1964). Therefore, the benefit to be derived from prescribed burning must be weighed against the costs of erosion, greater surface runoff and decreased productivity of the site.

The objectives of slash burning are to reduce fire hazard, facilitate regeneration, and to make the area more amenable to planting. These objectives are satisfied to a varying degree by slash burning. The increasing utilization of material that has previously been left on the ground after logging is reducing the need for slash burning as an aid in regeneration and planting. The increasing demand for pulpwood and chips should cause a continued reduction in the amount of slash left on the ground.

Increased utilization has implications with regard to fire hazard, also - the less slash, the lower the hazard. In addition, the standard of fire prevention and suppression should be higher in the province, in general, with better equipment and communication, and especially on areas under sustained-yield management licences.

The decreasing need for slash burning along with an increased awareness of the damage to watersheds caused by slash burning should result in a more discriminating choice of areas burned. Three points in this premise need elaboration. (1) The B.C. Forest Service must recognize that slash burning is not needed to the same extent it once was (in fact, it may be considered doubtful that slash burning has ever been needed to the extent it has been practiced). (2) Forest Service personnel must be taught to recognize the possibility of watershed damage by burning. (3) The

designation of areas to be slash burned must be based on an evaluation of each area individually. Williams (1966) suggested some investigations into slash burning that were needed, among which was a study of the effect of various intensities of burn on the site and in reducing the fire hazard. There is a definite need for guidelines to evaluate (1) the fire hazard before slash burning, (2) the probable reduction of this hazard by burning, and (3) the probable damage to other watershed values by slash burning.

In the report of the 1945 B.C. forestry commission, a recommendation was made that the Forest Act be amended so that slash burning would not be compulsory on the B.C. coast except where directed by the deputy minister. Although the Forest Act made slash burning compulsory on the coast the Forest Service did not enforce compliance in all cases. In 1944, 79 per cent of the area logged in the Vancouver Forest District was broadcast burned.

In 1948, the Forest Act was amended to require slash burning only in the Vancouver Forest District (Prov. of B.C. 1948). In 1964, slash burning was prescribed for 65 per cent of the area logged in the Vancouver Forest District, and the trend continued toward more broadcast burning and less spot burning (B.C. Dept. Lands, Forests, and Water Resources 1965). In 1967, the section of the Forest Act dealing with slash burning was again revised and now requires that slash be burned on logging operations throughout the province (Prov. of B.C. 1967). This means that the area slash burned in the province will greatly increase in the next few years.

However, instead of increasing, slash burning should be reduced

to a minimum because of the damage that may be caused by the practice. The alternatives to burning should be very carefully considered before being applied where slopes are steep, soils shallow, organic layers thin, or soils highly erodible.

Erosion Hazard Rating

In several preceding sections it has been emphasized that an increased awareness of the damage associated with misuse of land was necessary on the part of the B.C. Forest Service in general, and Forest Service field men in particular. It was suggested that training programs be initiated to create this awareness and to educate Forest Service personnel in watershed management.

A valuable tool for watershed management is an erosion hazard rating that would isolate the combinations of geology, soil, topography, and climate and rate these on the basis of erosion hazard. The rating can be one in which the factors are described and a method given for combining the individual factors of a particular area to obtain an overall erosion hazard rating. Or, the area can be mapped, with those units having a similar erosion hazard rating being delineated.

Such a rating of erosion hazard for a particular district would greatly assist a field man in managing his watersheds. It would enable him to prescribe logging and road construction methods for each area consistent with watershed protection.

Various methods of estimating erosion hazard have been formulated, several of which have been described in Chapter II. Some of these ratings deal only with soil properties, whereas others include some or all of the factors of vegetation, geology, elevation, aspect, and slope. Those methods that consider soil properties only are of limited value in rating the overall erosion hazard of a particular area, whereas some of the more-inclusive methods are based on empirical data that is lacking in British Columbia.

Several recent attempts at rating erosion hazard are promising for use in this province. Jeffrey et al. (1964) reported the relation between the type of surficial deposit and its susceptibility to erosion in the Oldman River basin of Alberta. This study indicated the value of surficial deposit mapping by itself and as the forerunner of more-inclusive erosion hazard mapping.

In a study to determine the usefulness and practicability of the landform-soil-vegetation classification system to forest management, Lacate et al. (1965) established an erosion hazard and slump hazard rating. The area of the study was divided into similar units based on features of the soil, vegetation, and physiographic position in the landscape. The erosion hazard rating was based on soil permeability, texture, stoniness, and slope gradient. Units were classified as having a high, moderate, or low erosion hazard.

A method of erosion hazard rating based on soil properties, geology, topography, vegetation, and climate is necessary to properly manage forest

land in British Columbia, but a less comprehensive system would be worthwhile and would stand a greater chance of being initiated. At the present time, the ideal system is one that could form the basis of a more elaborate system when more resources could be directed to the project, but which by itself would be of value also.

The B.C. Forest Service should initiate a survey to establish the relation of erodibility to the nature of surficial deposits and to establish a system of erosion hazard rating. This should be carried out in key areas to begin with, enlarging as resources became available to include other areas of interest as well as other variables such as topography, vegetation, and climate.

3. QUANTITY AND TIMING OF RUNOFF

The literature reviewed in a previous section provided evidence of the influence of the forest on water yield. The question is, how can the forests of British Columbia be managed to improve water yield?

In the section on water resources of British Columbia it was shown that precipitation during the growing season is insufficient in many parts of the province to grow crops. Even in those regions where annual precipitation is greater than 60 to 100 in., irrigation is often needed because of the seasonal distribution of precipitation. The dry period is usually concurrent with low streamflows, except for a short lag, so that irrigation water is scarce when needed most.

The objectives of water management where irrigation water is scarce may be to:

(1) Increase total runoff. This assumes adequate storage for the increased runoff.

(2) Increase runoff during the low streamflow period.

(3) Prolong spring runoff into the low-flow period.

Increase in Total Water Yield

The objective of increasing total water yield will be considered first. As indicated in Chapter IV, the B.C. Interior, especially the Southern Interior, is the region most in need of increased water yield. The Okanagan Valley will be used in the following discussion on water yield increases through forest management. In this area, present demand for irrigation water is almost equal to supply. The growth of the region depends on increased water supplies. Water diversion schemes have been considered, and one of these, the Shuswap-Okanagan diversion, will be discussed.

The forest area of Tree Farm Licence No. 9, located on the west side of Okanagan Lake, will be considered to indicate what forest management practices may be carried out, and to what degree the objectives may be achieved. The area is the site of the Terrace-Esperon Creek research watershed and has been described in the section on research watersheds in Chapter VII.

T.F.L. No. 9 occupies an important part of the Okanagan watershed from the point of view of water conservation. During the spring runoff, dammed lakes on the area are filled with water for subsequent use during the irrigation season. The water is released into Lambly and Powers Creek

and then piped or flumed to fruit orchards and vegetable farms. On November 1, 1966, five final and 10 conditional water licences were in effect on the T.F.L., and two were pending. Information in this section on T.F.L. No. 9 is from the third working plan for the area by S.M. Simpson Ltd. (1962).

Landslip due to poor logging practices and gulley erosion by heavy rains occurred before sustained-yield management was begun. No conflict exists now between water users and forest management, although anxiety did exist over the possible effects of logging and fire on the water supply. Protection against erosion is considered in the forest management of the T.F.L., but increased water yield and timing of runoff are not part of the management objectives.

T.F.L. No. 9 consists of three main cover types: Engelmann spruce-subalpine fir, lodgepole pine, and interior Douglas fir. The interior ponderosa pine cover type is represented but occupies only a small part of the watershed. The aspen type is also present on the T.F.L. Management of each of these cover types will be discussed in relation to water yield. The area and age-class distribution of the three main cover types is given in Table 5.

Table 5. Area by age class of forest cover types on Tree Farm Licence No. 9 (from S.M. Simpson Ltd. 1962)

Age class in Years	Cover Type		
	Engelmann spruce -subalpine fir	Lodgepole pine	Interior Douglas fir
	Area in Acres		
0 - 20	757	125	1,082
21 - 40	1,892	6,296	4,162
41 - 60	376	1,574	4,071
61 - 80	2,804	12,675	14,625
81 - 100	3,963		7,813
101 - 120	3,562	10,601	7,470
121 - 250	54,994		30,938
Total	68,348	31,271	70,161

Unmanaged forest. The initial assumption is made that the forest is presently unmanaged and no logging has taken place. The opportunity for improving water yields by forest management is greatest in those cover types at the higher elevations where both the annual precipitation and the amount received as snow are greatest. On T.F.L. No. 9 this means the Engelmann spruce-subalpine fir and lodgepole pine cover types.

Two approaches are possible for applying the results of cutting-water yield studies made in other areas to British Columbia. The actual increase, in inches, can be applied, with or without adjustment, to British Columbia cover types, or the percentage increase can be applied. Since neither method is completely satisfactory in that results cannot be extrapolated from one area to another without qualification, and since the use of actual yield increases has little more to recommend it than the use of

percentage increases, the latter will be used in the following examples because of ease of use.

In the following sections, the source of information for T.F.L. No. 9 is S.M. Simpson (1962) and for the Fraser Experimental Forest, Goodell (1958, 1964) and Love (1960).

The lodgepole pine cover type occurs between 3,000 and 6,000 ft. elevation on the T.F.L. Annual precipitation varies from 15 to 30 in., 50 to 60 per cent of which falls as snow, and annual water yield is about 10.5 in. (Runoff from Terrace Creek for the 1966 water year, the first full year of record, was 10.5 in. Using long-term climatic data for McCulloch, B.C., and Thornthwaite's method, the calculated runoff was 11.8 in. The Thornthwaite calculation is described in Chapter VII, in the section on the Terrace-Esperon Creek watershed. Because of the limitations of the data used in the calculation, and to be on the conservative side, the value of 10.5 in. is used.)

Studies have been carried out at the Fraser Experimental Forest in Colorado on the effect on water yield of lodgepole pine management (Goodell 1958, 1964, Love 1960). The study area is between 9,600 and 12,500 ft. elevation. Annual precipitation ranges from 15 to 30 in., two-thirds of which falls as snow, and annual water yield before logging averaged 13 in. Clear cutting 40 per cent of the area in strips produced a 67 per cent increase over predicted water yield from the cutover part of the watershed.

The two areas, T.F.L. No. 9 and the Fraser forest, are similar in annual precipitation, the per cent that falls as snow, and annual water yield. Assuming the same percentage increase on T.F.L. No. 9 for similar management, an increase of 67 per cent of the annual yield of 10.5 in., or 7.0 in., would be realized from the cutover area in the first year.

Annual increases in water yield will gradually decrease as the cutover area regenerates and a new crop is established. The period between cutting and a zero yield increase has been estimated at 25 years (U.S. Senate 1960) but Goodell (1964) considered 35-50 years more appropriate for the slower-growing spruce, pine, and fir stands of Colorado. Analysis of results of studies carried out at the Coweeta Hydrologic Laboratory in North Carolina indicated that a one-cut treatment could be expected to increase water yields for 35 or 40 years (Hewlett and Hibbert 1961). The stands of the British Columbia Interior are similar to those at the Fraser Experimental Forest so that an average value of 40 years as the regrowth period seems appropriate and will be used in the following examples.

The average yield increase over the 40-year period would be (7.0 + 0.0)/2, or 3.5 in., on T.F.L. No. 9. Assuming a rotation of 120 years, which is the rotation presently used for lodgepole pine on the area, the area cut annually is 1/120 of 31,271 acres (the area of the lodgepole pine cover type, from Table 5), or 261 acres. At any given time there will be 40 years x 261 acres/year, or 10,440 acres of pine between the ages of zero and 40 years contributing an average increase of 3.5 area-inches of water (an area-inch of water covers the area to a depth of one inch). This amounts to an increase of 3,045 acre-feet of water per year, or 11 per cent of the annual yield from the lodgepole pine cover type.

Thinning dense, young (35-year-old) stands of lodgepole pine at the Fraser Experimental Forest, leaving only 630 of the better trees per acre, spaced 8.5 ft. apart, increased water yield by 23 per cent. The same percentage increase on T.F.L. No. 9 would produce 0.23 x 10.5, or 2.4 in. increase in annual water yield. Assuming a recovery period of 20 years for the thinned stand, the average increase for stands between 35 and 35 + 20, or 55 years old, would be (2.4 + 0.0)/2, or 1.2 in. The area occupied by stands 35 to 55 years of age would be 20 years x 261 acres/year, or 5,220 acres, producing an annual increase of 1.2 area-inches, or 522 acre-feet of water.

The Engelmann spruce-subalpine fir cover type occurs between 4,000 and 6,600 ft. elevation on T.F.L. No. 9. Annual precipitation is between 20 and 30 in., and water yield about 10.5 in.

On the Fraser Experimental Forest this cover type occupies the area between 9,600 and 12,500 ft. elevation. Precipitation is between 15 and 30 in. annually, and water yield before logging about 13 in. Both single tree and group selection harvesting methods produced water yield increases of 23 per cent. Alternate clearcut strips produced a 20.1 per cent increase. The system presently in use on T.F.L. No. 9 is alternate clearcut strips, so this system will be assumed for this example.

A 20.1 per cent increase in water yield from the alternate clearcut strip watershed represents a 40.2 per cent increase from the clearcut strip itself. This percentage applied to T.F.L. No. 9 would give 0.402 x 10.5, or 4.2 in. of yield increase. The average increase during the 40-year recovery period would be (4.2 + 0.0)/2, or 2.1 in. The

rotation presently used in managing these stands on T.F.L. No. 9 is 120 years, which will be used in this example. The area cut over annually is 1/120 x 63,348 acres (the area of the Engelmann spruce-subalpine fir cover type, from Table 5), or 528 acres.

At any given time there will be 40 years x 528 acres/year, or 21,120 acres between zero and 40 years contributing an average increase of 2.1 area-inches, or 3,696 acre-feet of water, annually.

The interior Douglas fir cover type on T.F.L. No. 9 forms an irregular belt from Okanagan Lake, 1,100 ft. in elevation, to 5,000 ft. Annual precipitation ranges from about 15 in. to an estimated 25 in.

The annual yield is unknown but an estimate can be made as follows. Calculated by Thornthwaite's water balance method with climatic data for Kelowna, at elevation 1,175 ft. (described in Terrace-Esperon Creek watershed section) the runoff was 0.08 cm. (0.03 in.). The annual yield for the Terrace Creek watershed, elevation 4,300 ft. to 5,400 ft., is taken as 10.5 in. (as described in a preceding part of this section). Water yields from the interior Douglas fir cover type at similar elevations (3,000 to 5,500 ft.), with similar precipitation (18 to 22 in.), in the northwestern United States, vary between one and 20 in., averaging 7.0 in. (U.S. Senate 1960). The limits for this cover type on T.F.L. No. 9 are 0.03 and 10.5 in., with 5 in. being estimated as the average annual water yield.

Experience with the interior Douglas fir cover type is limited regarding water conservation, but management should produce a 0.5 to 1.0 in. increase in water yield (U.S. Senate 1960). This is a 7 to 14 per cent increase over the 7.0 in. average yield of this cover type in the

northwestern United States. Applying the average of 7 to 14 per cent, or 10 per cent, to the estimated water yield of 5 in. from this cover type on T.F.L. No. 9, gives 0.10 x 5, or 0.5 in. The average increase over the 40-year recovery period would be (0.5 + 0.0)/2, or 0.25 in.

Using a rotation of 120 years the area cut annually is 1/120 x 70,161 acres (the area of the interior Douglas fir cover type, from Table 5), or 585 acres. At any given time there will be 40 years x 585 acres/year, or 23,400 acres, between zero and 40 years of age contributing an average annual increase of 0.25 acre-inches, or 488 acre-feet of water.

On T.F.L. No. 9 the interior ponderosa pine cover type occupies an area from elevation 1,100 ft. to a maximum of 4,000 ft., but few stands are found above 3,000 ft. Annual precipitation is about 13 in. at lower elevations, reaching an estimated 20 in. at the higher elevations. Annual water yield from this cover type is less than from the Douglas fir cover type and is estimated to be 2.5 in.

The ponderosa pine cover type in northwestern United States is located between elevation 3,000 and 5,500 ft., where annual precipitation averages between 18 and 22 in. Water yields range from 0.5 to 15 in. with an average estimated at 4 in., according to the U.S. Senate report on evapo-transpiration reduction (1960). This report stated that the management of this cover type is mostly concerned with second-growth stands, many of which are overstocked and producing poorly. Measures to increase water yields by reducing interception of precipitation are likely to be most advantageous.

Most of the ponderosa pine type on T.F.L. No. 9 has been logged in the past because of accessibility. Present stands are more often open and scattered than dense. Because of this, because the area of this cover type on T.F.L. No. 9 is small, and because a percentage increase of the already small annual water yield would be small, no yield increase will be attributed to management of this type.

The aspen cover type occurs as a sub-climax type replacing the interior Douglas fir cover type after fire. At present it is of little economic importance as timber, but may be important from the point of view of water use. Conversion to other species may be advantageous to both forest and water management, and should be considered.

Studies in western Colorado showed that, through the growing season, aspen withdrew five inches more moisture from the top eight feet of soil than did spruce, and nine inches more than grassland. But there was little difference in the amounts used from the top four feet of soil (U.S. Senate 1960).

Brown and Thompson (1965), in western Colorado, reported that during the growing season aspen used an average of 4.3 in. more water from the top eight feet of soil than did spruce. However, the spring soil moisture was significantly higher under the aspen. Because this difference in available moisture was almost equal to the measured differences in water use the authors concluded that it is impossible to attribute differences in water use solely to the type of vegetation. The studies reported in Chapter II on evapotranspiration have not indicated higher water use by aspen.

The evidence, then, does not indicate that conversion to other species would reduce evapotranspiration. Furthermore, because the soils of T.F.L. No. 9 are shallow, seldom exceeding 36 in. (S.M. Simpson Ltd. 1962, Lacate et al. 1965), this conclusion is even more valid. However, because aspen is foliage-free in winter, snow accumulation should be greater than under coniferous trees which intercept more snow allowing greater evaporation losses. The conversion of aspen to spruce or pine might result in a reduction of water yield if the stands of pine and fir remained uncut. However, cutting pine and spruce stands would result in a water-yield increase that might more than offset the greater snow accumulation under aspen. This is especially pertinent considering that under present management aspen is not utilized. Because of these factors, no yield increase will be attributed to aspen stand management.

The water yield increase which would be obtained by managing T.F.L. No. 9 for timber production, with some consideration for increasing water yields, would be 7,751 acre-feet (from Table 6).

Table 6. Estimated water yield increase from logging T.F.L. No. 9, by cover type

Cover type	Water yield increase in acre-feet
Lodgepole pine - harvesting	3,045
- thinning	522
Engelmann spruce-subalpine fir	3,696
Interior Douglas fir	488
Interior ponderosa pine	Nil
Aspen	Nil
Total	7,751

The increase in water yield of 7,751 acre-feet is about 5.2 per cent of the annual water yield from the lodgepole pine, Engelmann spruce-subalpine fir, and interior Douglas fir cover types before these areas had been logged. That is, the water yield from this area, before any logging, could be increased by logging with present cutting systems and rotation periods by about 5.2 per cent per year. This increase would provide enough water to irrigate 3,875 acres of land with an average water duty of two acre-feet per year. That is, every 45 acres of forest managed intensively for timber products will provide an increased water yield sufficient to irrigate one acre in the North Okanagan area.

Present forest management. For the preceding example the assumption was made that no logging was being carried out on the area. However, the area is being logged, and many of the practices are the same as were used in the example. It is reasonable to conclude that forest management of T.F.L. No. 9 is adding close to 7,751 acre-feet of water annually to the Okanagan Valley water supply.

The 7,751 acre-feet would be less by 522 acre-feet because thinning in young lodgepole pine is not carried out under present management. A further reduction should be made because present forest-management practices are based solely on forestry needs, e.g., width and direction of strip cutting, and not on water production. A reduction of 10 per cent will be made to take this into account and will provide a conservative figure of 6,976 acre-feet of water. This would provide irrigation water for 3,488 acres of land, or one acre for every 49 acres of managed forest.

Forest management and water production. If water production were considered part of the forest management of T.F.L. No. 9 the annual water yield could be increased substantially over present yields.

Forty years was taken as the period required for a water yield increase to decrease to zero after cutting. With a rotation of 120 years any given area would be contributing to a water yield increase only 40/120 or 33 per cent of the time. Any decrease in rotation age would increase the percentage of time the area is contributing to a yield increase. If the rotation were shortened to 80 years, a 50 per cent increase would be obtained in the yield produced by forest management on a 120-year rotation. An 80-year rotation is not unreasonable, especially in view of the trend toward a pulpwood economy in the B.C. interior. Therefore, the rotation age will be considered, briefly, to determine if, solely from the timber production point of view, rotations could be shortened.

If maximum wood production is the aim of forest management, the rotation age is when M.A.I. (mean annual increment) culminates. In a study of lodgepole pine and Engelmann spruce in the British Columbia Interior, Stanek (1966) reported that, on the best sites, maximum M.A.I. was reached at age 35 by lodgepole pine and 70 by Engelmann spruce. For the poorest site, the age at which M.A.I. culminates is 80 for lodgepole pine and 130 for Engelmann spruce. On medium sites the ages are 50 for lodgepole pine and 120 for Englemann spruce, indicating that for maximum wood production a rotation of 120 for Engelmann spruce is justified, but a rotation half as long as presently used is indicated for lodgepole pine.

The reduction in rotation period for lodgepole pine from 120 to 50 years would increase water yields from this cover type by 240 per cent, from 3,045 acre-feet to 7,292 acre-feet, as shown by the following calculation:

Total area of cover type:	31,271 acres
Rotation:	50 years
Area cut annually:	1/50 yrs. x 31,271 acres = 625 acres/year
Area contributing to water yield increase:	40 yrs. x 625 acres/year = 25,000 acres
Annual water-yield increase:	25,000 acres x 3.5 in. x 1 ft./12 in. = 7,292 acre-feet = 7,292/3,045 x 100 = 240 per cent

As Stanek (1966) pointed out, the rotation may be increased beyond the culmination of M.A.I. to take advantage of the higher value of, for example, larger size or more clear wood. The culmination of M.A.I. in value terms has also been used to set rotation periods. In these cases the value of the product is considered but the cost of achieving it is not. This introduces the need for consideration of financial rotations.

The financial rotation maximizes the present net worth of the site, i.e., it is that rotation for which the difference between present worth of future revenues and present worth of present and future costs is maximum.

The use of financial rotations in forest management has been advocated by Gafney (1960), Haley (1964), Pearse (1965), and Smith and Haley (1964). Financial rotations for coastal Douglas fir are generally shorter than present rotations on all but the poorest sites. Dobie (1966) reported that financial rotations were 60 and 70 years for coastal Douglas fir on

sites 160 to 175. On site 140, Smith and Haley (1964) indicated that the financial rotation of coastal Douglas fir ranged from 64 to 54 years for interest rates of three to six per cent. This calculation was based on a marginal tree of eight inches diameter at breast height and open-to-normal stand densities. The financial rotation was longer for larger trees but even for 12-inch marginal trees the rotation was shorter than 120 years.

Whether shorter rotations for interior species would be indicated by the financial rotation is not known. If so, water yield increases would be the result. Even on the coast there are areas that would benefit from increased water yield, and water conservation is an added argument in favor of a rotation length approaching that calculated on a financial basis for wood production.

If financial rotations of 50 years for lodgepole pine and 80 years for Engelmann spruce and Douglas fir were indicated for the B.C. Interior, the annual water yield increase would be 14,003 acre-feet, or twice the increase that is produced by present forest management. Rotations of 50 and 80 years for the species indicated are realistic especially in a pulpwood economy.

Forest management primarily for water. If a forested area were managed primarily for water yield but with timber production an important secondary consideration, a shorter rotation would generally be better. If a rotation age of 40 years were chosen, the rotation would equal the regrowth period, assuming, as in the previous example, a regrowth period of 40 years, and water yield increases would be continual.

A rotation of 40 years would produce a water yield increase from T.F.L. No. 9 of 22,544 acre-feet, or 15,568 acre-feet more than from present management, as shown by the following calculations:

Lodgepole pine cover type

Area contributing to water yield increase: 31,271 acres
Annual water yield increase: 3.5 in. x 31,271 acres x $\frac{1 \text{ ft.}}{12 \text{ in.}}$ = 9,121 acre-feet

Engelmann spruce-subalpine fir cover type

Area contributing to water yield increase: 68,348 acres
Annual water yield increase: 2.1 in. x 68,348 acres x $\frac{1 \text{ ft.}}{12 \text{ in.}}$ = 11,961 acre-feet

Interior Douglas fir cover type

Area contributing to water yield increase: 70,161 acres
Annual water yield increase: 0.25 in. x 70,161 acres x $\frac{1 \text{ ft.}}{12 \text{ in.}}$ = 1,462 acre-feet

Total water yield increase on T.F.L. No. 9: 22,544 acre-feet

If timber production is a secondary consideration, a market for 40-year-old timber must be available. Only the most optimistic forecasts of small tree utilization or increased growth rates suggest this probability for the B.C. Interior. The example does indicate, however, the increased water yields available from forest areas managed primarily for water.

Control of phreatophytes. Another means of increasing water yields is the control of phreatophytic vegetation. Phreatophytes grow along stream courses and because their roots extend to the water table they transpire at a much greater rate than non-phreatophytes. Phreatophytes pose a relatively greater problem in arid regions where water is already in short

supply than in humid, forested areas.

Phreatophytic vegetation can be reduced by cutting or chemical spraying but control requires that substitute vegetation be established in its place. In the western United States, control of phreatophytic vegetation may make possible a saving of 25 per cent of the water used by that type of vegetation (U.S. Senate 1960). Robinson (1958) estimated that 400,000 acre-feet in Nevada and 700,000 acre-feet in Arizona could be saved annually by phreatophyte control.

In the British Columbia Interior, control of the cottonwood (Populus spp.), willow (Salix spp.), and alder (Alnus spp.) growing along streams would increase water yields. The water use by such vegetation is not known but in the Okanagan Valley, for example, phreatophyte control between the lake and the forest fringe should produce a significant saving.

Trees growing along streams or on moist-site areas within the forest use large amounts of water. Clearing such sites would increase water yield. Jeffrey (1964), referring to a recent study in land-vegetation typology (Jeffrey et al. 1964), indicated the possibility of distinguishing such areas as an aid to their management by analyses of soil, physiography, and lesser vegetation. Horton et al. (1964), in recognition of the need for management of bottomland and stream-bank areas, produced a guide for use in surveying phreatophytic vegetation.

Whereas phreatophyte control on the grassland areas near the lake could be recommended, at least on a trial basis, in such areas as the Okanagan Valley, such treatment of forested areas in the province is not

warranted at present. Where timber values permit, such areas could receive cutting priority in order that the high water use be reduced. However, cutting alone will not control phreatophytic vegetation and on such sites regrowth is rapid. Further control is not presently warranted.

Timing of Water Yields

An increase in annual water yield may be desirable only if sufficient storage is available to hold the water until it is needed. The timing of runoff is often much more important than the amount of runoff, especially when considering ways to augment present supplies.

The Southern Interior of British Columbia would benefit greatly from prolonged spring runoff if it could be carried over into the season of greatest irrigation use. It would be beneficial even if only a part of the runoff could be detained until irrigation use had decreased the amount of water in storage making room for the later runoff. In the other regions of the province, prolonging runoff from parts of watersheds may de-synchronize runoff and aid in flood prevention.

Timing of water demand. In the Okanagan Valley, for example, peak irrigation demand probably occurs after June 15 in most years. O'Riordan (1966), using the soil moisture budget method with estimates of potential evapotranspiration from Penman's formula, showed that at Penticton a soil having a four-inch moisture storage capacity (i.e., holding four inches of available moisture in the top four feet) would require less than 4.5 in. of supplemental irrigation water in May and June, 90 per cent of the years. (By supplemental irrigation water is meant that water that

must be added over and above that supplied by the soil and precipitation.) The comparable value for July is 4.2 in. A finer textured soil, for example one with a moisture storage capacity of 8 in., would require less than 1.6 in. of supplemental water in June, but 4.2 in. in July, in 90 out of 100 years.

O'Riordan's study of selected stations in the south central Interior of British Columbia gives the irrigation requirements by months for soils of different moisture storage capacity at different levels of probability. This may, in effect, be used as a table of drought return periods in which the degree of drought is indicated by the amount of supplemental irrigation required and the period is expressed as a per cent probability.

Whereas peak demands for water for irrigation occur in July in the Okanagan, peak streamflows occur in May and early June. As examples, the peak flow periods will be given for those streams whose hydrographs are illustrated in this thesis.

Mission Creek, 1953-1961 (Fig. 5): May 15 - June 15

Mission Creek, 1965 (Fig. 1): June 1 - 15

Lambly Creek, 1924, 1925, 1927 (Fig. 4): May 15 - June 15

Whiteman Creek, 1957-1964 (Fig. 5): May 15 - June 15

Terrace Creek, 1965 (Fig. 1): before June 1

Terrace Creek, 1966 (Fig. 2): May 7

Timing of water yield. As in most areas, peak runoff and irrigation use do not coincide in the Okanagan. Where water is scarce during the irrigation season, any means of either increasing low flows for the irrigation season, or prolonging high spring flows into the irrigation

season, should receive attention.

Studies cited in previous sections have shown that forest management can prolong spring runoff and increase low summer flows in some regions. Reducing the forest cover thus reducing moisture loss by transpiration will normally increase low flows. Prolonging spring runoff depends to a large extent on influencing snow accumulation and melt rates.

The Fraser Experimental Forest in Colorado is similar in many respects to the Okanagan area. Forest stands are lodgepole pine, Engelmann spruce, and sub-alpine fir in the Okanagan above 3,000 ft. elevation and at much higher elevations in the Fraser forest. The climatic factors are given in Table 7.

Cutting in the Fool Creek watershed on the Fraser Experimental Forest increased water yields but the increase was confined mostly to the spring runoff period (Hoover and Shaw 1962). The authors suggested that in places having deeper snowpacks than the central Rockies, timber harvest would probably have a greater effect on the timing of runoff.

Table 7. Climate and water yield in the Okanagan, B.C., and at the Fraser Experimental Forest, Colorado

Climatic or water yield factor	Okanagan (2,500-8,000 ft. elev.)	Fraser Expt. for[1] (9,000-13,000 ft. elev.)
Mean annual temperature	37°F.[2]	35°F.
Mean January temperature	16°F.[2]	15°F.
Mean July temperature	56°F.[2]	55°F.
Annual precipitation	28 in.[2]	24 in.
Annual snowfall, water equivalent	5-20 in.[3]	16 in.
Annual snowfall as a percent of annual precipitation	about 50	about 67
Annual water yield	11 in.[4]	12 in.
Annual water yield as a percent of annual precipitation	40	50

[1]From Goodell (1958).

[2]Data are for McCulloch, B.C., at elevation 4,100 ft. (Source: B.C. Dept. of Agr. 1965).

[3]Water equivalent of snowpack in the Okanagan varies from five inches at lower elevations (4,200-4,500 ft.) to 20 in. at higher elevations (6,000 ft.). (Source: B.C. Dept. Lands, Forests, and Water Resources 1965).

[4]Annual water yield as calculated by the Thornthwaite method (Thornthwaite and Mather 1955) which is very close to the observed water yield from Terrace Creek for 1966, the first full year of record.

The Okanagan region has an annual snowpack not much different in amount than that at the Fraser forest. If the results from the Fool Creek watershed are transposed to the Okanagan, then, it must be concluded that there is little probability of affecting runoff timing by forest management in the Okanagan. However, such transposition, or extrapolation, of data from one region to another is hazardous. Even though, as in this case, vegetation and climate are similar, soil, geology, and physiography may affect the water regime in a completely different manner.

Considering the relatively small snowpack in the Okanagan region, as well as the results of the Fraser Experimental Forest investigations, the conclusion seems warranted that forest management, while it may prolong runoff for some length of time, cannot prolong it the three to five weeks necessary to make use of it during peak irrigation demand. However, in the B.C. Interior any increase in total yield or delay in melt is worthwhile, and is a legitimate objective of forest management.

Snowpack management. The quantity of runoff is increased by forest management mainly through transpiration reduction and by increased snow accumulation. Transpiration reduction is basically a function of the amount of timber harvested and is little affected by cutting method except in the case of a riparian cut. However, the cutting method can greatly affect snow accumulation as well as the rate of snowmelt.

If water yield increase is one of the objectives of forest management, that cutting method should be used that permits the greatest snow accumulation. On the other hand, if prolonging runoff later into the summer season is the objective, then that cutting method should be chosen that

most effectively reduces the melt rate. Often, however, both increased quantity of runoff and delayed snow melt are the objectives, in which case a compromise is necessary between a cutting method that permits greatest snow accumulation and one that permits shading of the snowpack.

The results of some of the investigations into the influence of forests on snow accumulation and delivery of water yield were reviewed in Chapter II. The influence of the forest on snow accumulation and melt depends on the density, height of trees, position of trees with regard to adjacent trees, and on the topography associated with the forest site. These factors determine the effect of the forest on wind, shade, radiation, and pondage of cold air (Anderson 1963). Different species will affect wind and radiation to different degrees depending on such factors as density, form, and albedo of the foliage. However, the effect of the species differences are generally confounded with stand characteristics such as crown closure and height, and topographic variation. Therefore cutting prescriptions for snow management depend mainly on topography and on stand rather than species characteristics.

Anderson (1956) suggested a wall-and-step strip cutting designed as an "ideal forest" for maximizing snow accumulation and delaying melt. With this method, the forest is cut in strips oriented across slopes, perpendicular to the direction of maximum solar radiation. Successive strip cutting would proceed generally to the south, toward the direction of maximum solar radiation. After one rotation, a wall-and-step forest would be established, with the walls to the south providing shade and the

steps to the north giving the least back radiation.

The wall-and-step method of cutting would be well suited to forest conditions and snow management objectives in the B.C. Interior. Anderson's investigations into snow accumulation and melt were carried out in the Tahoe National Forest, California, at about 39°N. latitude. For maximum snow-melt delay, Anderson suggested strip widths of 0.5H to 4H. In British Columbia, strips could be wider with no increase in direct solar radiation reaching the snowpack, because of the lower elevation of the sun. For example, on a 20 per cent slope, on the 21st of June, the width of strip shielded from direct solar radiation by trees to the south would be twice as great at 52° north latitude (about the latitude of Williams Lake, B.C.) than at 39° north latitude. The same holds for the shortest day of the year. (This was calculated using the ephemeris of the sun and solar-altitude charts in the Smithsonian meteorological tables (List 1963).)

The following prescriptions for cutting with the objective of maximizing snow accumulation and delaying snow melt are patterned after Anderson's recommendations mainly, but also with consideration for the wider strip cutting possible in British Columbia.

On northerly aspects strip widths should be about 1.5H for slopes less than 20 per cent, and from 2H to 4H on slopes exceeding 20 per cent. Strips should be oriented east-west.

On southerly aspects, strip widths should be about 1.5H on less than 20 per cent slopes and about 0.75H on slopes greater than 20 per cent. Strips should run east-west.

On easterly and westerly aspects, cutting strips should be about 1.5H wide and should run northeast-southwest and northwest-southeast, respectively. These strips would run obliquely up and downhill and should have a strip cut at the lower end along the contour to trap cold air drainage and delay snow melt.

At least three cutting cycles should be planned for each rotation, in which case the initial cutting strips should be spaced three strip widths apart. Subsequent cutting strips should be made parallel to the original cut, progressing in a southerly direction.

The disposition of slash also influences snow accumulation and melt. If slash is left as it falls, melting will occur where the snow thinly covers the slash. The alternative is to burn, windrow, or lop and scatter the slash. While burning may be a satisfactory method of slash disposal in some situations it cannot be recommended because of the many situations where slash burning would have possible harmful effects on the soil. Windrowing slash near the downhill wall of the cut strips delays snow melt by contributing to cold air ponding. Windrowing by bulldozer cannot be recommended in many cases because of the soil disturbance that results. Piling slash near the downhill wall may be carried out, but in many cases would not be practical. Lopping and scattering just enough to reduce the height of the slash will not only contribute to delaying snow melt but may also protect the soil, especially where the soils are highly erodible.

Transpiration reduction. The second point to be considered in water-yield timing is an increase in low flows resulting from transpiration reduction by cutting the forest.

The water balance of the Okanagan area has been calculated using data for McCulloch, B.C., and Thornthwaite's method (Thornthwaite and Mather 1955), and is described in Chapter VII. Based on monthly averages for temperature and precipitation, a soil moisture deficit is indicated for June to September (Fig. 6). If the water saved by transpiration reduction due to cutting goes into soil-moisture recharge, it may mean a shorter period of soil moisture deficit, but not necessarily an increase in stream flow. While considering this, along with the Fool Creek results, the fact that many watershed studies do indicate increased low flows from cutting would lead to the expectation of some increase in low flows in the Okanagan.

Shuswap Diversion to the Okanagan

Pennington (1961) discussed the irrigation needs of 148,000 arable acres in the north Okanagan region and concluded that no single source of water could be developed to satisfy the needs by gravity alone. One source of supply, Sugar Lake, 50 diversion-miles east of Armstrong would serve only 30,000 acres and the cost of the diversion would probably exceed $350 per acre. The scheme was considered impractical because much of the potentially-irrigable land is too high in elevation to receive sufficient pressure from a gravity system.

An alternate proposal is the diversion of the Shuswap River, near Enderby, into Okanagan Lake. This diversion, for which engineering and feasibility studies have been conducted, would run from the Shuswap River south by way of Fortune and Deep Creeks (B.C. Dept. of Agr. 1966). The

scheme would supply irrigation water for the north Okanagan as well as supplementing the south Okanagan supply. The cost of delivery, excluding distribution, would be about $320 per acre irrigated in the Spallumcheen valley (excluding any payment for water entering the south Okanagan region).

To put the water yield aspect of forest management into perspective, the increased yields from T.F.L. No. 9 will be related to the area that will be irrigated by the Shuswap diversion.

The average annual water duty in the Shuswap area is 1.8 acre-feet, and in the Vernon area 1.3 acre-feet (Pennington 1961). The diverted water will serve both areas so an average value of 1.6 will be used in the present discussion.

If the 148,000 arable acres in the north Okanagan region received 1.6 acre-feet annually, the total requirement is 236,800 acre-feet. T.F.L. No. 9, if managed for timber with water production considered, would produce 5,253 acre-feet more water on its 170,000 acres than if it were unmanaged. This amounts to 0.03 acre-feet of water increase per acre of managed forest. Therefore, it would require 236,800 acre-feet/0.03 acre-feet per acre, or 7.9 million acres of managed forest with cover-type areas in the same proportion as on T.F.L. No. 9, to produce the increased yield to irrigate the 148,000 acres. Even if the forest were managed primarily for water, with rotations of only 25 years, it would require 1.8 million acres.

The point is, for water demands as great as would be satisfied by the Shuswap diversion, water must be imported from other watersheds. The most efficient forest management, with water production given high priority,

cannot supply the amount of water required in such cases, especially where precipitation, itself, is low. This is not meant to imply that water yield improvement by forest management is not worth-while. On the contrary, changes in water yield and timing are useful and needed in many cases, and are legitimate objectives of forest management. However, to provide water in the amount that would be supplied by the Shuswap diversion requires more than forest manipulation.

Flooding

There is no lack of evidence indicating that removal of the forest, whether by fire or cutting, increases peak flows. This has been shown by research carried out in California (Hoyt and Troxell 1934), Colorado (Bates and Henry 1928, Goodell 1964), North Carolina (Meginnis 1959), and West Virginia (Reinhart et al. 1963). However, Rothacher (1965a) reported no increase in flow after cutting in western Oregon, and Satterlund and Eschner (1965) reported that after reforestation of a watershed in New York state, snowmelt runoff was faster, although later, than before. The authors' explanation for the faster runoff is given in Chapter II of this thesis.

The weight of evidence indicates that, except in particular cases, runoff peaks are higher after cutting, and the danger of flooding is therefore greater.

The probability of flooding is higher on small creeks because of the greater possibility of (1) a large proportion of the watershed being cut over or burned, (2) soils, geology, and physiography being homogeneous

(under given conditions the influence of each of these variables on runoff is the same right across the watershed), and (3) a single meteorologic event, e.g., a heavy rain, encompassing the whole watershed.

The custom of laying out compartments coinciding with watershed boundaries and of cutting a complete watershed before moving to the next increases the probability of flooding of small creeks. For example, timber sales presently being operated on Windermere Creek, in the East Kootenay region, occupy about 20 per cent of the area and are to be completed in 10 years. Other sales are pending, which means that in the next 10 to 12 years most of the watershed will be cut.

Of course, in steep terrain logging costs are likely to be less when the operating unit is a single watershed than when the operating unit includes parts of adjacent watersheds and the height of land between them. The shorter the period that road systems are used, the cheaper the total cost of maintaining the road for logging use, also. This is especially true where no post-logging measures are taken to control erosion on roads that will be little-used or unused. Even where post-logging erosion-control measures are taken and periodic maintenance carried out, it is cheaper to maintain roads for limited or no use than for logging use. Because of these factors, the tendency is to log whole watersheds and to harvest the greatest amount of timber possible per mile of road.

This attitude toward logging and road costs is prevalent, but considers only the short-run costs. It neglects the long-term benefits of well-planned logging layouts and of road systems that have been well

planned, located, constructed, and maintained, and on which erosion is minimal.

The larger the watershed the greater is the probability that varied soils, geology, physiography, and land use exist. This allows a compensating influence on runoff and reduces the chance of flooding. While physiography and geology cannot be altered by man, both soils and land use can. Maintaining the watershed in various land uses, each of which influences the flood potential in such a way as to compensate for the others, would be the ideal way to manage a watershed. The influence on runoff of different land uses is not so well defined, however. In some cases, though, cutting part of a watershed instead of leaving it completely forested reduces the flood hazard, for example. This causes runoff coming from the cutover to be out of phase with that coming from the forested part so that the high flow period is lengthened and the peak reduced.

In the preliminary report on flood control in the Fraser River basin, reference was made to the Wagon Wheel Gap experiment (Fraser River Board 1958, p. M-18). The report recognized the influence of cutting on volume and timing of runoff but concluded that "in the Fraser River basin, the areas cut for logging are extremely small in relation to the vastness of the forested areas, and as long as this is so the flow of the river, as measured at Hope, will not be affected appreciably, although deforestation could give rise to flooding locally" (p. 18).

The area of the Fraser River basin is 90,000 square miles or 57.6 million acres (Andrews 1963). The volume of timber cut in British Columbia

in 1964 was 9 billion f.b.m. (feet board measure) (B.C. Dept. Land, Forests, and Water Resources 1965). Assuming for the purpose of illustration that the cut per acre is 15,000 f.b.m., the area cutover was 600,000 acres. If this represented the average annual area cut and if it were all cut on the Fraser River watershed, only 600,000/57,600,000, or one per cent, of the basin would be cut annually.

Even on the assumption that the total provincial cut was taken from the Fraser River basin the effect on flooding would not be great. The actual cut on the basin is only a fraction of the cut assumed herein and is not likely to have any appreciable effect on flooding, especially on the middle and lower reaches of the river. The conclusion reached by the Fraser River Board seems justified. However, as Haddock (1957) pointed out, granted that ideal watershed conditions could not have prevented the 1948 Fraser River flood, the burned, logged, and otherwise damaged lands probably contributed much more than their share of water and debris.

The conditions existing in the spring of 1948 point out the factors that cause flooding of large river basins in British Columbia. The Fraser River flood of 1948 resulted from a moderately heavy snow pack which did not melt appreciably until the beginning of June. Usually snow melt runoff from the lower mountain slopes of the Fraser River watershed is completed by the last week of May, with runoff from the higher slopes occurring somewhat later (Reynolds 1955). However, in 1948, the late spring, combined with a heavy snow pack, resulted in a heavy runoff from the lower slopes occurring at the same time as runoff from the upper slopes. The longer

the snow pack persists in the spring, the greater is the chance of heavy rains falling on the snow pack, creating rapid melt and runoff.

From high-water marks left on the rock walls of the Fraser Canyon, it has been estimated that the discharge from the Fraser River in 1894 exceeded that of 1948 by about 16 per cent. However, the damage caused by the 1948 flood was much greater due to the increased industrial, residential, and agricultural use of the flood plain. In 1948, 16,000 people had to be evacuated from their homes, 50,000 fertile acres were flooded, and the total cost of flood fighting, rehabilitation, and dike re-building amounted to $20,000,000 (MacAlpine 1964, Reynolds 1955).

The March 1, 1967, snow survey showed that snow packs in British Columbia are heavier than usual for this time of year. Above to well-above average accumulation of snow is concentrated at the higher elevations. Many snow courses have recorded the highest March 1st measurements in their periods of record, particularly on the Columbia and Upper Fraser watersheds (B.C. Dept. Lands, Forests, and Water Resources 1967b). During the soil-priming months of September and October, 1966, precipitation at the lower elevations was normal to slightly below normal (B.C. Dept. Lands, Forests, and Water Resources 1967a). Therefore, the snow-melt loss to soil priming will not be much greater than average.

Streamflow during the spring and summer runoof period is expected to be above to well-above average on the major rivers of the province (B.C. Dept. Lands, Forests, and Water Resources 1967a). However, the temperature and precipitation patterns of April, May and June will dictate to a large

degree the maximum stages which will occur on these rivers.

Flooding on small streams, however, is a problem which can be greatly influenced by forest management. The examples discussed in the section on erosion are also pertinent to the discussion of flooding. The evidence cited previously indicated that road location and construction were responsible for the flooding of the unnamed creek and Brodie Creek, and for the slide on Giveout Creek which increased the probability of a flood on that watershed. This suggests that whereas removing tree cover does increase peak flows it is usually the combination of cutting and faulty location and construction of associated road systems which causes flooding. Of the two, faulty location and construction of roads has the greater influence in that if not properly carried out, runoff is concentrated and soil movement occurs which can dam off natural channels and cause flooding.

The method of cutting the forest can aid in flood prevention by the resulting effect on rate and timing of snow melt. Cutting in narrow strips, about 0.5H wide, along the contour will delay spring snow melt. This practice should be carried out on high-elevation north slopes in conjunction with wide-strip cutting of low-elevation southern slopes to de-synchronize snowmelt runoff from the two areas, thus reducing the chance of flooding.

Although the titles indicate that the subject of the Fraser River Board reports includes flood control in the Fraser River basin, flooding of only the Fraser River is dealt with. As stated previously, the conclusion of the Fraser River Board concerning the effect of logging on Fraser River flows seems justified. However, the validity of dismissing the role of forests in flood control in the Fraser River basin in only a few

paragraphs is questioned. Very little is written of this role in the preliminary report of the Board (Fraser River Board 1958), and even less is included in the final report (Fraser River Board 1963). On the small streams in the Fraser River basin, logging and road construction do affect flooding, and forest management does, therefore, have a role to play in flood control. The attitude toward this role, as indicated in the Fraser River Board Reports, is common and must be changed if watersheds are to be properly managed in British Columbia.

Minimum standards must be established for logging and road construction with regard to flooding as well as erosion, and enforcement of the standards must be carried out. Detailed suggestions for logging and road systems to protect watershed values have been given in preceding sections, and these are applicable to flood control also.

4. FISHERIES

Wickett (1958) reviewed the environmental factors affecting pink and chum salmon production referring to Vancouver Island rivers, mainly. He discussed the effect of low water levels on migration of adults and egg deposition, and the effect of extreme floods on population reduction. He concluded that changes in survival rate can be so great due to "normal" environmental variation that prediction of populations over long periods will depend on improved climatic forecasts made for years ahead. The possibility of such forecasts is extremely remote. The possibility of some degree of flow regulation by forest management is less remote.

Philpot (1962) reviewed the literature pertaining to forest management and the fisheries with special reference to the British Columbia salmon fishery. In this section the fisheries problems of the province that are associated with forest management will be discussed with recommendations for improving the situation.

Aerial Spraying of Forests

Pesticides. While the ideal forest would be resistant to insect attack, such forests are not in the foreseeable future. Biological controls such as parasites, predators, or disease organisms have been successful in some cases against introduced forest pests, but against native pests such as the spruce budworm, positive results have yet to be achieved (Webb 1959). Balch (1953) stated that when it represents the only way to protect a forest from serious loss, spraying must be undertaken. But this does not imply prolonged or continuous use as in agriculture because in forestry it is not necessary to keep insect populations as low as in agriculture (Webb 1959).

Spraying operations may cover an area of a few hundred acres to several thousand square miles. The dosage for defoliating insects has usually been one pound of DDT, or less, per acre. Webb (1959) stated that dosages of this size on small areas have seldom caused severe adverse effects on other forms of life, and recovery is usually fast. Serious effects are more likely to result from extensive spraying, especially when repeated.

Beginning in 1952, large areas of northern New Brunswick were sprayed with DDT (one pound per acre) to control the spruce budworm. Contrary to Webb's (1959) statement that forest spraying does not imply prolonged spraying, some areas in New Brunswick have been resprayed at intervals of one, two, or three years. Yet the budworm population expanded and by 1957, 11.5 million acres had been sprayed, much of it two or three times (Pritchard 1959). Studies of fish populations have indicated that several species have been adversely affected, particularly young salmon and brook trout, although populations recovered if the respraying interval were greater than two years (Keenleyside 1959).

On northern Vancouver Island, an infestation of black-headed budworm (Acleris variana (Fern.)) had built up by 1956 to high hazard proportions. Between June 10 and 20, 155,000 acres were sprayed with one pound of DDT dissolved in wood-penetrating oil with an emulsifier and blended to one U.S. gallon with diesel oil. All five species of Pacific salmon and rainbow, steelhead, and cutthroat trout are indigenous to the sprayed area. By June 10, the seaward migration of the pink, chum, and spring salmon fry, and also that of coho, sockeye, and steelhead smolts should have been complete (Crouter and Vernon 1959).

On four of the major streams of the sprayed area damage to fish and fish-food populations was severe (Crouter and Vernon 1959). Tests indicated that the spray could be considered "safe" to young coho salmon below about 0.05 p.p.m. (parts per million), where "safe" meant the absence of mortality with one week exposure at 10°C. (Alderdice and Worthington 1959).

In June and July, 1960, the effects were assessed of spraying at the rate of one-quarter pound of DDT per acre on Northern Moresby Island, Queen Charlotte Islands, for control of black-headed budworm. The assessment revealed that fish populations would be affected by spraying at the rate of only one-quarter pound of DDT per acre if applied directly over the streams. Leaving a one-half mile swath on each side of the major salmon-producing streams left aquatic fauna unaffected, and significant mortality of resident fish did not occur (Can. Dept. of Fish. 1965).

An alternative to DDT for control of the black-headed budworm, phosphamidon, has been studied at Moran Creek, B.C. A direct application of one pound per acre on a small, coho-salmon stream under extreme conditions of drought, caused no mortality to caged coho fry nor to indigenous coho and trout fry, although fish-food populations were affected (Can. Dept. of Fish. 1965).

In 1962, a test was made of the effects on fish of phytoactin L-318, used in aerial spraying for control of white pine blister rust. The test was carried out at Sugar Lake near Vernon, B.C., with phytoactin at a concentration of 200 p.p.m., applied directly to lake water. The assessment indicated that use of the spray appeared to be safe but the recommendation was made that more information should be gathered on its toxicity to aquatic life before further use (Can. Dept. of Fish. 1965).

Tests of different insecticides used in forest insect sprays were carried out at Nanaimo, B.C., with the result that only phosphamidon and thuricide could be considered as possible improvements on DDT with regard

to its effect on fish (Can. Dept. of Fish. 1965).

Studies have been carried out in recent years to assess the effect on fish of aerial spraying of log booms to control infestations of ambrosia beetles (Gnathotrichus sp. and Trypodendron sp.) (Jackson 1960, Werner and Waldichuk 1961). This aspect is, however, outside the scope of watershed management and this thesis.

Silvicides. Aerial spraying for control of deciduous trees and shrubs is also used as a means of eliminating competition for coniferous species. However, such sprays have not been shown to affect aquatic life. The lack of literature on the fishery aspect of such silvicides is an indication of either the lack of concern over their use or the lack of knowledge regarding their effects.

Discussion. It is probable that the use of forest insect pesticides will increase in British Columbia even though the effects of spraying are sometimes extremely harmful to fish populations. Because of this, minimum standards for fisheries protection should be established for aerial spraying, and where feasible, standards above the minimum should be followed. Following are recommended minimum standards to be followed in insect control by aerial spraying:

(1) Insecticides should be used only where cultural or biological controls cannot achieve the necessary level of protection.

(2) The most selective pesticide should be used so that other forms of life are harmed as little as possible.

(3) Only the minimum effective amount should be used. Concentrations should not be increased to gain added assurance of success.

(4) Application should be in accordance with prescribed use.

(5) Spraying should be coordinated with effective-kill dates for the insect and the period when fisheries will be harmed least.

(6) Water courses should not be used as application boundaries. The danger is that (a) the water boundary will receive a double dose of spray, once when treatment has ended for a short period and again when treatment has resumed, or (b) the water course will receive treatment in two successive years, once when the year's work has concluded, and again the following year when work has resumed.

(7) Water courses should not be sprayed where it is feasible to avoid them. This should be considered particularly in areas where fish congregate.

(8) Where extensive use of aerial sprays is planned, there should be consultation with game and fishery biologists.

(9) Protection of the fishery resource must depend on fishery-oriented research. Dependence on forestry-oriented research to properly consider the fisheries would be a mistake.

Logging Operations

In 1945, the Canada Department of Fisheries' witness before the Sloan commission stated that federal officials were vested with sufficient authority to restrict those logging practices that were a challenge to the perpetuation of the salmon industry. Sloan (1945) suggested that the B.C. Forest Service should aid in the protection of fish stocks and should have

the power to terminate any form of tenure held by an operator guilty of practices detrimental to the salmon run.

The Canada Department of Fisheries' brief to the 1956 Royal Commission stated that many of the logging practices harmful to the salmon fishery had been almost completely eliminated, e.g., log-skidding down salmon streams and depositing logging debris in streams. But the department suggested that conditions be included in logging contracts to indicate the responsibility of operators toward the fishery resource (Whitmore 1956).

Some of the recommendations of the 1956 brief have been implemented in part. Pennel (1959) described an arrangement in the Prince Rupert area between the provincial Forest Service and the federal Department of Fisheries. Salmon streams have been indicated on forestry maps by fisheries officials. Where salmon streams are located in timber-sale areas the fisheries department recommends the clauses of the forest act that would provide adequate protection of the salmon stream. These clauses are included in the logging contract and fisheries officials carry out periodic checks to see that the clauses are being followed.

Logs and debris often form obstructions in stream channels which hinder fish migration. Where these can be attributed to a logging operator, the operator must remove them; otherwise the fisheries department clears the obstruction.

In the sections on erosion and flooding in British Columbia, recommendations, aimed at reducing both erosion and flooding by forest management, were made. High turbidity and sedimentation, and flood flows are

detrimental to fish and the recommendations made in previous sections pertain to the fisheries also. In this section, only those situations harmful to the fish populations that have not been covered previously will be discussed.

The procedure outlined by Pennel (1959) regarding the liaison between forestry and fisheries personnel is one that should be in use throughout the province. Each district office of the Forest Service should maintain a set of maps on which fisheries personnel have indicated the salmon and trout streams. Timber-sale applications on areas which include such a stream should then be referred to the fisheries department, and clauses based on this department's recommendations should be written into the logging contract.

A large watershed should not be completely logged at one time, nor within a period of only a few years. Spacing the cut over a longer period keeps environmental conditions from fluctuating to the extremes (e.g., water temperatures and flow regimes from a partially cut watershed are not as far from normal as are those from a completely cut watershed).

The 1945 Canada Department of Fisheries' brief to the Sloan commission recommended that a one-half mile belt of timber be left along all salmon streams (Whitmore 1956). This is impractical with no hope of ever being implemented. However, many fishery biologists recommend a leave strip of some width along salmon streams. Cormack (1949), working in the mountain headwaters of the Crowsnest Forest Reserve, in Alberta, recommended a leave strip of 60 ft. on both sides of a trout stream in order to provide shade for maintaining the cool temperatures of the stream and to maintain stable

stream banks.

One of the arguments against the practice of leaving strips of standing timber, besides that of losing that volume of wood, is that such strips are prone to windthrow. Besides being a timber loss this may result in so much debris in the streams and unstable banks caused by uprooting that the stream is in worse shape than if cutting had been carried out right down to the water's edge. The chance of such an occurrence emphasizes the need for careful consideration of the requirements of each logging contract by both forestry and fisheries personnel. Only in unusual cases should all merchantable timber be cut right up to the banks of perennial streams. Some windfirm trees, whether of merchantable or unmerchantable species, should be left along all streams populated with fish.

Logging debris must be kept out of stream channels to protect fish populations. Normal debris, accumulated over a period of time, is more stable than logging debris which has been deposited in one or two seasons. Therefore, normal debris is not usually the hazard that logging debris is, in that high flows can more easily move logging debris, the accumulation of which can form obstructions to fish migration as well as forming barriers behind which potential flood waters may back up. Organic material requires oxygen for decomposition, reducing the oxygen available for fish respiration. It matters little whether the organic material is normal or logging debris except that logging debris can be kept out of channels. Inspection of streams must assure that streams are being kept clear of such debris.

Log Driving

It is interesting to note that no mention was made of log driving in the 1945 fisheries department brief to the Sloan commission. It was stated in the 1956 brief that the practice had almost died out but occasional attempts were still made to revive it, usually without success (Sloan 1956). Other evidence presented to the 1956 commission indicated that log driving was far more extensive than the federal brief indicated. In 1954, log driving was begun on the Fraser River from Spuzzum to Hope. Driving on the Fraser was also carried out from Lytton and Williams Lake. The Kitsumgallum River was being driven in 1956 and tests had proven the Nass River driveable for a distance of 75 miles (Sloan 1956). Tributaries of the Skeena, the Kalum and Zymoetz (Copper) rivers, were also being considered for driving (Pennel 1959).

Attempts are still being made to increase log driving on particular rivers in British Columbia. Disregarding a federal order banning log driving on the Stellako River, the provincial government issued a permit to a sawmilling company to drive the river (Vancouver Sun 1966a). The river had been driven before 1965, but in that year a federal-provincial experimental drive indicated that spawning grounds had been damaged. Because of the limited spawning gravel in the river, the ban on log driving was issued. The provincial government requested further investigation by the B.C. Research Council (Vancouver Sun 1966a). A report has been completed by the Council and forwarded to its client, but it has not yet been made public (B.C. Res. Counc. 1966).

The driving of logs down stream affects the fisheries in the following ways. The first step in log driving is readying the channel for the drive, i.e., straightening and grading the channel, and blocking off side channels and back-water areas with earth-moving machinery. This procedure damages eggs, fry, and adults by the movement of the gravel of the stream beds and by changing the flow characteristics of the stream. Also, because side channels and back-water areas are blocked off, much of the spawning, rearing, and feeding grounds are eliminated.

Log driving itself causes mechanical damage to the eggs deposited in shallow gravel beds by gouging, and riding and rolling over the beds. Logs that become stranded on sand and gravel bars may divert water around the bar so that the fish eggs are exposed to slow-flowing water or the air. Bark which has been abraded from the logs may build up on stream bottoms cutting off oxygen supplies to the incubating eggs as well as depleting oxygen supplies by its decomposition.

The larger the river the less damaging is log driving to the fisheries because of greater depths of water and the fact that improvements to stream channels must be carried out by means other than putting heavy equipment into the stream channel. On rivers the size of the Fraser, fish appear to be unharmed by log driving (Pennell 1959).

There is ample evidence to show that log driving on some streams is harmful to fish populations. The value of the fisheries to British Columbia's economy can be judged to some extent by the following data. In 1964, the fisheries of the province produced $90 million worth of fish

products, $49 million of which was from the salmon fishery. Exports totalled $32 million and 16,600 men were employed on fishing boats, others being employed in the industry on shore (B.C. Dept. Ind. Devel., Trade, and Commerce 1965).

In contrast the forest industry produced products worth $900 million (net value of production) in 1964, exported $680 million worth in 1963, and employed 80,000 persons in 1964 (B.C. Dept. Ind. Devel., Trade, and Commerce 1965).

However, to the value of the commercial fisheries must be added some part of the dollar value of the tourist industry, because fishing is one of the tourist attractions of British Columbia. In addition to these is the value of fishing streams to sport fishermen and to non-fishermen who enjoy contact with this aspect of nature. These values are difficult to quantify and perhaps should not require quantification.

Attempts have been made to set a dollar value on the recreational benefits of a fishing stream. Seiker (1955) related the value of water stored for power and irrigation to the benefits foregone to fishermen because of the lack of water in a stream. If the recreational use of the hypothetical stream were worth 28¢/day/fisherman, it would be worthwhile to discharge sufficient water to maintain fish. Seiker concluded that most people would appraise a day's recreation at more than a dollar.

It is questionable whether the recreational benefits of fishing streams can be adequately assessed in dollars and cents. It may be that the majority of people would prefer to bear the possible increased cost

of log transportation by a method other than stream-driving rather than forego the benefits of fishing streams. Whether this is true or not, there is ample evidence that stream-driving is harmful to fish populations in some streams. Therefore, it is recommended that stream-driving be restricted to those streams where evidence indicates that fish will not be seriously harmed by driving.

CHAPTER VI. THE MODEL APPROACH TO FOREST HYDROLOGY

1. INTRODUCTION

In North America for the past 40 years investigation into the hydrologic role of forests has been carried out mainly on research watersheds. These watershed studies have often been of an applied nature, the objectives being to provide data for land management within a particular region. The evidence from these studies has sometimes been conflicting and the results difficult to apply to land use problems in other areas.

Conflicting evidence can be understood considering the many factors which interact with the forest in its hydrologic role. As Kittredge (1948, p. 45) wrote:

> Vegetation is almost infinitely variable and it is reasonable to expect that itsinfluences will be equally variable. The environment is also extremely complex and variable.

During early watershed studies many of the factors in the hydrologic role of the forest were not appreciated as being involved at all, nor were those that were appreciated, completely understood, e.g., the effect of forest openings on air turbulence and precipitation catch. The operation of the physical laws of energy exchange under forest conditions, especially convective heat transfer, are not yet fully understood.

One of the problems encountered by research workers in watershed management is the application of results from research watersheds to larger regions. Larger basins do not have the same homogeneous characteristics as smaller basins and cannot be easily compared to them. This is an

inherent weakness in watershed research and results in difficulty in establishing methods for management of the resource.

The research watershed approach has been a necessary part of the evolution of scientific thinking in the watershed management field. There are still objectives which can best be met by research watershed studies, especially by those which are more inclined toward fundamental studies aimed at discovering the reasons for watershed behaviour, not just the behaviour.

It is probably true that the next step in the evolution of watershed management is now due. There is available, now, information which can be applied to watershed management. Future forests can be designed to meet specific objectives, and the designs tested by observing the results over one or several rotations, or mathematical stand models can be constructed and management simulated on computers. Simulation requires that forest conditions be expressed in physical terms. "To the extent that forest conditions can be expressed in physical terms and these terms related to water yield and control, then forests can be designed which will most closely meet water requirements" (Anderson 1960, p. 1734).

2. MODELS FOR WATERSHED MANAGEMENT

A logical step in watershed management at the present time is to apply the knowledge that has been gained over the years. One approach to this is by designing models, based on present knowledge, to predict the influence of forest management on water yield. The model represents the system as understood by the researcher, and it should be as comprehensive as possible while avoiding unnecessary complexity. Systems may often be represented verbally, physically, or mathematically. While the use of

physical models in hydrology is promising, the mathematic model seems to promise more immediate use of accumulated knowledge in this field.

Models are used for convenience. Expressing models in the symbolism of mathematics provides "a kind of shorthand of logic" (Snyder and Stall 1965, p. 88). An advantage is derived from manipulation by the rigid rules of mathematics and numerical analysis. Communication is more precise because an equation is less likely to be wrongly interpreted than verbal communication of complex relationships. Models offer advantages from the standpoint of computation, as well.

In 1960, Crawford and Linsley presented a model of the hydrologic cycle which could be solved on a digital computer to give mean daily streamflow when daily precipitation values were used as inputs. An improvement of that model has resulted in the Stanford Watershed Model Mark IIB (Crawford and Linsley 1964). This model permits the calculation of a continuous hydrograph based on average hourly rainfall and daily evapotranspiration in the watershed. The model has been tested on eight watersheds (five in California, and one each in Maryland, North Carolina, and Texas) representing wide differences in topography, vegetation, and geology. The fourth edition of the Stanford watershed model has since been presented (Crawford and Linsley 1966).

The functions and limitations of men, models, and methods in hydrologic analysis were discussed in an interesting report by Snyder and Stall (1965). The use of electronic computers in watershed research has also been dealt with (Kelly 1963).

Review of Watershed Models

There has been some work on the model approach in watershed management but little that has related forest treatment to water yield. Anderson (1960) constructed regression models based on data from California. He related snow accumulation to shade by trees and to the height of, and distance to, trees to the north of the measurement point. Models for snowmelt, rain-snow floods, and sediment discharge were also constructed.

Rantz (1964) demonstrated a rational method of computing snowmelt runoff as opposed to the empirical method of which Anderson's is an example. In the study by Rantz the formulas were based on the physical laws of heat exchange with constants to reflect the effect of such environmental influences as forest cover and basin exposure. The method is interesting and perhaps lays the groundwork for future studies. However, many of the independent variables are meteorological observations not generally available.

The objective of a study at the Fraser Experimental Forest in Colorado was to relate snowmelt runoff to its causes using (1) the statistical approach, and (2) the physical approach (Garstka et al. 1958). In the statistical approach correlation analyses were made for 33 combinations of 19 independent variables (including temperature, relative humidity, dew point temperature, wind, and solar radiation). The conclusion was that in estimating snowmelt runoff "the temperature factor is at least as good as, and in many cases better than a combination of other factors used in correlation analyses" (Garstka et al. 1958, p. 93).

The physical approach consisted of using an equation expressing the physical relationship of wind, air temperature, and water vapour pressure as they interact to make heat available for the melting and evaporation of snow.

The models described above rely heavily on meteorological observation. For example, given the value of five meteorological variables, four geological variables, two topographical variables, and one cover variable (area of bare cultivation) the flood peak discharge can be estimated by one of Anderson's (1960) equations.

Described in the section on interception were equations to predict interception given the depth of intercepted storage, leaf surface-to-crown area ratio, evaporation rate, and storm length (Horton 1919), and interception at a point in an opening given the precipitation and the distance to the edge of the nearest crown (Niederhof and Wilm 1943).

A Rational Interception Model

A comprehensive model is needed which will consider the influence of the forest on all aspects of the hydrological cycle. This is needed so that the effect on water yield and regime of any forest management proposal may be tested and the results considered before the plan is carried out. This is especially true since the advent of mathematical stand models has made possible the simulation on computers of stand growth under various management schemes (Newnham and Smith 1964).

Objective. The objective in this section is to construct a rational interception model using the most easily measured stand variables or the relationships existing between such variables and other stand variables.

Ideally, they should be measurable on aerial photographs.

Beginning assumptions. Based on the studies reported in previous sections the following relationship holds for interception of precipitation by forest trees directly over a given point on the ground.

$$I = f(PI, LUC, Sp, Se, A, TS)$$

where I = interception
PI = precipitation intensity
LUC = location under crown
Sp = species
Se = season
A = age
TS = tree size

To simplify the first stages of the construction of the model the following assumptions will be made. These will be dealt with later.

(1) As shower intensity and size increase the interception percent decreases. Assume that from one year to the next the average intensity and amount of rainfall per shower is constant so that these variables can be omitted from present consideration.

(2) Interception varies with species because of branching habit, foliage density, and crown width or volume. To begin with only one species will be considered so that this variable may be omitted.

(3) Interception varies with season because of (a) foliage variation with season, and (b) variation in shower intensity and amount. Assume that from year to year the effect of (a) is constant. Assumption (1), above, has taken care of (b).

(4) Interception increases with age until about the age at which current annual increment culminates and then decreases with increasing age. Presumably, this indicates that interception varies with amount of foliage. Assume, then, that interception is a function of crown volume and omit age.

(5) Interception varies with size of timber. Two considerations are involved here. Either (a) the variable affecting interception is not size nor amount of crown cover (stands of small-sized trees, even with complete crown closure, have smaller percentage interception than large-sized stands) but crown volume, in which case tree size can be omitted because crown volume is to be included; or (b) interception is influenced by tree size in that it varies with the height differential between individual or small groups of trees and the rest of the stand. If such is the case this variable may be omitted for the present assuming that the stand being considered is of uniform height.

(6) The final assumption is (a) interception under a single canopy will not vary with distance from the bole (i.e., an average value will be considered), and (b) there is no influence by adjacent trees on precipitation in forest openings.

Constructing the model. The investigations described in the section on interception indicate that interception as a percentage of seasonal precipitation ranges from 20 to 40 for spruce, hemlock, and Douglas fir. McMinn (1957) reported interception in pure Douglas fir stands on Vancouver Island of from 20 to 40 per cent with a mean interception of 29.5 per cent. In the following section a model will be constructed for Douglas fir.

Considering the assumptions made above, interception by a single tree may be described as a function of crown volume. A tree of a given size would have maximum crown volume if grown in the open, in which case interception would be maximum, or 0.40, the top of the range. If the tree had less than maximum crown volume then

$$Imax = 0.40 \frac{CV}{CVmax}$$

where Imax = the upper limit of the fraction of total rainfall that is intercepted by a single tree of given CV
CV = crown volume
CVmax = the maximum crown volume possible for the tree (i.e., open-grown)

But CV varies between 1/2 CW^2 x CL (forest-grown trees) and 1/3 CW^2 x CL (open-grown trees) for ~~spruce~~ Douglas fir (Ronay 1961), where CW and CL are crown width and length, respectively. So that

$$Imax = 0.40 \times \left[\frac{\frac{CW^2}{K} \times CL}{\frac{CW^2max}{3} \times CLmax} \right]$$

$$= 0.40 \left(\frac{3}{K}\right) \left(\frac{CW^2}{CW^2max}\right) \left(\frac{CL}{CLmax}\right)$$

where CWmax and CLmax = crown width and crown length, respectively, of the tree if open-grown
K = crown volume constant which is dependent on stand density.

However, it seems reasonable to assume that CA, the area of the vertical projection of the crown, has a greater influence on interception than does crown length. That is, of two trees of equal CV, the one having the larger CA will have greater interception because of greater evaporation due to greater foliage exposure to air movement and radiation. A method of weighting the two variables is needed. In the absence of empirical data, values will be assigned arbitrarily; when there is evidence for a change, it can be made.

Because the crown-width term is the ratio of CW of the particular tree to the maximum CW possible for a tree of the same diameter (i.e., open

grown), the crown-width term will never be greater than 1.0, and similarly for the crown-length term. A fraction less than 1.0 raised to a power less than 1.0 is greater than the original fraction. Therefore, raising the crown-width term to the 0.8 power will increase its value. Raising a fraction less than 1.0 to a power greater than 1.0 reduces its value. Therefore, raising the crown-length term to the 1.2 power will decrease its value. This will have the weighting effect desired.

The relationship between CW and D (diameter at breast height) has been established for some species. The ratio CW/D ranges from 0.7 for very dense stands of Douglas fir to 2.0 for open stands of the same species (where density refers to the number of trees per acre and CW is in feet and D in inches) (Smith 1965a). For open-grown coastal Douglas fir, Smith (1966) reported the relation

$$CWmax = 5.9 + 1.50D$$

Smith et al. (1961) reported the relation for Douglas fir

$$CL = 13.1 + 1.938D + 4.3CW/D$$

For a given diameter, CLmax may be obtained by substituting CWmax for CW in the above equation. The interception equation may now be written

$$Imax = \frac{1.2}{K} \left(\frac{(CW/D \times D)^2}{(5.9 + 1.50D)^2} \right)^{0.8} \left(\frac{13.1 + 1.938D + 4.3CW/D}{13.1 + 1.938D + 4.3\left(\frac{5.9+1.50D}{D}\right)} \right)^{1.2}$$

$$= \frac{1.2}{K} \left(\frac{(CW/D \times D)^2}{(5.9 + 1.50D)^2} \right)^{0.8} \left(\frac{13.1 + 1.938D + 4.3CW/D}{19.55 + 1.938D + \frac{25.37}{D}} \right)^{1.2}$$

The above equation is for interception by a single tree. To convert this to an area basis, the term expressing crown area in square feet, CA, can be expressed as a proportion of a unit area. The acre is a convenient

unit because many stand characteristics are defined on an acre basis. Multiplying the equation by CA/435.6, or its equivalent, $0.0018CW^2$, converts Imax to Imax%, where Imax% is the maximum percentage of total rain falling on an acre intercepted by the single tree.

The maximum interception on the acre as a per cent of rainfall is the sum of Imax% calculated for each tree on the acre. The single-tree procedure allows the calculation of interception for each species represented in the stand.

Where the stand is composed of one species and is homogeneous, average stand values may be used for K, D, and CW/D, and a multiplying factor, number of trees per acre, added to the equation. Because 43,560 x crown closure is the area in square feet occupied by tree crowns on a given acre; and $0.7854CW^2$ is the area of the tree crown of width CW; then the number of trees per acre can be estimated given crown closure and average crown width, both of which can be obtained from aerial photos. The equation is (Smith 1965a)

$$NT = \frac{43560 \times CC}{0.7854\overline{CW}^2}$$

where NT = number of trees per acre
CC = crown closure expressed as a decimal
$\overline{CW}$ = average crown width.

For a homogeneous stand of coastal Douglas fir the final form of the equation is

$$TImax\% = \frac{1.2}{\overline{K}} \left(\frac{(CW/D \times \overline{D})^2}{(5.9 + 1.50\overline{D})^2} \right)^{0.8} \left(\frac{13.1 + 1.938\overline{D} + 4.3CW/D}{1.955 + 1.938\overline{D} + 25.37/\overline{D}} \right)^{1.2}$$

$$x\ (0.0018\overline{CW}^2)\left(\frac{43560\ x\ CC}{0.7854\overline{CW}^2}\right)$$

$$= \frac{119.798CC}{\overline{K}}\left(\frac{(CW/D\ x\ \overline{D})^2}{(5.9 + 1.50\overline{D})^2}\right)^{0.8}\left(\frac{13.1 + 1.938\overline{D} + 4.3CW/D}{19.55 + 1.938\overline{D} + 25.37/\overline{D}}\right)^{1.2}$$

where TImax% = the maximum interception on the acre as a percentage of rainfall
$\overline{K}, \overline{D}$ = average K and D values for the stand.

For an individual Douglas fir the final form of the equation is

$$Imax\% = \frac{1.2}{K}\left(\frac{(CW/D\ x\ D)^2}{(5.9 + 1.50D)^2}\right)^{0.8}\left(\frac{13.1 + 1.938D + 4.3CW/D}{19.55 + 1.938D + 25.37/D}\right)^{1.2}$$
$$x\quad 0.0018CW^2$$

$$= \frac{0.00216}{K}\left(\frac{(CW/D\ x\ D)^2}{(5.9 + 1.50D)^2}\right)^{0.8}\left(\frac{13.1 + 1.938D + 4.3CW/D}{19.55 + 1.938D + 25.37/D}\right)^{1.2}$$
$$x\quad (CW/D\ x\ D)^2$$

where Imax% = the maximum percentage of total rain falling on an acre intercepted by the single tree.

Similarly, models of minimum interception by a tree (Imin%) and by a stand (TImin%) may be constructed and the range of interception expressed as TImin% to TImax%.

Adjusting for beginning assumptions. The model may now be refined by adjustments for the original assumptions. It is likely that the range between maximum and minimum can be decreased substantially for a particular region as testing of the model is undertaken and further data are obtained.

(1) One assumption was that only one species would be considered. However, the model may be used to estimate interception by other species by substituting the appropriate species factors in the equation.

(2) Age was omitted and it was assumed that interception varies with crown volume. No correction is required because this assumption is a valid one.

(3) Correcting the model for height variations within the stand is necessary because such variations play a substantial role in interception. There are data showing the variation in interception with different stand heights, but little on variation within the stand.

For the stand interception model a measure of height variation as well as average height should be considered. The standard deviation of height expressed as a percentage of average stand height (i.e., the coefficient of variation of height) may be weighted and combined with the interception equation as a multiplying factor.

For the single tree model the methods can range from (a) the sum of the ratios of height difference to horizontal distance of the individual tree and its neighbours, to (b) the coefficient of variation of height of the stand.

Height may be measured in the field, on aerial photos, or estimated for stand density classes from the relationship of height to diameter or crown width (Smith 1965b, Smith and Bailey 1964, and Smith, Ker, and Csizmazia 1961). In the absence of data it is suggested that the multiplying factor range from 0.95 for stands having little height variation to 1.05 for stands having large coefficients of variation of height.

(4) The next assumptions for which the model needs adjustment are (a) precipitation in forest openings is not influenced by adjacent trees, and (b) under a single canopy interception does not vary with distance from the bole. Although both (a) and (b) are incorrect, (b) can be omitted from further consideration by specifying that a value averaged for the full width of the tree crown be used, as it has been in the model.

As for part (a), above, numerous studies indicate the influence of adjacent trees on precipitation in openings. In the model it was assumed that from the edge of the crowns to the centre of such openings precipitation was the same as in extensive openings. Neiderhof and Wilm (1943) established the relationship

$$I = 0.234GP - 0.102r + 0.423$$

where I = interception, in inches
GP = gross precipitation, in inches
r = distance from any point in an opening to the edge of the nearest crown, in feet.

This relation would differ in degree for stands of different heights but as an initial refinement it can be incorporated into the model. Expressed as a percent of GP_o the expression can be integrated over the range of r for each opening, or for the r of the average stand opening, to obtain the percentage of GP reaching the ground in such openings. These can then be converted to per acre values by multiplying by the ratio of the area of the opening, in square feet, to 43,560. The total precipitation reaching the ground on a given area is then

$$TF = GP - I + Po$$

where TF = throughfall, in inches
Po = precipitation in openings

(5) The model represents seasonal interception and average storm size and intensity for the season. To estimate interception for a single storm a factor should be introduced to adjust for intensity and size of storm.

There is little pertinent data on storm intensity and interception. Factors other than storm intensity have greater influence on interception especially where rains are typically gentle, as on the west coast of British

Columbia, Washington, and Oregon (Bruce 1959, Frevert et al. 1955, and Murray 1964). Storm size, on the other hand, is one of the most important factors. For Douglas-fir stands in Western Oregon and Washington Rothacher (1963) established, for the summer season (May-September), the following relationship:

$$TF = 0.8311GPss - 0.046$$

where TF = throughfall, in inches
GPss = gross precipitation for a single storm, in inches.

Ninety-six per cent of the variation in throughfall was accounted for by storm size.

Therefore, the model will be adjusted so that interception for a single storm of given size may be estimated, but storm intensity will receive no further attention.

The above equation can be transformed to estimate interception assuming that stemflow is negligible in Douglas fir as Rothacher's (1963) study indicated. Then

$$Iss = 0.1689GPss + 0.046$$

where Iss = single storm interception, in inches

From Rothacher's report the following were derived: average percentage interception; size of the average storm, in inches of rain; and amount of interception during the average storm, in inches. Interception for storms of various size was calculated and expressed as a fraction of the interception during the average storm. This value was plotted over the single storm precipitation, the relationship being linear and expressed by the equation

$$Iss/Iave = 0.305 + 1.075GPss$$

where Iave = the average interception for all storms, in inches.

Assuming the relation holds for British Columbia as well as Washington and Oregon then

$$\left[(TImin\%)(GPp)\right] \leq Iave \leq \left[(TImax\%)(GPp)\right]$$

where TImin% and TImax% describe the limits of the estimate of average interception over the season
GPp = gross precipitation for the season, in inches.

In other words, $\left[(TImin\%)(GPp)\right]$ and $\left[(TImax\%)(GPp)\right]$ are both estimates of the same thing, average interception over the season, or Iave. The upper limit may be found by substituting $\left[(TImax\%)(GPp)\right]$ for Iave so that

$$Imaxss = \left[0.305 + 1.075GPss\right] \left[(TImax\%)(GPp)\right]$$

where Imaxss = the upper limit of the estimate of interception during a single storm, in inches.

Similarly the lower limit of the estimate of interception during a single storm may be computed so that

$$Iminss \leq Iss \leq Imaxss$$

This discussion has neglected the effect of foliage changes during the season on interception. This will be discussed briefly in (6).

(6) The final assumption was that interception, although varying from season to season, was constant from year to year. The changes that take place from year to year are caused by stand changes, and these have been allowed for in the model. The model has been constructed for interception during the spring through autumn seasons. For estimation of single storm interception the changes in foliage density during these seasons may be

great enough to warrant consideration. However, because of the absence of data on this aspect, no correction to the model is suggested.

3. FURTHER RESEARCH NEEDS

In the preceding section only the first step in a comprehensive water yield model was treated, i.e., the interception of rain by tree crowns. Models are also needed to estimate snowfall interception, storage, and melt, as well as infiltration, evapotranspiration losses, and finally, streamflow.

A snowfall interception model should follow the method used in the rainfall model. Studies described in the section on snow interception have reported amounts of snowfall interception under various forest conditions. These should be used in conjunction with such studies as "The surface geometry of a closed conifer forest in relation to losses of intercepted snow" (Satterlund and Eschner 1965) and "Interception processes during snowstorms" (Miller 1964), both of which describe the processes involved.

Snow accumulation in the forest is described by the snowfall interception model. Snow accumulation in forest openings is a function of the ratio of width of opening to height of surrounding trees, topography, wind direction, as well as characteristics of the storm.

Using the results of other studies in conjunction with the interception models on which infiltration, availability of water for evapotranspiration, and runoff depend to a large degree, models can be constructed for infiltration, evapotranspiration, and runoff. However, studies must be carried out to evaluate the effect of forest cover on surface runoff and infiltration rates. The stocking, or crown closure, of forest stands affects

not only interception but also the amount of rainfall that reaches the soil surface with reduced velocity. This affects surface compaction and infiltration rates. Percolation is influenced by the presence of tree roots, which in turn is a function of several factors, one of which is density.

The effect of changing the density and crown closure of stands on infiltration, percolation, and surface runoff must be studied in order to construct models that will be useful for forest management relative to water yields. Such models will be extremely gross initially, but as more knowledge is gained of these relationships, and with inclusion of factors of geology, soils, and topography, more useful models will result.

CHAPTER VII. WATERSHED STUDIES IN BRITISH COLUMBIA

This chapter deals mainly with the following watershed studies being carried out in British Columbia:

(1) Terrace-Esperon Creek experimental watershed. This watershed has been established in the Okanagan Valley by the Faculty of Forestry, University of British Columbia, to determine the effect of intensive forest management on water yield and quality.

(2) Windermere and Sinclair Creek watersheds in the East Kootenays. In this chapter Windermere Creek is calibrated with Sinclair Creek to enable measurement of water yield changes brought about by the planned logging of Windermere watershed.

(3) Watching Creek watershed in the Kamloops region. An analysis is made of pre-logging and post-logging streamflow from the Watching Creek watershed.

In addition, other studies dealing with watershed management in British Columbia are discussed along with research needs in the province.

1. RESEARCH WATERSHEDS

The Terrace-Esperon Creek watershed has been established as a research watershed and the Windermere-Sinclair Creek and Watching Creek watersheds have been treated as research watersheds in the analysis. A discussion is warranted, therefore, of research watershed objectives and the criteria used in the selection of research watersheds.

On January 1, 1965, the International Hydrologic Decade began. This was sponsored by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). The objective of the IHD program is "to accelerate the study of water resources and the regimen of waters with a view to their rational management in the interest of mankind; to make known the need for hydrological research and education in all countries; and to improve our ability to evaluate resources and to use them to the best advantage" (IHD 1965a,p. 3).

In 1965, 169 hydrology projects were being sponsored cooperatively by federal and provincial agencies and universities (IHD 1965). By the end of 1966, approved IHD projects totalled 172 (IHD 1966b).

In order that Canadian research watershed studies may be carried out to meet IHD aims as well as national needs, the Canadian National Committee held a seminar on research basin studies in January, 1966. The proceedings have been published as "Guidelines for research basin studies" (IHD 1966a). This publication has been used as reference in the following sections on representative and experimental watersheds.

Objectives of Research Watersheds

A research watershed is a drainage basin in which the relationship between runoff and the factors affecting runoff are studied under natural conditions or under conditions modified by man. The research carried out on research watersheds may be applied or fundamental, or, preferably, a combination of both. The fundamental study aims at providing a better understanding of the natural hydrologic processes, whereas the applied

study aims at providing data which can be applied to land and water management, generally within a particular region. Within these two categories the objectives vary considerably depending on the problems being investigated.

Representative Watersheds

Research watersheds may be classed as either representative or experimental (IHD 1966a). Representative watersheds are established to allow study of the existing conditions of a region, the objectives being:

(1) To provide data on all parameters of the hydrologic cycle in order to develop statistical or physical models for major climatic or geologic areas. The hydrologic characteristics of other areas may be synthesized from the principles derived from these models.

(2) To provide an outdoor laboratory in which particular aspects of the hydrologic cycle may be investigated, such as snow accumulation and melt.

Toebes (1965) outlined the requirements for representative watersheds. There should be a sufficient number of watersheds established to represent all important hydrological regions, and they should be typical of these regions in size and other physical characteristics. They should have reasonably uniform physical conditions for quantitative determination of watershed characteristics and data interpretation. The watershed should be maintained without change as much as possible. Where changes do occur, their nature and degree should be recorded.

Experimental Watersheds

Experimental watersheds are established with the intention of modifying the natural conditions, the objective being to evaluate quantitatively the resulting effect on various factors of the hydrologic cycle. Experimental watersheds must be calibrated over a period of years in order that the hydrologic behaviour of the watershed be established either with relation to climatic variables on the same basin (Reigner 1964), or with relation to the hydrologic behaviour of a control watershed (Reinhart 1958). Striffler (1965) described a fairly new approach, the multi-watershed method, in which a number of watersheds are selected representing different conditions of the factors being evaluated (vegetative cover, size, or watershed disturbance). The hydrologic phenomenon being analysed, e.g., storm runoff or sediment yield, is statistically related to such independent variables as watershed area, soil types, forest density, and rainfall. The advantages cited for this method are (1) a range of conditions is sampled, and (2) greater flexibility is permitted in the selection of watersheds.

Changes in the hydrologic behaviour of single experimental watersheds have been shown to be the result of land use changes (Anderson 1955, Whelan 1950). A variation of this method is the instrumentation of adjacent watersheds having different land uses, as was done on the Sperbelgraben and Rappengraben in Switzerland (Burger 1954). In this example the difference in streamflow from the watersheds was attributed, in part at least, to the difference in land use. Wicht (1943), however, stated that the study cannot be said to have proved this.

In the case of two or more watersheds the relationship between the one designated as control and the others is established as a basis for comparison after the non-control watersheds have been modified by treatment.

To choose an experimental watershed a selection group should be formed of specialists in geology, meteorology, soils, forestry, wildlife management, and other fields with special consultants in such fields as forest insect and disease surveys and photo interpretation. The group should then establish the criteria on which the watershed is to be selected, based on the research objectives.

The main consideration in choosing a research watershed is that it not be atypical of the region to which research results are to be applied. That is, if results are to be applied to the management of Engelmann spruce-subalpine fir stands above 4,000 ft. elevation on the east slopes of a mountain range, then the experimental watershed should be located in an area having these characteristics. The topography, geology, soil, and climate of the experimental area should also be typical of the region.

Homogeneity. The homogeneity of such factors as climate, vegetation, and geology is an important criterion in the selection of a research watershed. According to Hore and Ayers (1964) research watersheds must be limited in size to between 10 acres and 25 square miles to achieve homogeneity. Brown (1964) questioned this view suggesting that this size limit may produce problems from a geologic standpoint because very small structures and textures of the geological materials must be considered if the watersheds are small.

Although homogeneity of research watersheds is considered a requirement, very little has been written about how the degree of homogeneity can be ascertained and what range is acceptable. "The difficulty arises in that, before, we can determine the degree of homogeneity which exists, we will probably have to complete a major portion of our study" (Slivitzky and Hendler 1964, p. 291). It is not likely that a major portion of the study would have to be completed, but certainly some part of the study would have to be carried out before the degree of homogeneity could be determined. The possibility exists that a period of study would prove the choice of watershed to be a poor one and that the watershed should be discarded in favor of another. Much of the cost of establishing the basin as a research watershed would not be recovered. To minimize the loss from such an occurrence the watershed should be instrumented, at first, only to the degree necessary to provide information on the homogeneity of the watershed. If the trial period indicated that the watershed was acceptable, the remaining instrumentation would be carried out and the watershed established as a research watershed.

The hydrologic parameter most commonly evaluated on research watersheds has been surface runoff. This is due to its relative ease of measurement and the need for this basic data for management of the water resource. Surface runoff is also the best single integrator of all the factors influencing the hydrologic processes. However, the selection of experimental watersheds is usually based on physical characteristics because streamflow data are generally unavailable until the study has begun (Sopper and Lull 1965).

Several methods have been used in an attempt to describe watersheds quantitatively. Among these are hypsometric curves, stream density, stream order, mean slope, channel slope, and watershed dimensions. Of these, the hypsometric or area-elevation curves seem most useful. The area-elevation curve is usually drawn with elevation on the ordinate scale and area below a given elevation, as a percent of total area, on the abscissa. The area-elevation ratio curve may also be used, in which elevation expressed as the ratio of unit elevation to the total elevational difference between the summit and base level of the watershed is plotted over the ratio of unit area to total watershed area. However, area-elevation ratio curves give valid comparisons of watershed land forms only where watersheds of similar size and elevation range are being compared. A dimensional area-elevation curve is a more meaningful parameter in watershed hydrology (Aronovici 1966).

When dealing with those factors that are used as criteria for choosing experimental watersheds, including hypsometric curves, the question arises as to the degree of homogeneity that is required.

An experimental watershed is to be representative of the region to which the results are to be applied, but the region is not homogeneous in vegetation, geology, topography, and soil. A watershed that is homogeneous is not, therefore, representative of the region as a whole. However, the influence of individual watershed parameters on the hydrologic behaviour of the watershed can be determined with less cost and with greater accuracy when the degree of homogeneity of the parameters is high.

The results from treated experimental watersheds would be applicable to similar watersheds within the region. But the question arises as to their applicability to the whole region where similar watersheds having a high degree of homogeneity of those factors influencing the hydrologic cycle comprise only a part of the region. However, the results of companion studies that have been carried out on the watershed to explain the hydrologic processes can be used in conjunction with the results of the watershed treatment to permit valid extrapolation to the larger region. Where the hydrograph of the experimental watershed is similar to the composite hydrograph of the whole region there is still greater assurance of the validity of extrapolation.

Experimental watersheds must be chosen by (1) an evaluation of each of the established criteria for each watershed, with those that are definitely unsuitable being rejected, and (2) a comparison of candidate basins on the basis of the results of the first step. The procedure for carrying out these two steps will be discussed in a succeeding section.

Vegetation. One of the first steps in choosing a forested experimental watershed is determining the forest type in which management problems and interest exist. The experimental watershed should be of the same type and have similar values for such parameters as volume/acre, stand height, average diameter, and species composition. To facilitate the choice, the average and range of values of these factors that are acceptable should be established at the start of the selection process. Not only should the experimental watershed be typical of the forest cover type but sub-basins

within the watershed must also be typical.

A disease and insect survey should be made so that watersheds are not chosen which have a higher than average incidence of disease or insect population.

Attention must be paid to the pertinency of research results after 10 or more years. If by the time results are available from the experimental watershed the cover type has been completely logged, the research is of little value to management. In such a case effort would better be expended in another direction, for example, companion or plot studies.

Geology. The geology and particularly the hydrogeology of the watershed should be such that long-term hydrologic investigations can reasonably be carried out. Stratigraphy should be hydrologically homogeneous and groundwater instrumentation should not be excessively costly.

There should be no chance of the bedrock catchment area exceeding the topographic catchment area; otherwise unmeasured leakage into or out of the watershed will result. There should be no major structural disturbance in the watershed, e.g., faulted zones should be avoided because of the chance of leakage through them beyond basin boundaries. A topographic indication of faulted zones is a structurally controlled drainage pattern, e.g., a rectangular or trellis pattern.

Soil. The soil mantle over the watershed should be deep enough that manipulation of the forest cover would have a perceptible hydrologic effect. As a general guide, 75 per cent of the watershed should have a depth of surficial material of five feet or more. The soil and surficial material on the watershed should be representative of the

broader area where management based on the research will be applied.

Topography. Slope and aspect conditions should be avoided in which springs and flow between sub-basins are liable to be present. Areas should be avoided in which there are bogs, muskegs, large ponds, or numerous small ponds. It may be necessary to accept basins with some of these conditions but it should be recognized that their relation to the hydrologic behaviour of the watershed is often difficult to determine and costly to evaluate.

Accessibility of the watershed as well as accessibility on the watershed must be considered. A good internal road network should be possible without causing conditions leading to accelerated erosion. Good access is needed to allow the installation and servicing of an adequate instrumentation network.

A circular or oval-shaped watershed often has a combination of some of the following characteristics: gravity-controlled drainage, dendritic drainage pattern, good basin symmetry, and sub-basins of approximately the same size and hydraulically similar. All of these offer advantages for research watersheds.

A rectangular watershed, on the other hand, may be indicative of structurally-controlled drainage with dipping, resistant, folded or faulted bedrock forming basin ridges with less-resistant materials forming the valleys. The less resistant nature of the valley material may be caused by a highly-fractured zone, possibly extending outside the basin boundaries. Leakage out of the watershed may occur where streams cross or follow such zones.

Drainage. Drainage should be well-defined, dendritic in pattern, with perennial streamflow. Slopes adjacent to streams should be steep enough that channels do not require large artifical controls. A narrow flood plain with confined flow will facilitate stream gauging. However, it is desirable that slopes be not so steep as to hinder construction and access.

Suitable stream-gauging sites should be available on the watershed fulfilling the above requirement as well as the requirement that leakage under artificial controls be minimized. A stream-gauging site should be chosen, if possible, where bedrock or other relatively impermeable material is exposed. By examining the stream during extremely low flows and noting areas of diminished surface flow, underflow problems may be detected. It is likely that where the geologic criteria discussed above are satisfied, reasonable gauging sites may be found also.

Meteorology. Meteorological instrumentation can usually be arranged to suit the watershed chosen. Location of instruments must be done with some thought to access for servicing. The only caution is that the area chosen should not be an area of atypical precipitation or other climatic factors, but be typical of the climate of the region of interest.

Power. Another factor which can be legitimately considered is the proximity of electric power to the watershed and the feasibility of bringing it to the experimental area. The use of power for the instruments on the area as well as to provide heat in winter to keep weirs in operation has merit. However, the choice of experimental watershed need not depend on whether power is available, since the other criteria are much more

important and difficult to satisfy in combination.

Experimental watershed selection. A major source of information for this section has been reports of the Canada Department of Forestry and Rural Development, in files dealing with the selection of an experimental watershed in the lodgepole-pine cover type on the eastern slopes of the Rocky Mountains.

When the region of interest and the objectives of management have been defined, the next step is the selection of an experimental watershed. Following calibration and treatment of the watershed, analysis of results should provide guidelines for the management of the region to achieve the defined objectives.

The selection procedure outlined in the following paragraphs is only one of several approaches that may be employed. This procedure should permit the selection of an experimental watershed with a minimum of time and effort. However, circumstances, e.g., the objectives of management or the makeup of the group of specialists charged with the selection, may dictate changes in the individual steps, or the order in which the steps are carried out.

Selection of a forested experimental watershed should be the responsibility of a group of specialists in such fields as geology, meteorology, hydrology, and forestry. The first duty of this group is to establish the criteria on which the choice of watershed is to be made. The second duty is to list sub-regions within the general region in order of desirability from the point of view of those factors which are pertinent to the particular project, e.g., proximity to headquarters.

A study of maps covering the sub-region should be made in order to isolate those watersheds that offer some hope of satisfying the established criteria. At the same time, those areas may be eliminated whose ownership rules out their being considered. The forestry specialists on the selection group should then make an aerial photo examination of those watersheds indicated as prospects by the map examination. Those which conform to the forest cover criteria should be listed in order of priority including any other information gained from the photo examination.

At this stage, the status of both surface and sub-surface rights of each candidate basin should be checked and the possibility investigated of having rights, leases, and permits nullified. This may be accomplished by voluntary release of the rights by the holders, by arranging to have rights on other areas traded for those on the watershed, or by some other method. Where it is not possible to clear the watershed of such encumbrances they must enter into consideration of the acceptability of the candidate basins.

Surface and subsurface rights on areas adjoining the candidate watersheds must also be considered because of the influence that activities on nearby areas may have on the experimental watershed.

Each member of the selection group should then photo-examine each candidate basin and a revised list of the watersheds in order of priority should be established. An alternative step at this stage, and one that has greater merit where members of the selection group are inexperienced photo interpreters, is the employing of a consultant photo interpreter. The consultant should have wide experience and, preferably, training in

geology.

The selection group might then profitably make an aerial inspection of the remaining candidate basins followed by field examination of the surviving candidates.

If at any stage in the selection process all watersheds being considered have proven unacceptable, the procedure must be begun again with another sub-region. When candidate basins have been selected from top-ranking sub-regions, it must be recognized that there may be watersheds in lower-ranked sub-regions that better satisfy the established criteria. The degree of superiority of these watersheds may be enough to compensate for the lower-ranking of the sub-region. Therefore, unless top-ranking candidate watersheds satisfy the criteria to a high degree, lower-ranked sub-regions should be examined also.

Where the size of the region for which management guidelines are desired precludes the division into sub-regions, the decision must be made as to the acceptability of the top-ranking candidate basin as an experimental watershed.

2. OKANAGAN VALLEY-TERRACE AND ESPERON CREEKS

Objectives

The Terrace-Esperon Creek watershed is located on the west side of Okanagan Lake, on Tree Farm Licence No. 9 of S.M. Simpson Limited, a division of Crown Zellerbach Canada Limited. The objective of the study is to investigate the effect on water yield and quality of intensive forest management in a region of significant water demand. A companion study

will consider methods of increasing snow accumulation and prolonging runoff by forest cover manipulation.

The study was initiated early in 1965 and is being carried out by the Forestry Faculty of the University of British Columbia. The project received approval as an IHD (International Hydrologic Decade) project in 1965 and direct financing of the study has been by the National Research Council.

This area has been chosen for the following reasons:

(1) The Okanagan area is one of significant water demand and supply limitations.

(2) The cover type is Engelmann spruce-subalpine fir, at an elevation of 4,000-5,500 ft. This cover type is considered to have the greatest influence on water yield in the area.

(3) A landform-soil-plant ecology system of site classification has been completed for the area (Lacate et al. 1965).

(4) Complete forest cover maps, aerial photographs, and forest inventory data are available for the area.

(5) Access by wheeled vehicle is possible from May to mid-January in most years. S.M. Simpson Ltd. has a tracked vehicle which may be used for winter access.

(6) The cooperation of S.M. Simpson Ltd. was promised. The company has made available cutting records, forest cover maps, and aerial photos. Snow survey and meteorological observations will be carried out by the company in winter.

(7) The B.C. Water Resources Service in Kelowna has promised cooperation. Meteorological observations will be carried out

by this agency in summer. Assistance in locating and clearing stream-gauging sites was also promised.

(8) Sites were located at which stream gauging appeared feasible and at which there was natural control in the form of bedrock sills.

(9) While a formal selection committee had not been established, specialists of the various cooperating agencies considered such factors as geology, soils, and topography of the area.

Cooperating agencies have been

S.M. Simpson Ltd. (Crown Zellerbach Canada Ltd.), Kelowna

B.C. Dept. of Agriculture, Soil Survey Branch, Kelowna

B.C. Dept. of Lands, Forests, and Water Resources, Water Investigations Branch, Victoria

Water Rights Branch, Kelowna

Canada Dept. of Agriculture, Research Branch, Summerland

Canada Dept. of Northern Affairs and National Resources, Water Resources Branch, Vancouver

Canada Dept. of Transport, Meteorological Branch, Vancouver.

Description of the Region

Location. The Terrace Creek watershed lies on the western side of Okanagan Lake in the British Columbia Interior, at latitude 50°N., longitude 120°W.

The Okanagan Valley is recognized as an outstanding orchard area but since World War II the forest industry has become the most important element in the economy. Mills are now located in almost every settlement and a wide variety of wood products are produced. The area has all the

endowments necessary to cater to the tourist industry also: scenery, good fishing, hot summers, and lakes.

Mining has played an important part in settlement of the area although its present importance is slight. A significant influx of population occurred when gold was discovered on the lower Fraser River in 1857. This brought thousands of men through the Okanagan on the way to the gold gravels near Yale, Boston Bar, and Lillooet. Farming began and a small permanent population was established.

Apple growing on a commercial basis began near Kelowna in 1892, firmly establishing the communities of Penticton, Vernon, and Kelowna. Other fruits such as apricots and peaches grew well in the southern part of the valley and an integrated cooperative marketing system was established.

Nearly all of the orchards are found on sloping valley benches. Small upland lakes capture the spring runoff which is used for irrigation throughout the summer. The water is diverted into canals, ditches, pipes, or flumes, along the valley sides and re-diverted for individual orchards. Although the average amount of water used is closely related to soil texture (coarser soils requiring more water), type of crop, and frequency of application, the total depth of water applied during the season is usually larger in the southern part of the Okanagan than in the north. The usual requirement is three to four acre-feet in the south and one and one-half to two and one-half acre-feet in the north (B.C. Dept. Lands and Forests 1961).

The economy of the Okanagan is largely dependent on fruit growing and therefore on irrigation water. In certain sections of the valley especially, as well as the valley in general, water is scarce during the later part of the irrigation season.

The Okanagan Flood Control Project, administered by the British Columbia Department of Highways, was completed in 1959. This project was initiated as a means of water conservation and flood control. The channels between the lakes interspersed along the Okanagan River were improved and three dams were constructed, at Penticton at the south end of Okanagan Lake, at the south end of Skaha Lake, and at Vaseux Lake (Canadian National Railway 1963). This project is an indication of the two-pronged problem which exists in this area, as well as in many semi-arid areas, i.e., the over-supply of water during a particular season (often the season of minimum water use) and the scarcity during the season of maximum need.

As an indication of present water consumption relative to potential demand, it is noted that 50,000 acres are presently under irrigation in the Okanagan Valley which has close to 150,000 acres of irrigable land (Canadian National Railway 1963). The greater part of the potentially irrigable land is suitable only for irrigated pasture, but the demand for this type of land is likely to increase as indicated by the following projections from the Agricultural Outlook Conference of 1966 (B.C. Dept. of Agric. 1966). Beef production is expected to advance steadily in North Okanagan and double by 1985 in South Okanagan, with an increasing

proportion of the production coming from irrigated land. Dairy production is expected to double by 1985 in North Okanagan and the demand for irrigated pasture will increase for this use also. While tree-fruit production is expected to increase in value through higher yields and better quality, planting of new areas will likely be limited and demand for irrigation water will not increase greatly.

At present, the majority of irrigation districts, of which there are 30, each with its own system, depend on gravity to distribute water. Pressure systems are fast replacing gravity systems, impetus being provided by grants and loans available from the federal government under ARDA (Agriculture Rehabilitation Development Act). Pressure systems permit pumping water to some of the fertile hill slopes that are too far from the upland storage reservoirs for practical gravity distribution.

Although the water supply is adequate for present demands on existing systems, potential demand greatly exceeds present use and presently available supplies. Expansion of irrigation networks would be possible only by improvements in present, and development of new, storage reservoirs, and maximum use of available water. Losses from seepage and evaporation in open flumes, wooden pipes, and furrows amount to as much as 30 percent of the available water supply in some areas. The introduction of metal and cement pipe and sprinkler systems has resulted in substantial water economies.

Many of the small lakes on the plateau have been dammed in order to store some of the snowmelt water which runs off in spring and which otherwise would be lost to use. The better sites for engineering structures

have been utilized, the result being that while storage sites still exist the structures are costlier than in the past.

Research in other parts of North America has shown that forest management can influence the accumulation of snow and the melt rate. In the Okanagan, Engelmann spruce-subalpine fir stands, which occur at elevations of 4,000 ft. and higher, have the greatest influence on snowpack, melt rate, and runoff. Below this elevation soils are often more porous and deeper, and precipitation is less.

Physiography. The Okanagan Valley is in the southern interior of British Columbia. The physiography of this region and that of the whole province greatly influences the climate and commerce of the region as well as the characteristics of runoff. Following is a brief description of the physiography of the region.

The interior of British Columbia, between the Coast Mountains and the Rocky Mountains, contains a great diversity of land forms. These include low-lying plains and basins, plateaus in varying stages of dissection, highlands and mountains, all of which are part of the Interior System. Despite divergencies in physical appearance, a common geologic and physiographic development makes the group a unit and distinguishes it from the systems to the east and west.

The Interior System includes a large part of British Columbia, three major subdivisions of that part west of the Rocky Mountain Trench having been made (Holland 1964): the Northern Plateau and Mountain Area, the Central Plateau and Mountain Area, and the Southern Plateau and Mountain Area. The Thompson Plateau, the most southerly of the plateau areas in

the Southern Interior, includes the Terrace Creek watershed and the Okanagan Valley. This plateau has a gently rolling upland of low relief, generally between 4,000 and 5,000 feet elevation, but with prominences rising above it to 6,688 feet at Tahaetkun Mountain, and to 7,372 feet at Apex Mountain.

The plateau contains a great diversity of rocks. Paleozoic sedimentary and volcanic formations are intruded by granite. Large areas of older rocks are covered by Tertiary lavas.

The Pleistocene ice sheet left much of the area covered by thick glacial deposits. The ice moving south-east and south along the Thompson River produced land forms, somewhat like drumlins, oriented in the same direction. As this glaciation came to a close, the ice wasted. On its margins meltwater channels developed in which water flowed for a period, the channels then being abandoned. Series of channels were formed on slopes at successively lower levels as the ice surfaces disappeared. Examples of these channels are apparent in the Okanagan Valley. The irregular melting of ice in the large valleys created many glacial lakes into which silt-laden streams discharged. White silt banks, which can be seen on lower Okanagan Lake, are remnants of silt beds deposited in glacial lakes as the ice sheet retreated (Holland 1964).

Climate. The principal source of information for this section was Kendrew and Kerr (1955). The climate of the Southern Interior is a continental one of mild to medium intensity. Winters are cold and the area is under snow during most of December and January. Temperatures rise fast in March with spring being fairly dry, and summer warm with many hot

days and cool nights. Precipitation is light and well distributed over the year. The main movement of air masses is from west to east, and the amount of precipitation is dependent on elevation and exposure, the uplands receiving more. The winter climate is greatly affected by a series of low pressure systems that cross the country frequently bringing cloud and some precipitation. The systems often follow one another with scarcely a day between, and a series may persist for weeks. Occasionally the pattern may be interrupted by an influx of continental Arctic air lasting for a few days to a week or more.

Climatological factors and irrigation water provide a suitable environment for the growing of apples, peaches, apricots, and plums. However, the hazards of weather are present, and occasionally the results are serious. The most serious hazard is frost. In spring, especially, the chances of an inversion-frost on clear, calm nights is an ever-present danger and makes the choice of a site a very important consideration. In winter, abnormally cold weather accompanied by strong winds can be disastrous. The December cold wave of 1964 was of this type and many orchards, especially of soft fruits, were severely damaged. During such cold spells the smaller lakes in the valley bottoms are frozen but Okanagan Lake seldom freezes over. Okanagan Lake usually has shore ice during the winter, but only in the years 1916, 1950, and 1957 has ice stopped tugboat service on the lake (Allen 1964). The mean July temperature of few weather stations in the Okanagan Valley exceed 70°F. During that month the mean daily maxima generally exceed 80°F. but the cool nights cause the means to be substantially lower. Most of the valley stations have

recorded temperatures above 100°F. in the summer and night minima in winter of below -20°F.

The coastal mountain ranges condense much of the vapour in the westerly winds but the winds still contain considerable moisture. This moisture is precipitated on the west slopes of the uplands to a greater degree than on the east slopes, and to a decreasing degree as the air moves eastward over the Southern Interior. Thunder storms account for an appreciable amount of the summer precipitation, with many of the heaviest falls occurring during such storms (Kendrew and Kerr 1955).

Summaries of temperature, frost occurrence, and precipitation for Okanagan Valley meteorological stations are presented in Tables 8, 9, and 10.

Study Area

Location. Terrace Creek watershed is 15 miles north-west of Kelowna, on the west side of Okanagan Lake. It is 12.7 square miles in area and has an elevation range of 4,300 to 5,440 ft. Terrace Creek is a tributary of Lambly Creek which flows into Okanagan Lake. A sub-basin of Terrace Creek watershed, Esperon Creek, is 6.0 square miles in area with an elevation range of 4,400 to 5,440 ft. Stream-gauging stations are located at 4,300 ft. elevation on Terrace Creek and at 4,400 ft. on Esperon Creek (See Map 6).

Geology and soils. The rolling upland of the Thompson Plateau was produced by the glaciers of the Pleistocene epoch which covered all the area below 7,500 ft. (Jones 1959). The sediments left by the retreating

Table 8. Monthly, annual mean, and extreme temperatures in °F. (Source: B.C. Dept. of Agric. 1963.)

Station	Elevation (in feet)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Extremes High	Extremes Low	Record (yrs) Means	Record (yrs) Extr.
Kelowna	1160	26	30	38	48	56	62	68	66	58	47	37	31	47	102	-24	(1)	50
Penticton	1140	27	31	39	48	57	63	68	66	58	48	37	32	48	105	-16	(1)	56
Vernon	1582	22	26	36	47	56	61	67	64	57	46	34	27	45	104	-32	(1)	69
McCulloch	4100	15	20	26	36	45	50	56	54	49	39	26	20	36	98	-43	25	28
McCulloch (water year 1965)	4100	-	-	-	-	-	-	-	-	-	41	29	14	36	88	-40	na[2]	na[2]
		22	22	21	36	43	50	59	57	43	-	-	-					

[1]30-year standard average 1931-1960.

[2]Not applicable.

Table 9. Frost occurrence in the Okanagan Valley (Source: S.M. Simpson Ltd. 1962)

Station	Elevation (in feet)	Years of record	Last frost in spring		First frost in autumn		Ave. frost free period
			Average	Earliest	Average	Latest	
Kelowna	1160	49	May 12	April 16	Oct. 3	Nov. 13	144 days
Vernon	1383	26	May 6	April 9	Oct. 5	Nov. 13	152 days

Table 10. Monthly and annual precipitation in inches [1] (Source: B.C. Dept. Agric. 1963)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Snowfall
Kelowna	1.28	1.05	0.74	0.58	1.02	1.14	0.88	0.88	1.02	1.20	1.12	1.50	12.41	32.6
Penticton	1.22	0.89	0.77	0.73	1.12	1.35	0.94	0.77	0.78	0.94	1.08	1.15	11.74	26.7
Vernon	1.57	1.19	0.91	0.73	1.41	1.70	1.10	1.15	1.19	1.38	1.33	1.75	15.41	40.0
McCulloch	2.98	2.54	2.31	1.86	2.41	2.92	1.87	1.55	1.90	2.20	2.53	3.27	28.34	151.9
McCulloch	-	-	-	-	-	-	-	-	-	0.57	2.56	2.61	28.27	163.2
Water year 1965	4.76	4.16	0.68	1.26	1.31	3.24	2.07	4.00	1.05	-	-	-		

[1] Total precipitation is the sum of (inches of rainfall) and (inches of snowfall)/10.

MAP 6.

TERRACE–ESPERON CREEK WATERSHED

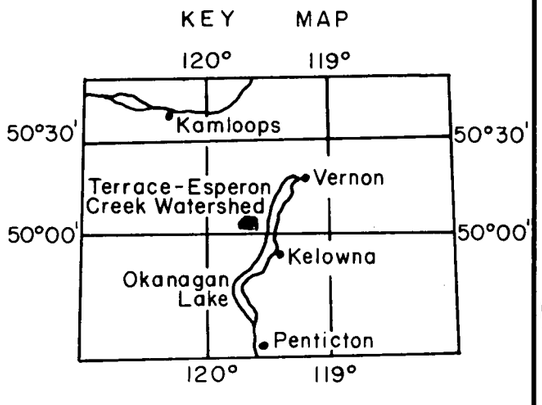
(I·H·D· PROJECT IWB-EB-11, BC-12)

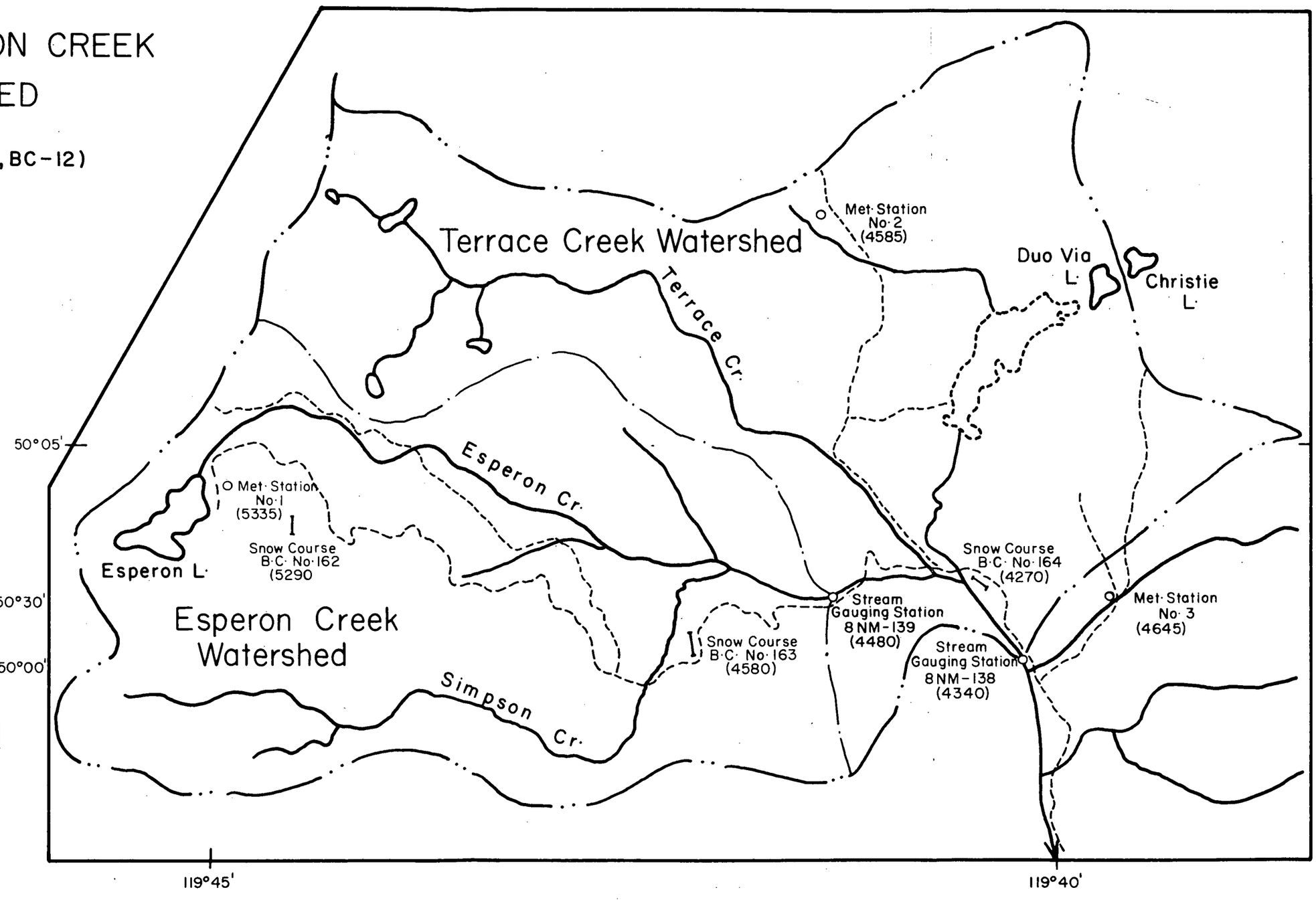
Scale: 1 inch = 1/2 mile

LEGEND

Streams
Roads
Main basin
Sub-basin
Elevation above sea level in feet (4580)

KEY MAP





ice further subdued the topography. Deeply incised creeks break the pattern at intervals. Shorts Creek to the north of the study area has cut a valley over 1,000 ft. deep and up to two miles wide. Below the study area, Terrace Creek has cut a valley half as large as Shorts Creek, but on the study area Terrace and its tributaries have done little valley-cutting.

Covering most of the area is a thin layer of till deposited by the retreating glaciers. The till is compact, of medium texture, and light in color. Bare rock is occasionally visible but is usually covered by the till or colluvium. Sandy, gravelly outwash overlays the till in most places to a depth of one to three feet, although it exceeds this depth in some of the stream valleys. At the junction of Esperon and Terrace Creeks the outwash is underlain by silt and fine sand (Lacate et al. 1965).

The upper part of the watershed is underlain by granitic rocks and the lower part by basaltic rocks (Jones 1959).

Forest type. The area is in the Interior Sub-alpine Section, SA2, as described by Rowe (1959). Stands of lodgepole pine and Engelmann spruce-subalpine fir are the major cover types. In the lodgepole pine cover type, lodgepole pine is found in either pure stands or heavily predominant in associations with Engelmann spruce and subalpine fir. Douglas fir and ponderosa pine are present in some areas of this cover type, but to a very minor degree. Lodgepole pine reaches heights of over 100 ft. on good sites. This cover type is found from the bottom to the highest elevation of the watershed. Lodgepole pine is a fire sub-climax species on sites at the upper elevations where Engelmann spruce and subalpine fir form the

climax vegetation.

The Engelmann spruce-subalpine fir cover type is composed of forests in which the spruce or a mixture of spruce and subalpine fir is dominant. Lodgepole pine is a common minor associate. There are considerable areas of virgin mature to overmature stands of this cover type which is the climax forest occupying the area from 4,000 ft. elevation to the highest elevation on the watershed. The spruce has a maximum height on good sites of 130 ft. The mature and over-mature stands of this cover type along with the lodgepole pine cover type contain very few natural openings and grow in dense stands having a crown closure of 80 to 100 percent (S.M. Simpson Limited 1962).

The Study

Instrumentation. In the autumn of 1965 automatic-stage recorders (Model A35, Leupold and Stevens) were installed on Esperon Creek (elevation 4,400 ft.) and Terrace Creek (elevation 4,300 ft.), replacing staff gauges installed in June, 1965. Natural controls are bed-rock ledges.

Three sites on the watershed were instrumented as listed below. The sites are at elevations of 5,335, 4,645, and 4,585 ft. and were chosen to sample the watershed with respect to elevation, aspect, and topography.

Met. Station No. 1 (elevation 5,335 ft.)

1 recording tipping-bucket rain gauge
2 hygrothermographs (one in the open and one in the forest)
2 "Ogopogo" evaporimeters
2 three-pen soil thermographs (one in the open and one in the forest; sensors at 3, 12, and 24 in. depths)
7 standard rain gauges in the forest
6 access tubes for soil-moisture determination with neutron probe (three in the open and three in the forest)

Met. Station No. 2 (elevation 4,585 ft.)

1 recording tipping-bucket rain gauge
1 hygrothermograph
2 "Ogopogo" evaporimeters
1 Class A evaporation pan
1 storage precipitation gauge
10 access tubes for soil moisture determination (two in the open and four at each of two sites in the forest)

Met. Station No. 3 (elevation 4,645 ft.)

1 recording tipping-bucket rain gauge
1 hygrothermograph
2 "Ogopogo" evaporimeters

Three snow courses were established on the watershed in 1965. The location of these and the meteorological stations are shown on Map 6.

Water balance. To calculate the water balance of the region Thornthwaite's (Thornthwaite and Mather 1955) method of computing the individual components was used with meteorological data (Tables 8 and 10) from McCulloch, B.C. This meteorological station has 28-year precipitation and 25-year temperature records. The closest station to the study area is Kelowna, only 25 miles southeast of the watershed at an elevation of 1,160 feet. Mean annual precipitation is only 12.41 inches at Kelowna, nestled in the valley, and it would be expected and is observable that precipitation is much greater at the elevation of the Terrace Creek watershed.

The Whiteman Creek and Lambly Creek basins (76 and 92 sq. mi. in area, respectively) for which comparisons between computed and observed runoff were also made, both have their outlets into Okanagan Lake. Whiteman and Lambly Creek discharges were compared with computed runoff because discharge from Terrace and Esperon Creeks has been measured for only a very short period whereas longer records exist for the other two

streams. Both Lambly and Whiteman Creeks are on the west side of Okanagan Lake, Lambly being the creek into which Terrace flows, and Whiteman Creek basin being just eight miles north of the study area.

Whiteman Creek is gauged at its outlet (1,150 ft. elevation) and Lambly above a diversion at the 2,000 ft. elevation but their maximum elevations run up to 6,688 ft. (Tahaetkun Mountain) on the Whiteman watershed, and 6,114 ft. (Whiterocks Mountain) on the Lambly Creek watershed. Therefore, it was thought that McCulloch, although 50 miles to the southeast and on the east rather than the west side of the valley, because of its elevation of 4,100 ft. would have a climate more similar to the watershed under study.

An estimate was needed of the water holding capacity (the amount of water held by the soil at field capacity) of the soils of the watershed for use in the Thornthwaite computation of the water balance. Brief soil descriptions and some information on depth of soil, rooting depth, field capacity, and depth to water table were available for the Terrace Creek watershed (Lacate et al. 1965). Predominant soil textures on the watershed are sandy loam to gravelly sandy loam. Field capacity is generally moderately low to low and rooting depths average close to 2.5ft. Estimates were made for the major soil types of the water holding capacity within the rooting zone. An unweighted average (the area of each soil type was not known) of these estimates was 12.7 cm. That is, that depth of soil that would contribute to moisture loss by evapotranspiration could hold 12.7 cm. of water at field capacity.

The figure obtained is, admittedly, a rough estimate of the true water-holding capacity, but it seems as valid as those used in many other studies. For example, in calculating the water balance of the University of Toronto forest Pierpoint and Farrar (1962) indicated that, because no data were available on the actual amount of water held by the soil, a capacity of 10 cm. was selected on the basis of the authors' knowledge of the soils of the area and of moisture relations of similar soils.

To check on the effect of different water-holding capacities on the computed runoff, and because some doubt existed as to the validity of the calculated value, the figure of 12.7 cm. was rounded to 12 cm. and values of 7 cm. and 17 cm. were also used. A computer program to calculate the monthly factors of the water balance by Thornthwaite's method was used on the U.B.C. IBM-7040. The results are presented in Tables 11 and A9.

Table 11. Computed (by the Thornthwaite method) and observed runoff

Water holding capacity in cm.	Computed runoff in cm.		Observed runoff in cm.			
	McCulloch data	Kelowna data	Whiteman Creek	Lambly Creek	Terrace Creek	
					1965	1966
7	32.43	3.92				
12	29.93	0.08	15.47	11.50	13.10	25.98
17	28.71	0.00				

The observed runoff was 11.5 cm. for Lambly and 15.5 cm. for Whiteman Creek. Calculated runoff was 30 cm. These differences are extreme and may be accounted for by one of the following:

(1) The climate at McCulloch is not representative of the two watersheds on the west side of the lake. This is probably true, but the degree of the difference will not be known until meteorological records for the west side have been accumulated for a period of time. It is possible that rainfall on the west side of the lake is significantly less than on the east side. Whiteman and Lambly Creeks have their upper (western) boundary along the height of land separating the Columbia and Fraser River drainages. Possibly there is very little spillover of precipitation as westerly flows of air are lifted up and over the divide. Perhaps as air rises from the Okanagan Valley the lifting of the air which has picked up moisture from the lake allows greater precipitation at McCulloch.

Snow surveys in 1966 indicated maximum snow accumulation on the Terrace Creek watershed of from 11.0 in. water equivalent on the lower snow course (No. 164) to 19.2 in. on the upper course (No. 162), whereas at McCulloch 6.0 in. water equivalent were recorded (Table A3). At the end of February, 1967, the water equivalent of the snowpack was 11.6-19.2 in. on the Terrace watershed and 6.7 in. at McCulloch (B.C. Dept. Lands, Forests, and Water Resources 1967b). Rainfall during the period June 12-September 30, 1966, was 3.43 in. at Meteorological Site No. 2, 5.13 in. at Site No. 3, and 5.44 in. at Site No. 1 on Terrace Creek watershed (Table A2), compared to 5.72 in. at McCulloch (Can. Dept. Transport 1966). These data indicate higher winter precipitation for the Terrace Creek area but higher summer rainfall for McCulloch. However, the period of comparison is too short to base any conclusion on the long-term averages

for the two areas.

(2) The climate of McCulloch is representative of the watershed at an elevation similar to McCulloch, but certainly not for the drier valley bottoms through which both Whiteman and Lambly Creeks flow before emptying into Okanagan Lake.

(3) Much of the discharge from the two creeks is lost before reaching the gauging station because of seepage to ground water due to the underlying rock strata or the soils over which the streams flow. This is especially true of Whiteman Creek which flows over a flat, gravelly, outwash fan before reaching the gauging station.

To check the hypothesis that McCulloch climate is representative of similar elevations on the west side, the water balance factors were computed using meteorological data for Kelowna (Table 10). The intention was to use the Kelowna data for the lower part of the watersheds and McCulloch data for the upper. From Table 11 it can be seen that little runoff will be produced in an area for which Kelowna meteorological data is applicable, and therefore its effect on a combined calculation of runoff would be very little.

If McCulloch data were applied to the upper parts of the watersheds, to arrive at a runoff of 15.47 cm. for the whole Whiteman watershed would require that 29.93 cm. of runoff be attributed to approximately 50 percent of the total watershed, and 0.08 cm. to the other 50 percent. (29.93 is the computed runoff using McCulloch data and 0.08 cm. is the computed runoff for Kelowna, both for a water-holding capacity of 12 cm. See Table 11.)

50 per cent of 29.93 cm. = 14.96 cm.
50 per cent of 0.08 cm. = 0.04 cm.
Total runoff = 15.00 cm. (compared with the observed runoff from Whiteman Creek of 15.47 cm.)

However, three quarters of the Whiteman watershed lies above the 4,100 ft. level (the altitude of McCulloch) and 50 percent lies above the 4,800 ft. level. This indicates, then, that either the climate at McCulloch is different than at the same elevation on the west side, or that the gauging stations are not measuring the total runoff.

Proportions of the watersheds to which Kelowna data and McCulloch data can be applied may be arrived at by arithmetic manipulation so that calculated runoff equals observed runoff. Such values would be meaningless in the light of the absence of observations to support the underlying assumptions.

As a point of interest the observed runoff from Terrace Creek in 1965 and 1966 was calculated and compared with the runoff computed by the Thornthwaite method. Considering the variations in annual values of precipitation and temperature which go into a long-term average of climate, the chance of the two values of runoff being similar is very remote when using a value of runoff based on only one season's record (summer 1965) and one year's record (1966). The values obtained by the computation along with the observed values are given in Table 11.

When the staff gauge was installed on Terrace Creek on June 2, 1965, it was thought that the maximum flow was just occurring. From observation it seemed unlikely that the stage had been higher earlier in the season.

As a rough check the hydrograph of Terrace Creek was compared with that of Mission Creek (Fig. 1). Mission Creek is on the east side of Okanagan Lake, with its gauging station at 1,600 ft. and the maximum elevation of its watershed at 5,000 ft. Mission Creek peaked on June 2 and it was assumed, then, that this was the date of peak flow for Terrace Creek. Not shown on the hydrograph of Fig. 1 is an earlier peak on Mission Creek which occurred in April. It was thought that this peak was caused by snowmelt at lower elevations even before melting at higher elevations had begun to contribute to streamflow.

It was then assumed that June 2nd was peak flow on Terrace Creek and that the hydrograph rose fairly steeply from winter base flow to the spring peak. Using as base flow for winter months the value of 0.5 cubic feet per second, the runoff for Terrace was calculated at 13.1 cm. This value is less than half of the Thornthwaite runoff calculation using McCulloch data.

It is possible that the flow on June 2nd was not peak flow, but evidence is lacking to support this view except that on that date there was no snow remaining on the ground up to an elevation of 4,500 ft. suggesting the possibility of an earlier peak. Data was not available on the 1965 runoff measured at the gauging stations on Whiteman and Lambly Creeks. Fig. 4, showing the hydrograph of Lambly Creek for 1924, 1925, and 1927 does show that maximum flow averaged for those three years did occur in May and that a break in the descending limb of the hydrograph occurred in June. The hydrographs of Mission Creek (1953-1961) and

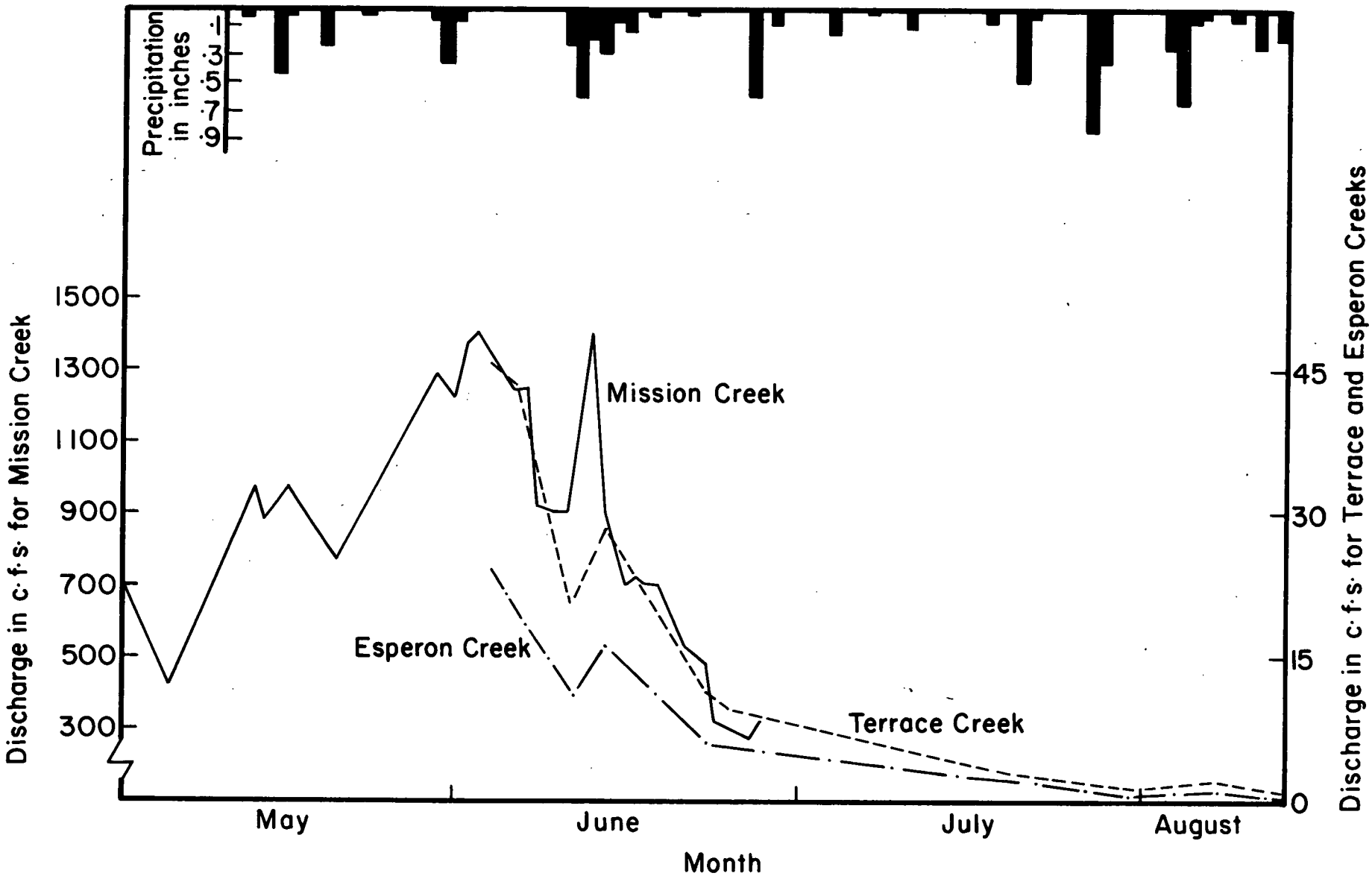


Fig. 1. Hydrographs for Mission, Terrace and Esperon Creeks and precipitation for McCulloch, B.C., May – August, 1965

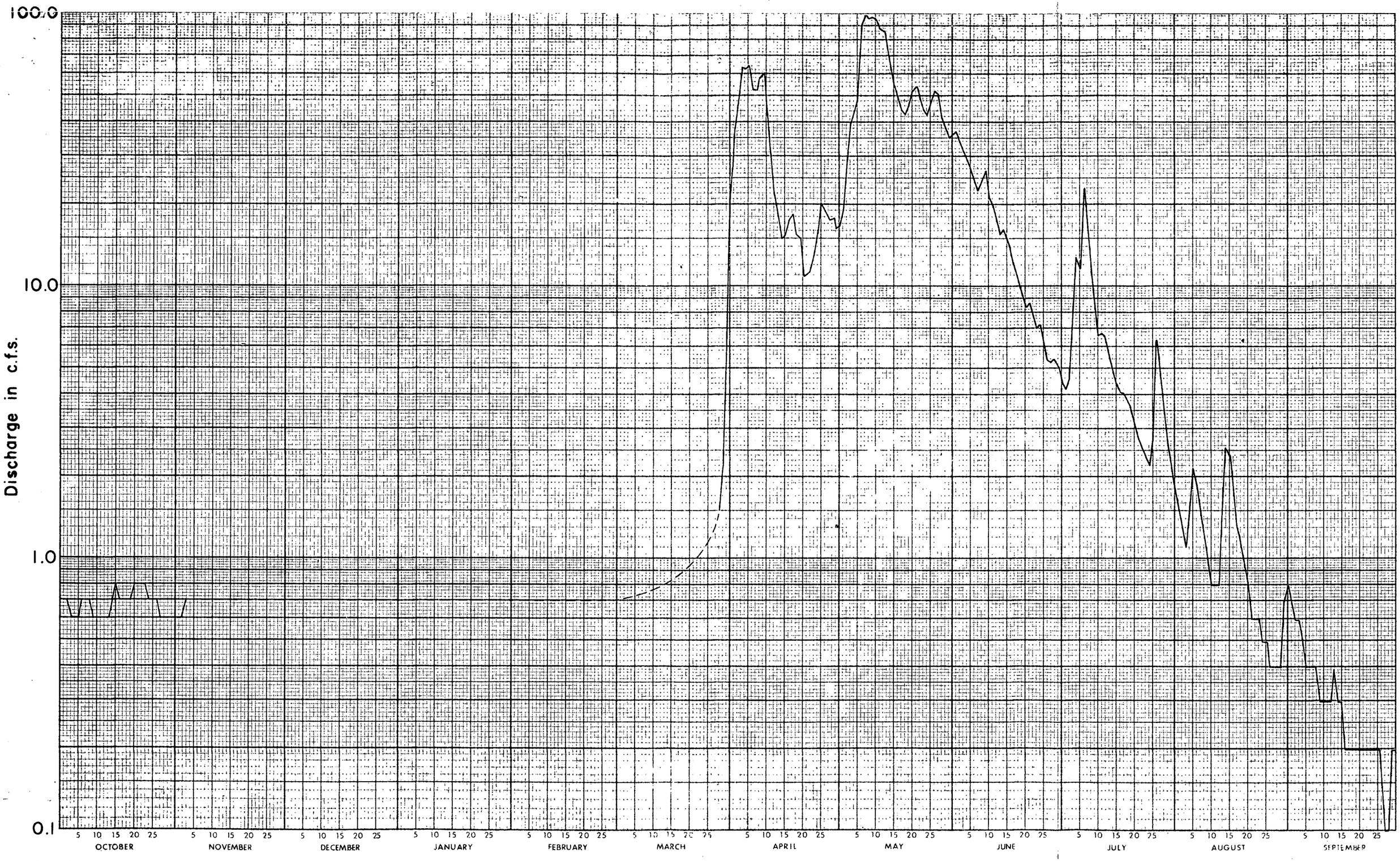


Fig. 2. Hydrograph for Terrace Creek, October 1, 1965 — September 30, 1966

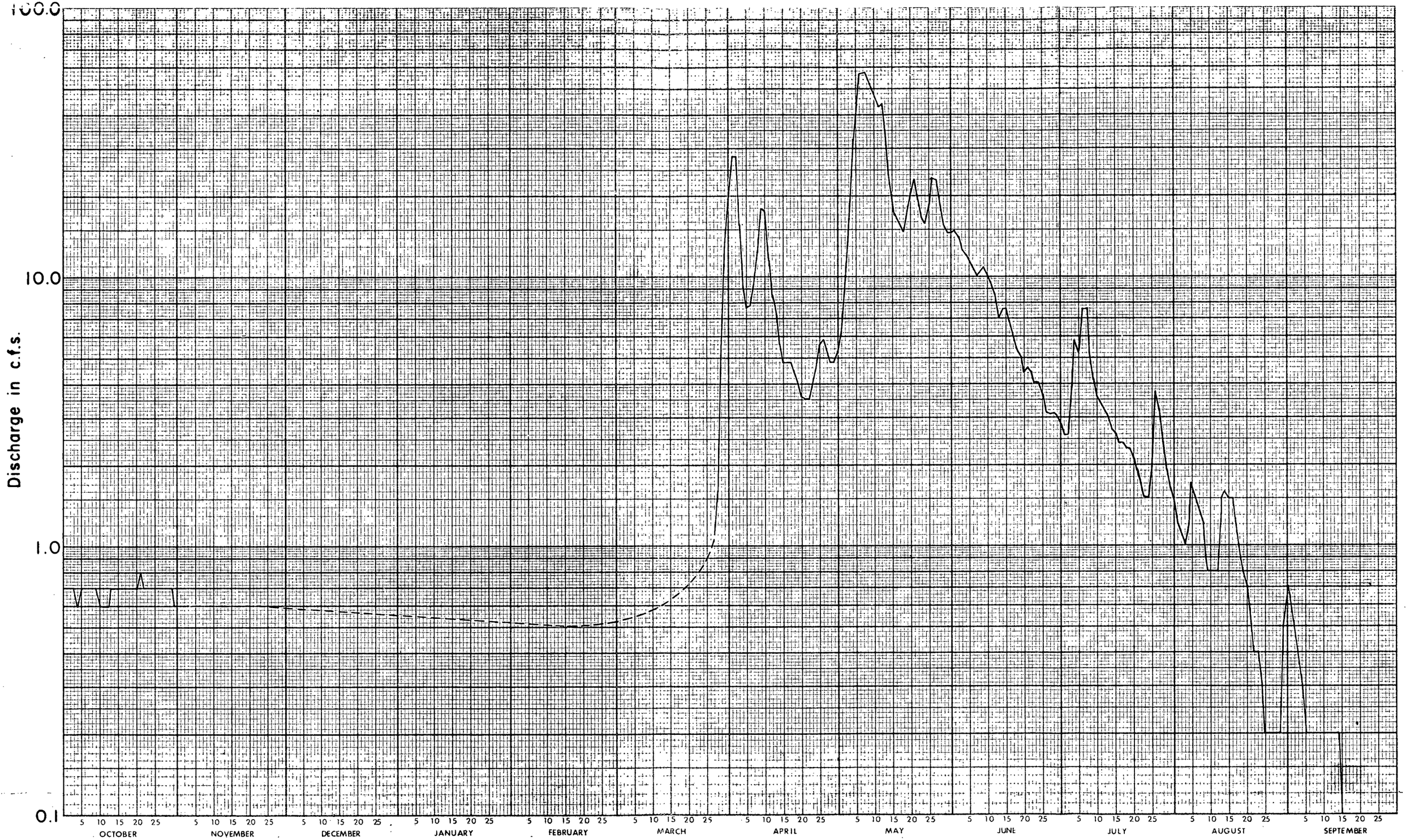


Fig. 3. Hydrograph for Esperon Creek, October 1, 1965 — September 30, 1966

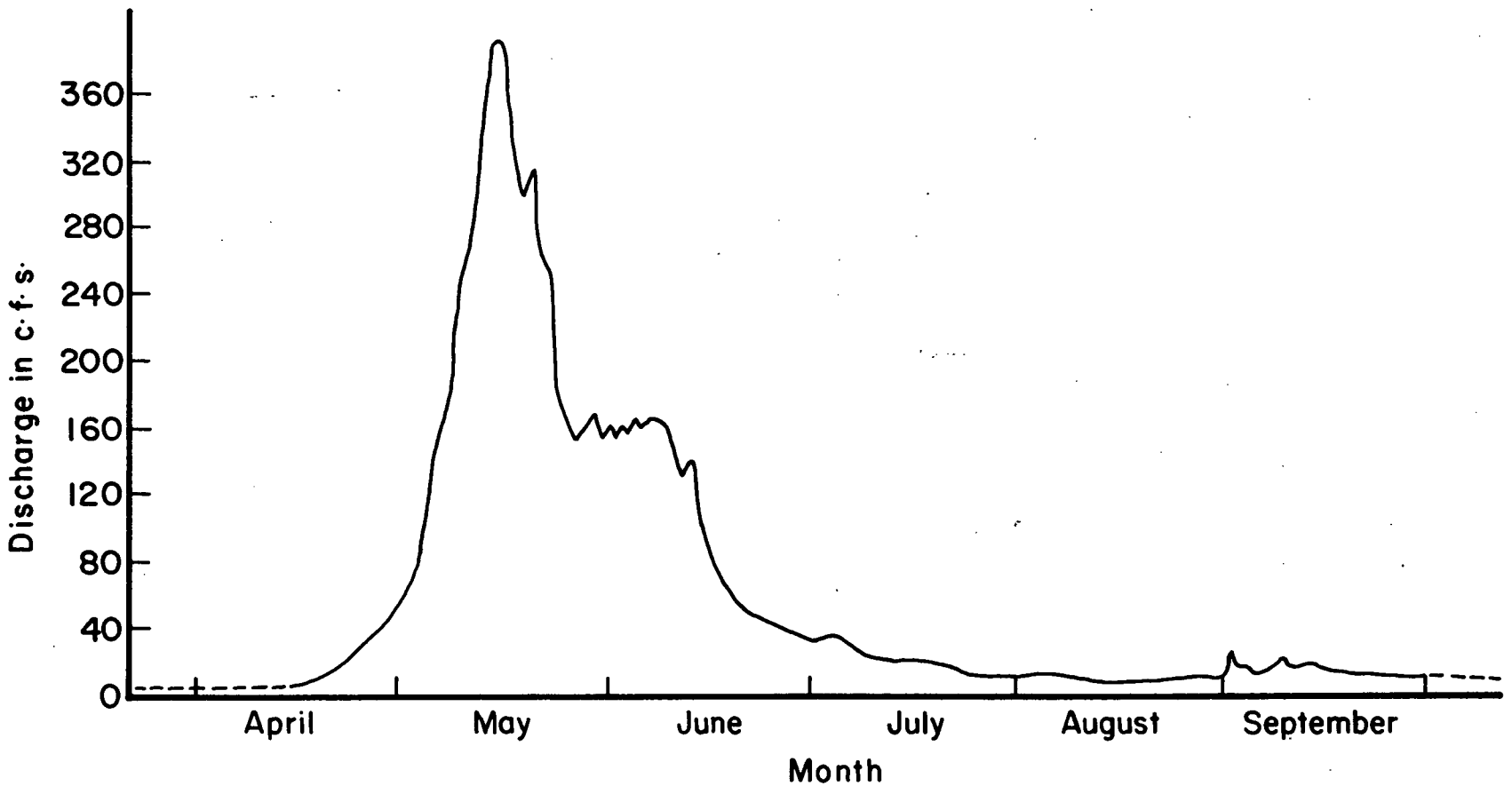


Fig. 4. Hydrograph of Lambly Creek above Stevens diversion for water years 1924, 1925 and 1927

Whiteman Creek (1957-1964) also show that, on the average, peak flow does occur in May (Fig. 5). Observed runoff for 1966, the first complete year of record, is much closer to the computed runoff than is the estimated 1965 runoff. The runoff recorded in 1966 from Terrace Creek was 25.98 cm. (Table 11), and lends support to the view that the peak flow in 1965 occurred before June. The hydrographs of Terrace and Esperon Creeks are presented in Figs. 2 and 3.

Therefore, whether or not the climate at McCulloch is different than that on the watershed, or whether Thornthwaite's method gives results close to observed runoff cannot be definitely ascertained from the very limited data available.

Fig. 6 is a diagram illustrating the results of Thornthwaite water balance computation. From this diagram it can be seen that for most of the growing season there is a moisture deficit (June through September). This is not an accurate representation of the period of water deficit, however, because monthly averages are used. It is possible that averages for the month show a deficit while parts of the month have been supplied with enough precipitation to supply the needs of vegetation for those periods.

Area-elevation relationship. Tables 12 and 13 give data on the area-elevation relationships for the two watersheds, Esperon and Terrace Creeks, and Fig. 7 shows this relationship in graphical form. The area-elevation curve is, in a sense, the basin profile. Its mean slope in feet per mile is a useful statistic for comparing basins. In Fig. 7 the

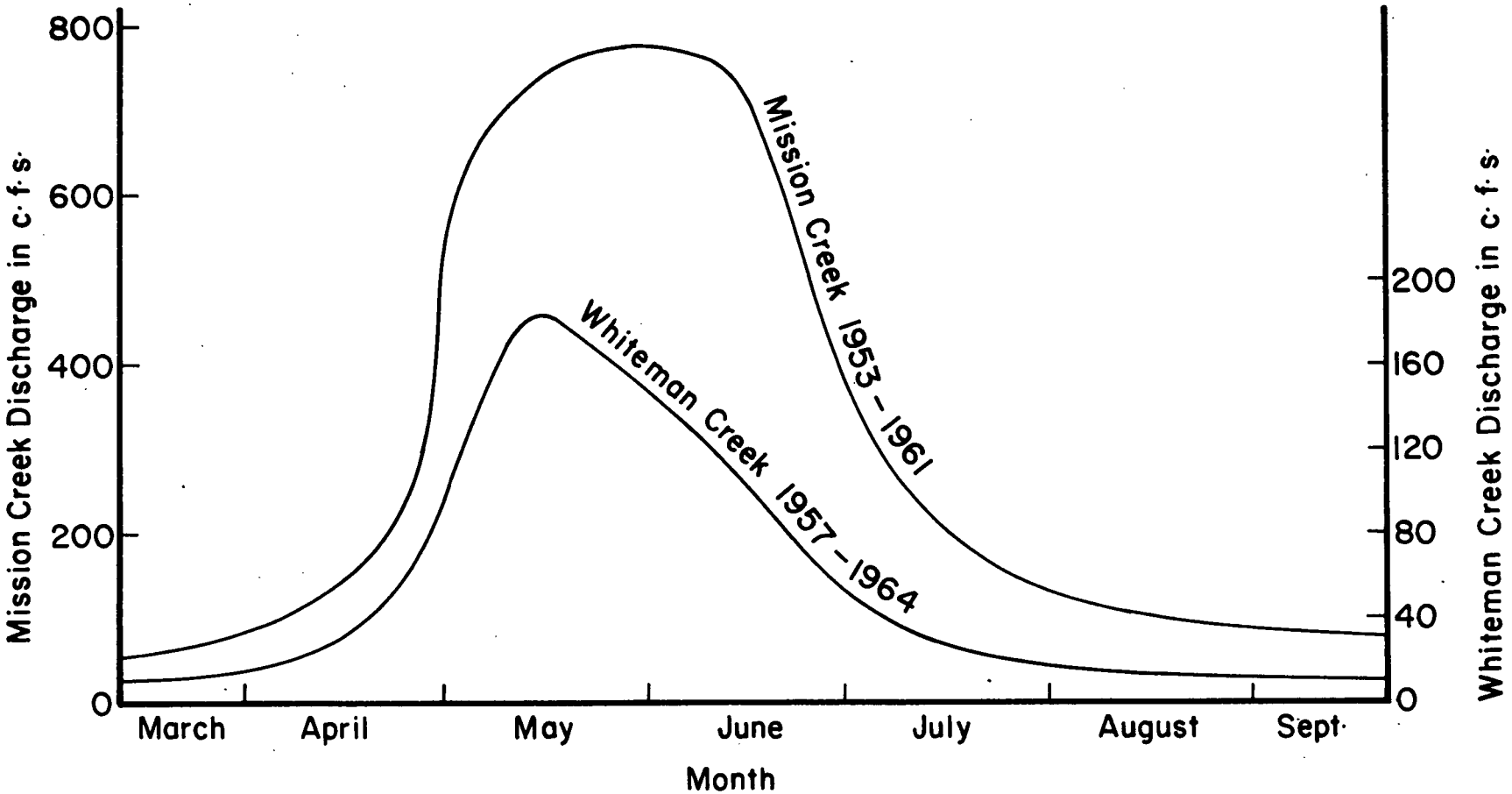


Fig. 5. Hydrographs of mean monthly discharge March – September for Mission and Whiteman Creeks

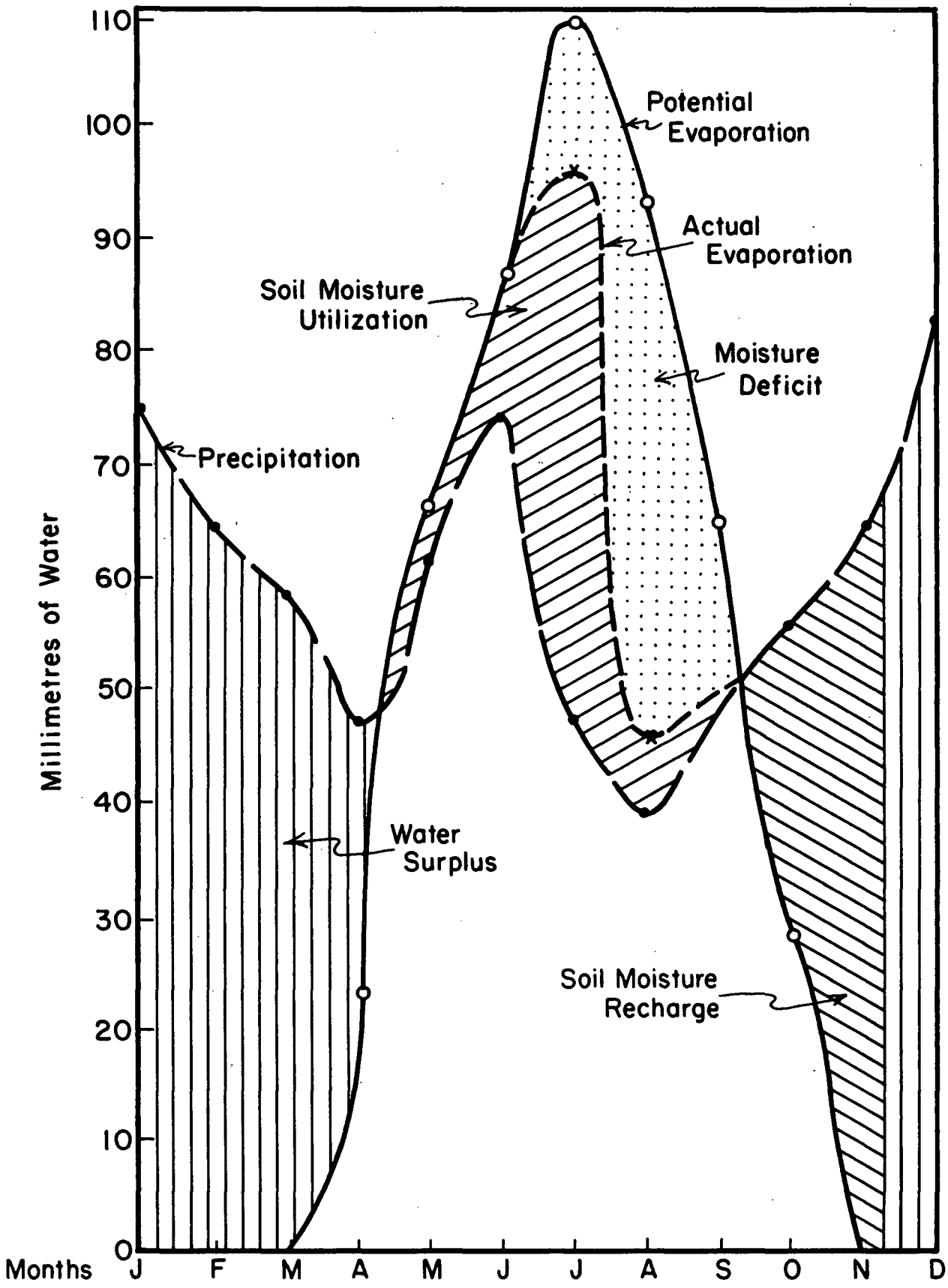


Fig. 6. March of mean monthly precipitation, actual, and potential evapotranspiration at McCulloch, British Columbia, based on Thornthwaite's equations

Table 12. Area-elevation relations - Esperon Creek watershed

Elevation (feet)	Area below (sq. miles)	Area below (percent)	Zonal area (sq. miles)	Mean zonal elevation (feet)
5,440	5.99	100	0.02	5,420
5,400	5.97	99.7	1.00	5,300
5,200	4.97	83.0	1.38	5,100
5,000	3.59	60.0	1.35	4,900
4,800	2.24	37.4	1.69	4,700
4,600	0.55	9.2	0.55	4,500
4,400	0	0	-	-

$$\text{Mean elevation} = \frac{\sum(\text{Zonal area} \times \text{Mean zonal elevation})}{\text{Total area}}$$

$$= \underline{4,921 \text{ feet}}$$

Table 13. Area-elevation relations - Terrace Creek watershed

Elevation (feet)	Area below (sq. miles)	Area below (percent)	Zonal area (sq. miles)	Mean Zonal elevation (feet)
5,440	12.70	100	0.02	5,420
5,400	12.68	99.8	1.17	5,300
5,200	11.51	90.9	2.28	5,100
5,000	9.23	72.6	2.06	4,900
4,800	7.17	56.4	3.33	4,700
4,600	3.84	30.2	3.56	4,500
4,400	0.28	2.2	0.28	4,350
4,300	0	0	-	-

$$\text{Mean elevation} = \frac{\sum(\text{Zonal area} \times \text{Mean zonal elevation})}{\text{Total area}}$$

$$= \underline{4,797 \text{ feet}}$$

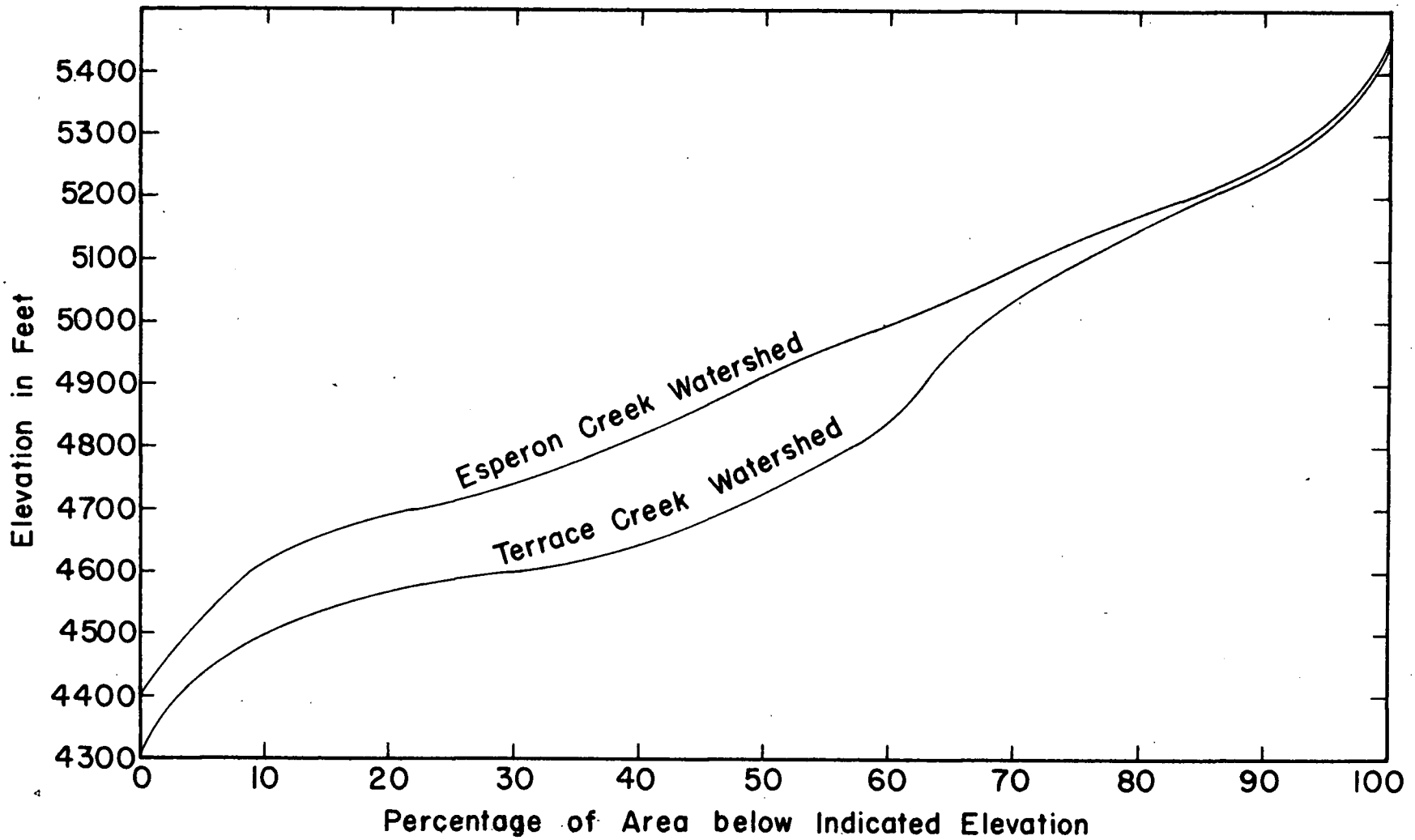


Fig. 7. Area — elevation curves for Esperon and Terrace Creek watersheds

two curves are shown to be quite divergent, but unless many such curves are being compared it is difficult to say whether this amount of divergency is normal. The mean slopes are 174 ft. per square mile on the Esperon Creek watershed and 90 ft. per square mile for Terrace Creek. These differences are not unexpected, however, because Esperon Creek is a tributary of Terrace Creek and its watershed is situated at the top of the study area.

Stage-discharge curves. Automatic stage recorders were installed on Esperon and Terrace Creeks in September, 1965, replacing staff gauges fixed in the stream channels. Stage-discharge curves relating discharge in cubic feet per second to the level of water in the stream channel were drawn for each stream for use with staff-gauge measurements. Streamflow June through August, 1965, was calculated from stage-discharge curves (Figs. 8 and 9) constructed using five pairs of measurements covering almost the full range of discharge. The measurements consisted of water level read from the staff gauge and discharge in cubic feet per second calculated from current meter (velocity) readings and channel cross-section measurements. The curves were easily made to fit the plotted points and the relationship is considered to be well defined.

Since September, 1965, streamflow has been calculated by the Water Resources Branch (now the Inland Waters Branch), Canada Department of Energy, Mines and Resources.

Hydrographs. The relationship of the discharge of the two creeks, Terrace and Esperon, is shown in Figs. 1, 2, and 3. Runoff patterns are

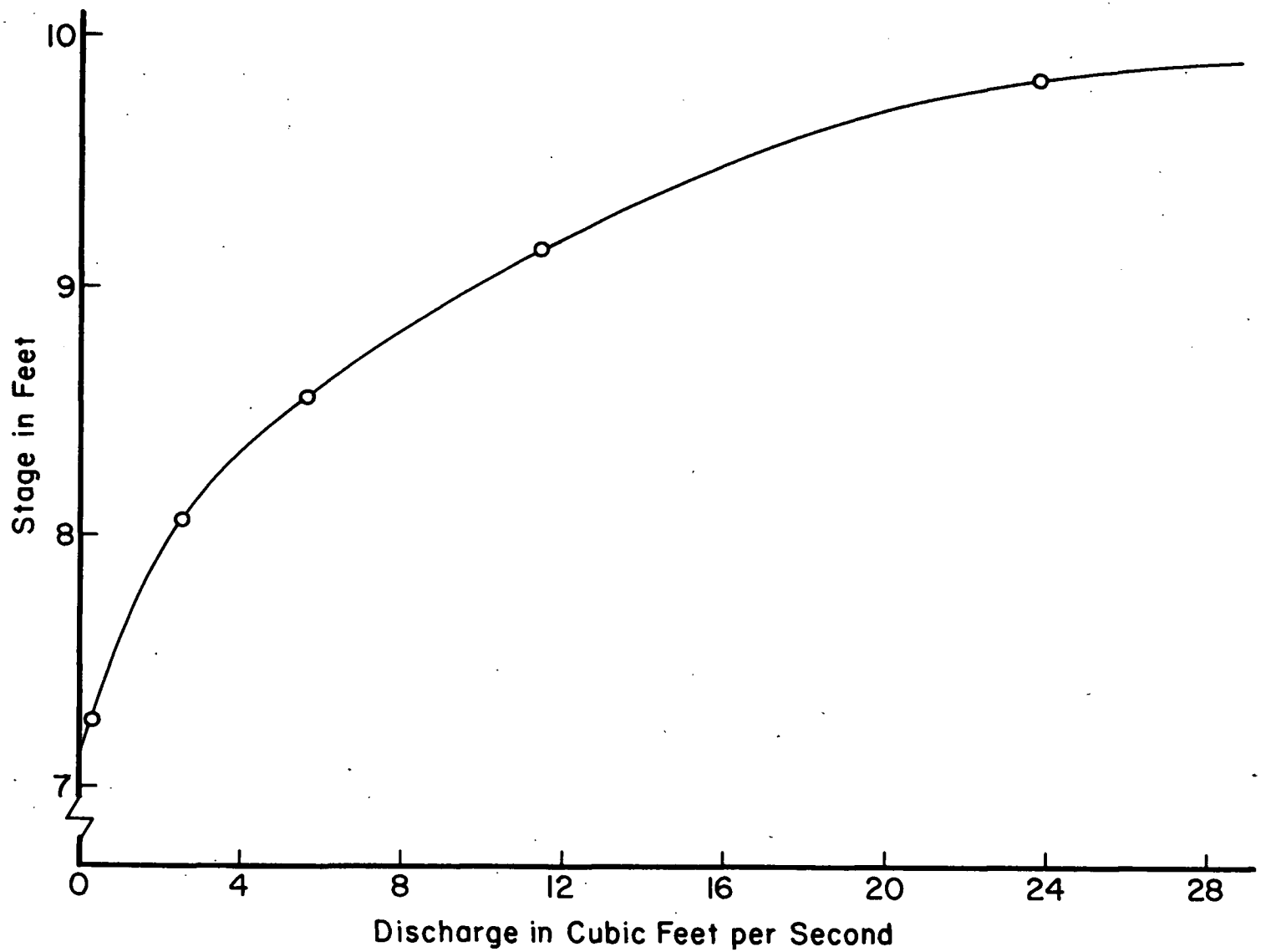


Fig. 8. Stage–discharge curve for Esperon Creek, 1965, for use with staff-gauge measurements of stage

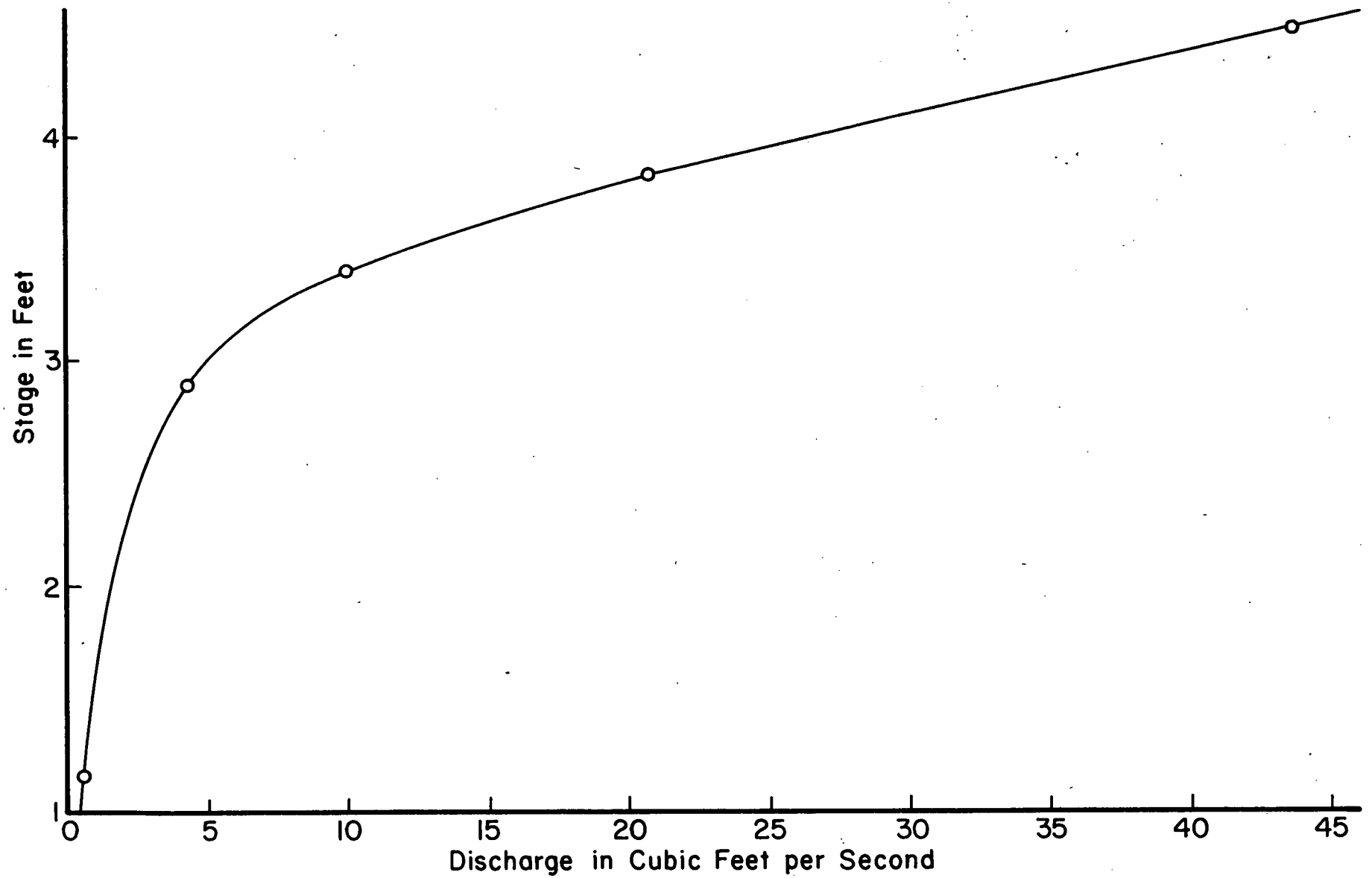


Fig. 9. Stage–discharge curve for Terrace Creek, 1965, for use with staff-gauge measurements of stage

similar and the response to precipitation as far as lag and degree are much the same (Fig. 1).

Mass curves of runoff. The double-mass curve of runoff is the cumulation of runoff at one gauging station plotted over the cumulation of runoff at a second station during the same period. If the data are proportional, the curve should be a straight line, the constant of proportionality between the quantities being represented by the slope of the line. A break in the slope of the curve may mean that (1) a change in the constant of proportionality has occurred due for example, to a change in the location of the measuring instruments or perhaps to a change in the streams themselves, or (2) the constant of proportionality is, in fact, not a constant at all rates of accumulation.

In the case of double-mass curves of runoff for Terrace and Esperon Creeks, because no change has taken place in the streams nor recording instruments, the curve should be a straight line if the proportion is constant throughout the range of accumulation rates. Using the method described by Searcy and Hardison (1960) a double-mass curve was plotted of discharge in acre feet per square mile from Terrace Creek against discharge from Esperon Creek for the period June-August, 1965 (Fig. 10).

Straight lines fitted to the plotted points passed through most of the points and were very close to the remainder. The lines came very close to passing through the origin which was expected. The constant of proportionality was 0.86, meaning that discharge per square mile from Terrace Creek is 86 percent of that from Esperon Creek.

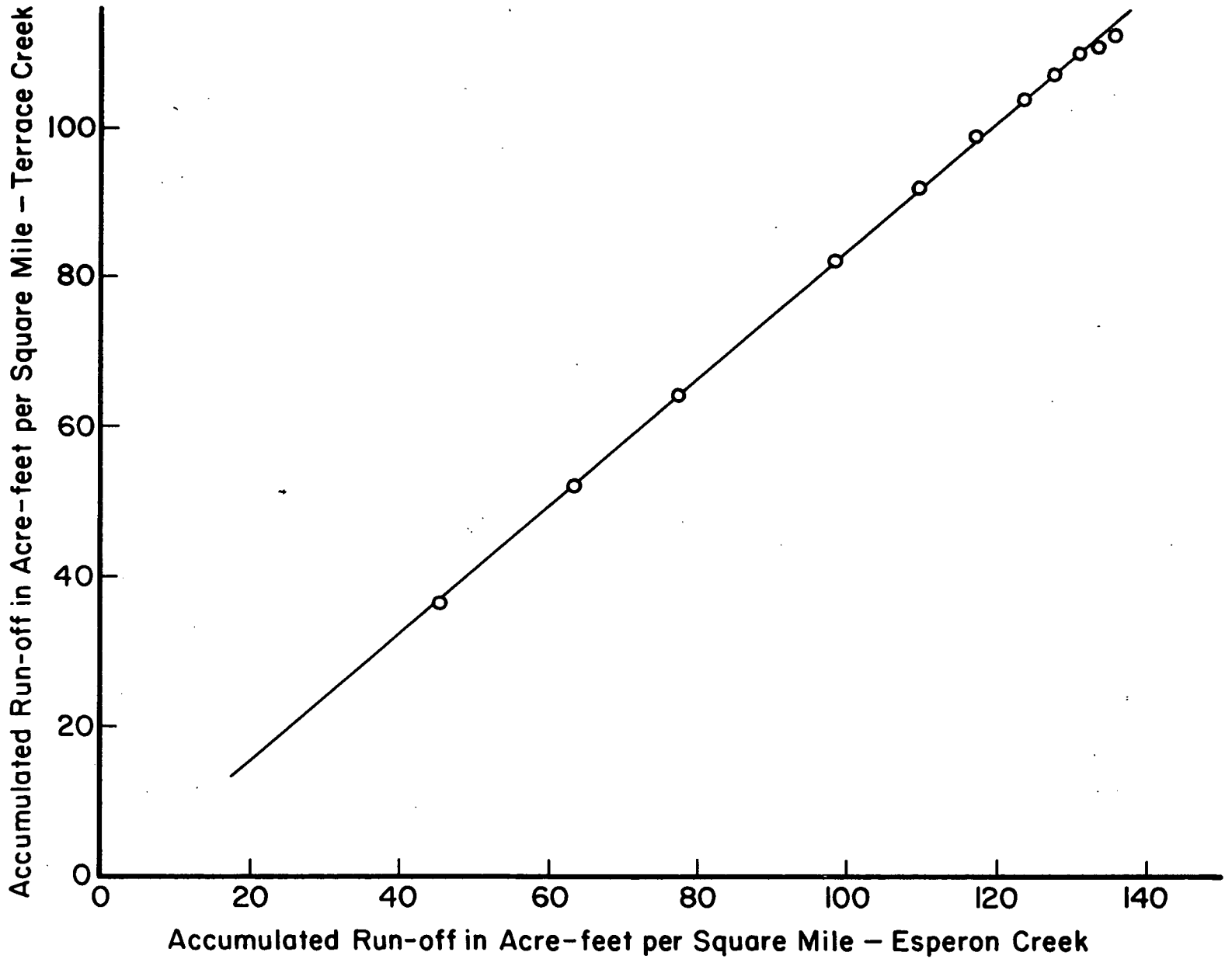


Fig. 10. Mass curve of runoff for Terrace – Esperon Creeks, June – August, 1965

Throughfall in a forest opening. An investigation was carried out from June 17 to October 13, 1966, to determine the amount of precipitation that reached the forest floor in a small forest opening in an Engelmann spruce-subalpine fir stand. Rain gauges were set up at 1, 3, 6, 10, 15, 21, and 35 ft. from the bole of an Engelmann spruce (dbh - 18 in., height - 90 ft., crown diameter - 25 ft.). The rain gauges were established in a line running N. 95° E. from the tree which was two chains east of a north-south clear-cut strip, eight chains wide. The gauge orifices were 18 in. above the ground. Rainfall, which was measured weekly, is presented in Table A2 and illustrated in Fig. 11.

Throughfall as a percentage of precipitation at the open site (Table A2) was 13, 27, 27, 37, 51, 73, and 79 at 1, 3, 6, 10, 15, 21, and 35 ft. from the bole, respectively. Directly under the crown at three and six feet from the bole, throughfall was the same but began to increase even while still beneath the crown (at 10 ft.) (Fig. 11).

Meteorological data. Meteorological data are to be abstracted by the Meteorological Branch, Canada Department of Transport. However, this has not yet been completed because of the number of projects involved in the IHD program. Precipitation data has been abstracted by the writer and is presented in Tables A1 and A2, Appendix I. Snow survey measurements and evaporation data are presented in Tables A3 to A6, Appendix I.

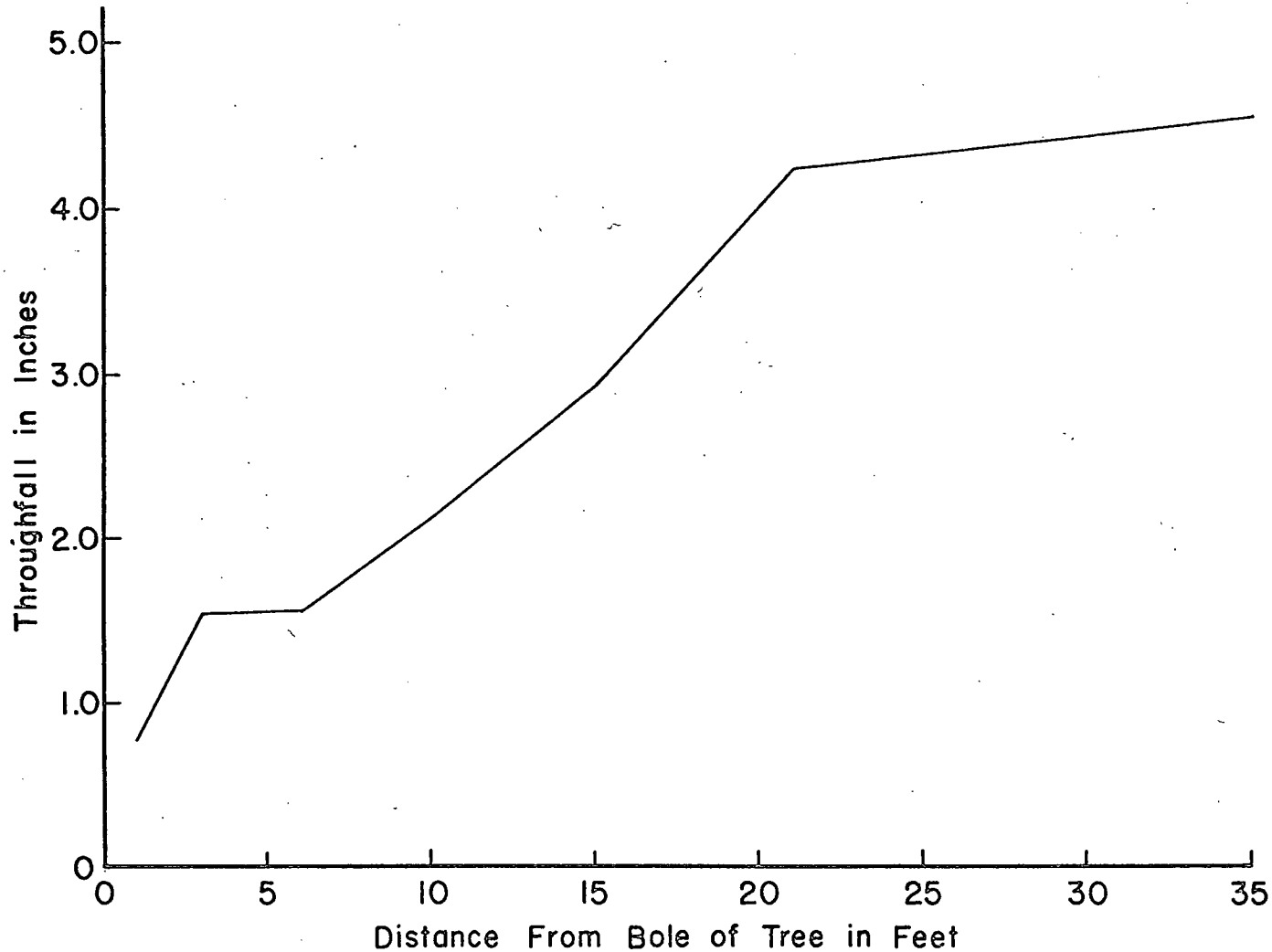


Fig. 11. Throughfall in an opening in an Engelmann spruce – subalpine fir stand at different distances from the bole of an Engelmann spruce, 18 in. dbh, 90 ft. in height, and 25 ft. crown width

3. EAST KOOTENAYS-WINDERMERE AND SINCLAIR CREEKS

Objectives

Two watersheds in the East Kootenay District of British Columbia have been chosen to gauge the effect of logging on water yield in that region. The study was begun by the Water Rights Branch, of the B.C. Water Resources Service, Nelson. The two watersheds, Windermere and Sinclair Creeks, are similar in geology, topography, and forest cover. They flow into the Columbia River 12 miles apart.

Partial records of streamflow for the two creeks are available for a number of years, but only since the 1959-60 water year have records been essentially year-round.

There has been no logging in the Windermere watershed until 1965, at which time logging of the first timber sale to be let on the area began. A second timber sale has been let but no logging done, and a third is to be let within the next year (Bancroft 1966).

The Sinclair Creek watershed lies mostly within the Kootenay National Park. It is not likely that logging has been carried out on that area outside the park, but if there has been it has been so long ago that the area has returned to forest cover (Bancroft 1966). No logging has taken place in the Park nor is any expected.

The objective of this study is to establish the relationship of the water-yield regimen of Windermere Creek with that of Sinclair Creek in order to estimate, using future flows from Sinclair Creek, the flows which would have been expected from Windermere had it not been logged. The objective then, is to calibrate the watershed.

Description of the Region

Location. The watersheds of the two creeks, Windermere and Sinclair, are located in the East Kootenay District of British Columbia, on the western slopes of the Kootenay Ranges of the Rocky Mountains. The slopes are drained by streams flowing west-south-west into the Columbia River which flows north-west another 200 miles before turning west through the Columbia Mountains and heading south.

The district was first explored by David Thompson, in 1807. The fur trade provided the first commerce for the area, with placer mining beginning about 1860 when gold was discovered. The lumbering and lode-mining industries began with construction of the railroad in 1883. Silver, lead, zinc, and gypsum are mined in the area now. The tourist industry is important to the economy of the area with scenery, natural hot springs, and hunting being the attractions.

The boom in orchard land which began in the Okanagan in 1900 spread to the East Kootenay shortly after, but it was not until 1914 that continued failure convinced settlers that the area was not suitable for tree-fruit growing. With irrigation the area is well suited to mixed farming (Kelley and Holland 1961).

Physiography. The Kootenay Ranges of the Rocky Mountains lie between the Kootenay River on the east and the Rocky Mountain Trench on the west, and consist of the Brisco, Stanford, and Hughes Ranges. The Hughes Range is that part south of Canal Flats. The Stanford Range runs from Canal Flats north to the Sinclair-Swede Creek divide, with the Brisco Range

being north of this divide (Henderson 1954). According to Walker (1926) the Stanford Range is the southern extension of a single range which for no apparent reason had been divided into the Stanford, Brisco, and further north, the Beaverfoot.

Windermere Creek watershed is completely within the Stanford Range. That part of the Sinclair Creek watershed south of the creek is also within the Stanford Range, the northern part being in the Brisco Range. Because of this and the fact that the Stanford Range is representative of the other ranges it will be discussed in more detail.

The Stanford Range is dominated by north-west trending, almost parallel ridges. These are deeply incised and partly dissected by transverse valleys. The ridge tops, which vary from broad and rounded to narrow, almost knife-edged, are 5,200 to 8,000 ft. elevation. Local relief within the range varies from 2,500 to 4,000 ft. and up to 6,000 ft. adjacent to the Rocky Mountain Trench or Kootenay River Valley. Indianhead Mountain is the highest summit in the Stanford Range at 8,820 ft. The lowest elevation in the area is 2,618 ft. at the northern boundary of the area, on the Columbia River (Holland 1964).

Erosional features typical of glaciation, such as cirques, U-shaped or hanging valleys, have not been observed in the Stanford Range. It is probable, however, that at one time ice covered the entire range because erratics (ice-borne rock fragments different from the bedrock on which they lay) have been found up to an elevation of 7,500 feet (Henderson 1954). A continental ice sheet covered the area and produced very little erosion.

From Canal Flats, the source of the Columbia River, northward, the Rocky Mountain Trench is a valley three to six miles wide, Columbia and Windermere Lakes being wider places in the channel. The river has very little gradient dropping only 80 ft. from Columbia Lake to Golden, a distance of 85 miles. The mountain systems, the Purcells on the west and the Kootenay Ranges on the east, rise steeply to elevations of 7,500 to 10,500 ft., with no foothills.

Three well-defined terraces occur on either side of the depression occupied by the Columbia River. These are composed mostly of stratified silts and gravels which dip at low angles toward the centre of the valley. Walker (1926) and Henderson (1954) believed that these deposits filled the valley at one time and that post-glacial excavation by the Columbia River developed the terraces. Rice (1937) suggested that at least some of the terraces were produced by deposition in local lakes which were flanked by blocks of stagnant ice.

A number of large depressions resembling kettle holes occur within the deposits on the Trench floor. Two bands of these, each one-quarter mile wide, run at right angles to the Trench, one near Fairmont Hot Springs and the other passing through the village of Invermere (Henderson 1954).

Many of the streams are small and intermittent. Others flow underground for part of their length, sometimes not emerging until reaching the terraces of the Columbia River. To a certain degree the underlying structure is reflected in the drainage pattern. Many of the oblique or transverse parts of the major streams are located along oblique or

transverse faults. North Windermere Creek is a good example of this. Similarly the longitudinal parts of many of the streams are located along longitudinal faults; an example is the main channel of Windermere Creek.

Climate. The climate of the region is dominated by eastward-moving moist air from the Pacific Ocean. The mountain systems which trend north-south act as barriers to air movement with the result that the western slopes receive the heaviest precipitation. Except where west-to-east gaps occur in the mountains the valleys paralleling the eastern sides of the ranges are characterized by dry climates.

In this section of the Columbia River valley winter air is drier than summer air and snowfall is light in the valley bottom. Two meteorological stations in the valley bottom, Invermere (2,840 ft. elevation) and Wilmer (3,100 ft. elevation), and Sinclair Pass (4,410 ft. elevation), have provided records of varying length during the period 1909 to 1955. A meteorological station was established at Radium Hot Springs in 1955. Annual precipitation at the valley stations varies from six to 14 in., and averages 11 to 13 in. Some summer months have had as little as one-tenth inch of rain. The summer (May-September) averages for the area are about six to seven inches, less than the moisture requirements for crops on well-drained land (Kelley and Holland 1961).

The full effects of mild maritime air are not felt in the area because of the mountains. The Rocky Mountains shield the area from polar air masses moving south in Alberta, although cold air does reach the region by way of mountain passes into the Rocky Mountain Trench. During some parts of the year warm dry air from the southern plateaus of the United

States reaches the upper Columbia River valley.

The mean annual temperature at the two lower stations, Invermere and Wilmer, is 40°F. with extremes of -43°F. and 101°F. having been recorded. Radium Hot Springs has a mean annual temperature of 39°F. and Sinclair Pass, 36°F., although extremes are no more severe than in the valley (B.C. Department of Agriculture 1925 to 1964).

The Study Area

Location. Windermere Creek flows in a west-southwest direction, entering Windermere Lake near the community of Windermere. The watershed is 33.2 square miles in area. The stream-gauging station (No. 8NA24, latitude 50°29'03", longitude 115°56'02"), at the bottom of the watershed at elevation 3,300 ft., is six miles north of Windermere, above diversions. The top of the watershed, on the Kootenay-Columbia River divide, reaches a maximum elevation of 8,600 ft. Mid-elevation is 5,950 ft. and the median elevation (the elevation above and below which half the basin area extends) is 5,270 ft. The area-elevation relationship of the watershed is illustrated in Fig. 12.

Sinclair Creek flows west-south-west to enter the Columbia River one mile north of Radium, approximately 13 miles north of the mouth of Windermere Creek. The area of the watershed is 34.1 square miles. The stream is gauged (station No. 8NA18, latitude 50°38'00", longitude 116° 02'48") at elevation 3,150 ft., below the outlets of the public swimming pools at Radium Hot Springs. The watershed has a maximum elevation of 8,800 ft., on the Kootenay-Columbia River divide. Mid-elevation and

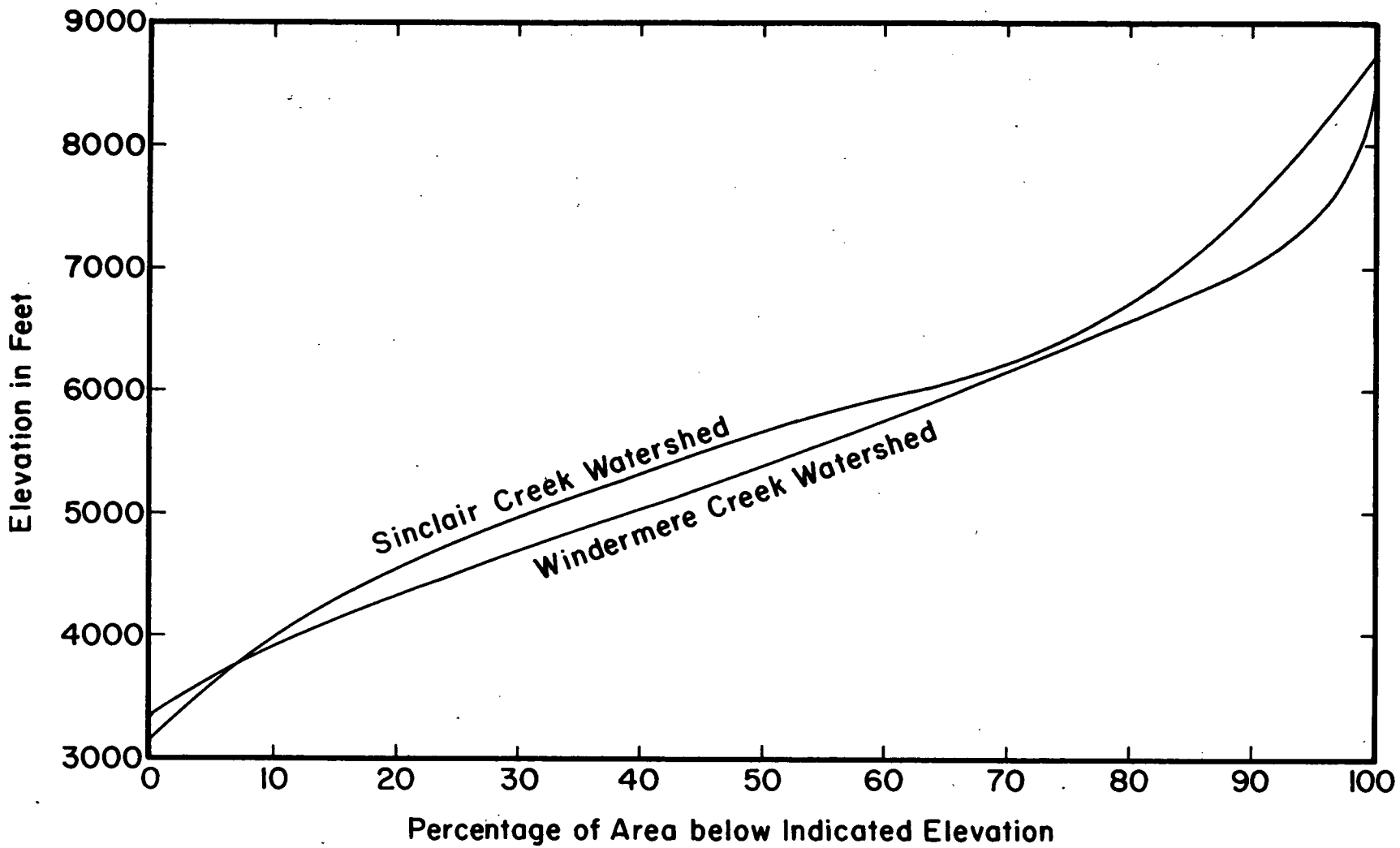


Fig. 12. Area – elevation curves for Windermere and Sinclair Creek watersheds

median elevation are 5,975 ft., and 5,710 ft. respectively. The area-elevation curve is given in Fig. 12.

Geology. In the Stanford Range the exposed rocks are all of sedimentary origin, making up a sequence that ranges in age from late Precambrian to Middle Devonian. Precambrian rocks consist of slates, quartzites, and pebble-conglomerates having a total exposed thickness of less than 700 ft. The rest of the section is comprised of Paleozoic rocks, mainly limestones, dolomites, and limy shales (Henderson 1954).

The strata are intensely folded and faulted, the folds being overturned to the southwest in contrast to the northeast direction of overturning in the rest of the Rocky Mountains at this latitude. Faults are especially numerous on the western side of the range and leaching has been active along the faults. Walker (1926) stated that there had been leaching along bedding and joint planes forming fragments which are boulder-like.

The two watersheds are similar in geologic history and in the location of strata and their sequence from the valley bottom to the top of the basins. The formations include shale, quartzite, and limestone, each recurring several times as the basin is ascended. Four fault lines traverse each of the watersheds at roughly the same elevation (Evans 1933, Walker 1926).

Forest type. Rowe (1959) classified the forest regions of the study area as Montane, up to about 2,500 ft. elevation, and Columbia above this. Halliday (1937) classified the area as Montane to 3,500 ft.

elevation, and Subalpine above. The older classification seems to fit the situation best. The Montane appears to reach the 3,500 ft. elevation, and above this the species are of the Subalpine rather than the Columbia forest region.

That part of the watershed in the Montane region is in the Ponderosa Pine and Douglas Fir Section as described by both Halliday and Rowe, although little ponderosa pine is found on the watersheds.

McLean and Holland (1958) divided their Douglas Fir Zone, which corresponds to the Montane Forest Region, into the Douglas Fir Groveland Sub-zone and the Douglas Fir Forest Sub-zone. Only the Douglas Fir Forest Sub-zone reaches into the study watersheds according to the elevation limits indicated by the authors. This zone occupies the 2,800-3,500 ft. elevation where precipitation varies between 15 and 18 in. annually. This zone is similar to that which occurs in the Okanagan Valley at the same elevation. Douglas fir is the climax tree and generally forms somewhat open stands. After logging and fire the area is frequently dominated by lodgepole pine and trembling aspen.

Above the Montane Forest Region is the Interior Subalpine Section of the Subalpine Forest Region (Rowe 1959) or Spruce-Fir Zone (McLean and Holland 1958). Engelmann spruce and subalpine fir are the dominant species in this zone with the spruce being more common. Douglas fir, western white pine, aspen, and lodgepole pine are also represented in this area with the lodgepole pine frequently forming dense stands after fire.

Calibrating the Watershed

Two methods of calibrating a watershed are in general use. One is the control watershed approach in which streamflow from the experimental watershed, before treatment, is related to that from a control watershed, the established relationship being used to detect changes in streamflow from the experimental watershed after treatment. This method requires that the two watersheds be close together so that they experience the same meteorological conditions during the period of comparison, and that they be similar in geology, topography, and vegetation. It assumes that the control watershed has no significant changes in vegetation after the calibration period.

The second method calibrates the experimental watershed on itself by relating streamflow to the factors that influence it. This method can be used with varying degrees of refinement from relating streamflow to precipitation only, to relating streamflow to precipitation, air temperature, humidity, groundwater, and soil moisture (Reigner 1964).

The control-watershed method is a reliable, proven method. The single-watershed approach is less costly because only one watershed needs instrumentation (although the instrumentation is more intensive). Both methods have the disadvantage of requiring many years for calibration. Five years is the minimum and a maximum of 15 years was required on the Workman Creek Experimental watershed in Arizona (Rich et al. 1961).

A variation in the control-watershed method is one in which annual or seasonal discharge is not compared, but the response to individual

storms is used to relate the two watersheds. Regression equations of rise-in-stage and time-to-peak following storms are calculated, the advantage being the shorter calibration period required because of the greater number of observations per year (Bethlahmy 1963). However, this method has yet to be used extensively and can hardly be called a proven method.

The remainder of this section describes the calibration of Windermere Creek watershed with Sinclair Creek watershed using the control-watershed method. The requirements of a control watershed appear to be met in Sinclair Creek watershed. The period of concurrent streamflow records for the two watersheds is short. Therefore, annual flows rather than peak or low flows will be used because of the probability of higher correlation of this variable on the two watersheds.

Usually in calibrating a watershed the variables calculated are the number of years of pre-treatment and post-treatment record required to detect a change in streamflow of a given size. In this study the periods are set and the value to be calculated is the least significant difference which can be detected.

Treatment on the Windermere Creek watershed began in 1965 when approximately 1.6 per cent of the watershed was logged. Because of the small fraction of the watershed logged in 1965 streamflow records for that year are included in the pre-treatment period, giving five years (1961-1965) of concurrent streamflow records for Sinclair and Windermere Creeks (Table 14). This sets the calibration period at five years.

Table 14. Discharge from Sinclair and Windermere Creeks, 1961-1965

Water Year	Annual discharge in acre feet[1]		Annual discharge in inches	
	Sinclair Cr.	Windermere Cr.	Sinclair Cr.	Windermere Cr.
1961	24,680	16,480	13.68	9.38
1962	18,820	14,780	10.43	8.42
1963	19,500	12,130	10.81	6.91
1964	24,680	13,340	13.68	7.60
1965	26,040	15,610	14.44	8.89

[1]From daily flow records tabulated by Water Resources Branch Canada Dept. of Mines and Technical Surveys, for Station No. 8NA-18, Sinclair Creek, and Station No. 8NA-24, Windermere Creek.

Windermere Creek watershed is in the Windermere Sustained Yield Unit as designated by the British Columbia Forest Service. Of the two timber sales on the watershed, one, of 648 acres, has not yet been logged, and the other, of 3,099 acres has had about 336 acres logged. Ten years have been allowed in the timber sale contract for removal of the timber on these two sales, one-tenth annually. One other sale is pending and others are likely to be let on the area so that in 10 years a sizeable part of the watershed will have been logged. Therefore, the post-treatment period will be taken as 10 years.

Analysis of covariance will be used to test the significance of the differences in streamflow between the two periods, after the data has been adjusted by regression to minimize the influence of variations in climate and other extraneous factors. Wilm (1949) described a method for calculating the number of years required to detect a given difference in streamflow based on the data available for the calibration period, assuming the

same number of observations before and after treatment.

Kovner and Evans (1954) modified Wilm's method to admit periods of unequal length and went on to present a graphic method for determining the smallest difference, significant at a given probability level, that can be detected, given the length of the two periods and the variance of estimate (calculated from the calibration period data).

The procedure is as follows (calculations are shown in Appendix II):

(1) Calculate the before-treatment regression of Windermere Creek discharge on Sinclair Creek discharge. The relationship is illustrated in Fig. 13, and expressed by

$$Y = 4.79 + 0.2374\ X$$

where Y and X = annual yield from Windermere Creek and Sinclair Creek watersheds, in area-inches

(2) Calculate the smallest significant difference which can be detected after treatment based on the variance of estimate for the calibration period, the number of years in the calibration and treatment periods, and a given probability level. This difference is 1.37 area-inches when the variance of estimate is 0.9715, the length of the periods is five and 10 years, and the probability level is 95 percent.

(3) Calculate the post-treatment regression and test the slopes of the pre- and post-treatment regression lines. If they are not significantly different, which is to be expected, calculate a weighted regression coefficient and new values for the Y-intercept for both the pre- and post-treatment regressions.

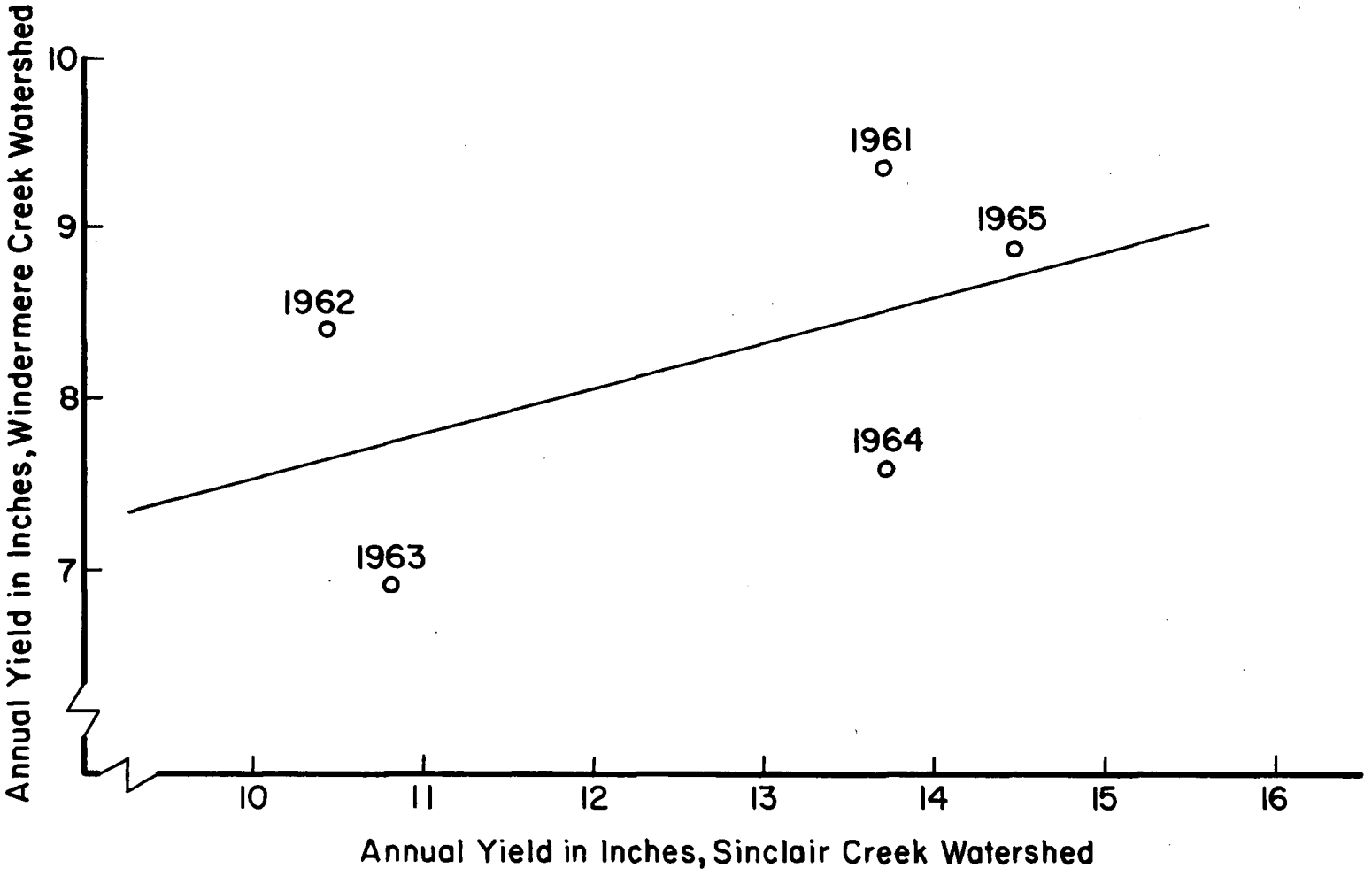


Fig. 13. Regression of yield from Windermere Creek watershed on yield from Sinclair Creek watershed

(4) Using the adjusted regression equations from (3) calculate the average pre- and post-treatment discharges from Windermere Creek corresponding to the 15-year (five-year pre-treatment plus 10-year post-treatment period) average discharge from Sinclair Creek.

(5) If the difference between pre- and post-treatment discharge from Windermere Creek is greater than 1.37 area-inches it is significant and can be attributed to logging of the watershed.

From Table A8, $sy.x^2$ is 0.9715; n_1 and n_2 are five and 10 years respectively; and for one degree of freedom for treatments and 12 for individual years ($n_1 + n_2 - 3$), F is 4.75 (Snedecor 1956, p. 246). The smallest significant difference, d, is then 1.37 area-inches or 16.6 percent of the average pre-treatment discharge from Windermere Creek.

The correlation of discharge from Windermere and Sinclair Creeks is poor, the correlation coefficient being only 51 percent (Appendix II), especially considering the apparent similarities of geology, topography, and forest type. However, the impressions gained from a brief examination of the two watersheds by the writer were that the soil is deeper on the Windermere Creek watershed, there is less bare rock exposed, the topography is not as precipitous, and the forest stands are denser. Another factor bearing on the dissimilarity of discharge from the two streams is the nature of the rock strata. Limestone is common on both basins (Henderson 1954) and sink holes occur. The Notice of Sale of Crown Timber for one of the Windermere Creek timber sales contains a clause restricting logging to a distance greater than two chains from any sink hole (B.C. Dept. Lands, Forests, and Water Resources 1964). Therefore surface flow may be

diverted to underground channels to different degrees on the two watersheds.

Mean annual discharge, 1961-1965, was 31.4 c.f.s. for Sinclair Creek and 20.0 c.f.s. for Windermere, with mean maximum discharges of 207.2 and 60.0 c.f.s. Low flows, however, were greater for Windermere Creek. Mean annual minimum flows were 11.5 c.f.s. for Windermere and 8.9 c.f.s. for Sinclair Creek, with summer (June 1-October 30) low flows averaging 18.1 and 14.5 c.f.s.

Although there are precipitation records for stations within the Sinclair Creek watershed none exist for the Windermere watershed. However, there is no reason to believe that precipitation is not similar on the two watersheds. The differences in runoff characteristics of the two creeks, i.e., higher annual and maximum flows from Sinclair, and higher low flows from Windermere Creek are consistent with the differences in the two watersheds outlined above.

The fact that the smallest significant difference in water yield from Windermere Creek is 16.6 percent of pre-treatment yield points out the need for watersheds with not only a high degree of similarity but watersheds on which runoff can be accurately measured. Windermere and Sinclair Creek watersheds were chosen for this study because (1) streamflow records were available, though only for a short period, (2) logging was just beginning on Windermere and would not be carried out on Sinclair Creek watershed, and (3) the watersheds appeared similar. The study points out that the selection of research watersheds requires a great deal more

consideration than this but it also points out that some value may be obtained from the analysis of existing records.

4. KAMLOOPS AREA-WATCHING CREEK

Objectives

The Watching Creek watershed is an area of 33.2 square miles, extending from an elevation of 2,900 ft. at the stream-gauging station to 6,000 ft. Summer streamflow records are available for the two four-year periods, 1950-1953 and 1962-1965. Logging began on the watershed in 1955, although the cut was small in both 1955 and 1956. A statistical analysis of streamflow before and after logging began has shown no significant change, but a graphical analysis has been made to determine if trends in maximum and minimum summer flows are noticeable.

Description of the Region

Location. Watching Creek is a tributary of the Tranquille River which flows southeast into Kamloops Lake and is part of the Fraser River basin. The Kamloops region of south-central British Columbia is similar in many ways to the Okanagan region described in the section on the Terrace-Esperon Creek watershed.

In 1858, the Fraser River goldrush began. The economic stimulation of miners' demands for transportation, supplies, and accommodation resulted in small farms, hotels, and stores being established in the settlement areas of Lytton, Spences Bridge, and Cache Creek. Cattle ranching began along the Nicola and Thompson Rivers. It was not until 1865, when gold

was discovered on the big bend of the Columbia River, that the commerce of the eastern part of the region began to grow (B.C. Dept. Lands and Forests 1958).

When the Canadian Northern Railway was completed in 1915 from Vancouver through the Yellowhead Pass via Kamloops and the North Thompson valley, the area north of Kamloops grew quickly. Cattle- and sheep-ranching and dairy farming became established and sawmills were in operation along the railway. Kamloops, itself, is an historic fur trading post that is older than the province. It was incorporated as a city in 1893 (Oberlander and Cave 1958).

Since the end of World War II the forest industry has become the major sector of the economy of the region. Agriculture is a close second with the tourist industry becoming increasingly important (B.C. Dept. Lands and Forests 1958).

Physiography. The Kamloops region is on the Thompson Plateau, Interior Plateau Section of the Southern Plateau and Mountain Area (Holland) 1964). The physiography of the Thompson Plateau is described in the Terrace-Esperon Creek watershed. The north and south branches of the Thompson River join at Kamloops and flow southwest to the Fraser River. The Thompson Plateau has been eroded in this region by the Thompson River and its main tributaries, forming valleys up to 3,500 ft. deep with broad, gently rounded hills (B.C. Dept. Lands and Forests 1958).

Stream erosion is still active with valleys being generally steep sided and narrow, although terraces have been formed along the larger

streams. The terraces are important agriculturally; farming can be carried on because of the soil which has been built up and water for irrigation is available from the streams that cross the terraces.

Climate. Precipitation in the Kamloops region varies from eight to 10 in. in the valleys (at 1,100 to 1,200 ft. elevation) to about 13 in. at 2,200 ft. Early spring is the dry season with March and April receiving the least amount of rain. June is the wettest month, receiving up to three times as much rain as March (B.C. Dept. Agric. 1963). Valley temperatures average five to 10°F. higher than the uplands in July and January. The warmest valley sites are those along the North and South Thompson and Nicola Rivers.

Mean monthly temperatures and precipitation for Pass Lake, just outside the watershed at elevation 3,200 ft., and Kamloops airport, elevation 1,133 ft., are given in Table 15, for the period May-September. At Pass Lake precipitation is almost 34 percent higher for the five months and mean monthly temperatures average eight to 11°F. lower than at Kamloops.

The Study Area

Location. The Watching Creek watershed is on the Tranquille Plateau in the Tranquille Provincial Forest, about 15 miles north-northwest of the city of Kamloops. The watershed is about six miles long (north-south) by five miles wide (east-west) and 33.2 square miles in area. Watching Creek runs south through the basin then four miles southwest to the Tranquille River.

Table 15. Rainfall and mean temperatures for Pass[1] Lake and Kamloops[2] for May-September averaged for the years 1962 to 1965

Month	Mean monthly rainfall in inches		Mean monthly temperature in °F.	
	Pass Lake	Kamloops	Pass Lake	Kamloops
May	0.86	0.60	46	56
June	1.39	0.92	53	64
July	1.70	1.24	58	68
August	2.38	1.72	57	67
September	1.31	1.23	50	58

[1]From records collected by Canada Dept. of Agriculture Research Station at Kamloops, B.C.

[2]From B.C. Dept. of Agric. (1962-1965).

The watershed is currently being logged by timber sale, logging having begun in 1955, and cattle are ranged on the area, about 1,000 head being currently ranged there. The Canada Department of Agriculture, Research Branch, is conducting investigations into range problems in the area and maintains a meteorological station at Pass Lake during the May-October period.

Soils. A detailed soil survey of the area has not been conducted but the soils generally belong to the Grey Wooded group (B.C. Dept. Lands and Forests 1958).

Forest type. The lower part of the watershed is in the Ponderosa Pine and Douglas Fir Section (M-1) (Rowe 1959) of the Montane Forest Region. On the lower slopes in this section, open ponderosa pine stands are

interspersed with grassy openings. Douglas fir, lodgepole pine, and aspen stands occupy the higher elevations in this section with grassy openings occurring also (Rowe 1959). Above 4,000 feet Rowe's Interior Subalpine Section (SA-2) occurs with Engelmann spruce and subalpine fir being the common species (B.C. Dept. Lands and Forests 1958).

The greater part of the watershed is of immature timber with only a few small blocks of mature timber. The lower part of the watershed is mainly non-commercial stands (B.C. Dept. Lands and Forests 1956).

The Study

Logging began on the Watching Creek watershed in 1955 and since then 6,125,000 cu. ft. of timber have been taken out. Amounts cut each year are as follows (Payne 1966):

1955	-	9	M. cu. ft. (thousand cubic feet)
1956	-	100	"
1957	-	973	"
1958	-	240	"
1959	-	575	"
1960	-	359	"
1961	-	375	"
1962	-	1,140	"
1963	-	1,299	"
1964	-	629	"
1965	-	281	"
1966	-	145	"

For the 1950-1953 period streamflow records are available for June, July, and August with May or September records available for several of the years. The record for the 1962-1965 period covers the months of May to November, except in 1962 when October and November flows were not recorded. Therefore, the only months covered consistently are June, July, and August.

Those few records that include May show that peak flows occurred in that month in five of the seven years, and in June in the other two years (1950 and 1964). From the peak in May (or June), flow steadily decreased, being less in September than in August in five of the seven years, and less in October or November than in September in two out of three years. That is, the three months, June, July, and August seldom include the annual maximum or minimum flows.

Fig. 14 shows the accumulated June-August runoff plotted over time. There is no discernible change in trend between the two periods, 1950-1953 (before logging) and 1962-1965 (after logging began). It appears that total summer runoff is the same in the two periods. The effect of precipitation must also be considered - precipitation amounts may have been different in one of the periods thus masking a change in the runoff pattern. Fig. 15 is a double-mass curve showing accumulated runoff plotted over accumulated precipitation, where precipitation is that recorded at the Kamloops airport (1,133 ft. elevation). Runoff has been accumulated as in Fig. 14, i.e., for the three summer months of each year, whereas precipitation has been accumulated for a water year of September to August.

The October 1-September 30 period is usually taken as the water year (Linsley et al. 1958, p. 72). Precipitation falling in autumn often goes to ground water recharge which contributes to runoff the next spring and summer. In this study, with a runoff period of June to August, a water year beginning in October would infer that September precipitation, if included in the analysis, influenced the runoff of the preceding three months. This is impossible, so a water year was chosen in which runoff

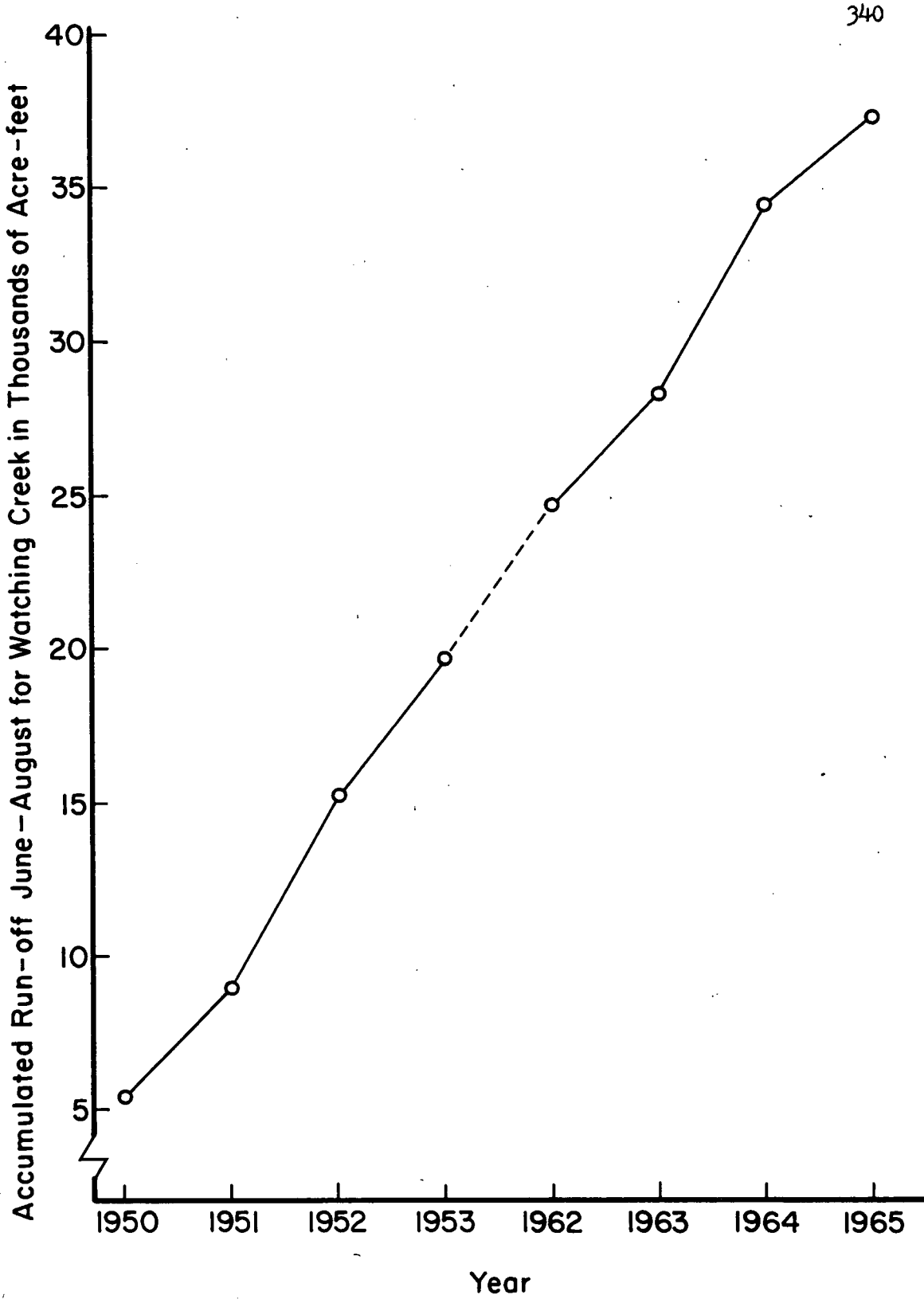


Fig. 14. Accumulated June — August runoff from Watching Creek for periods 1950 — 1953 and 1962 — 1965

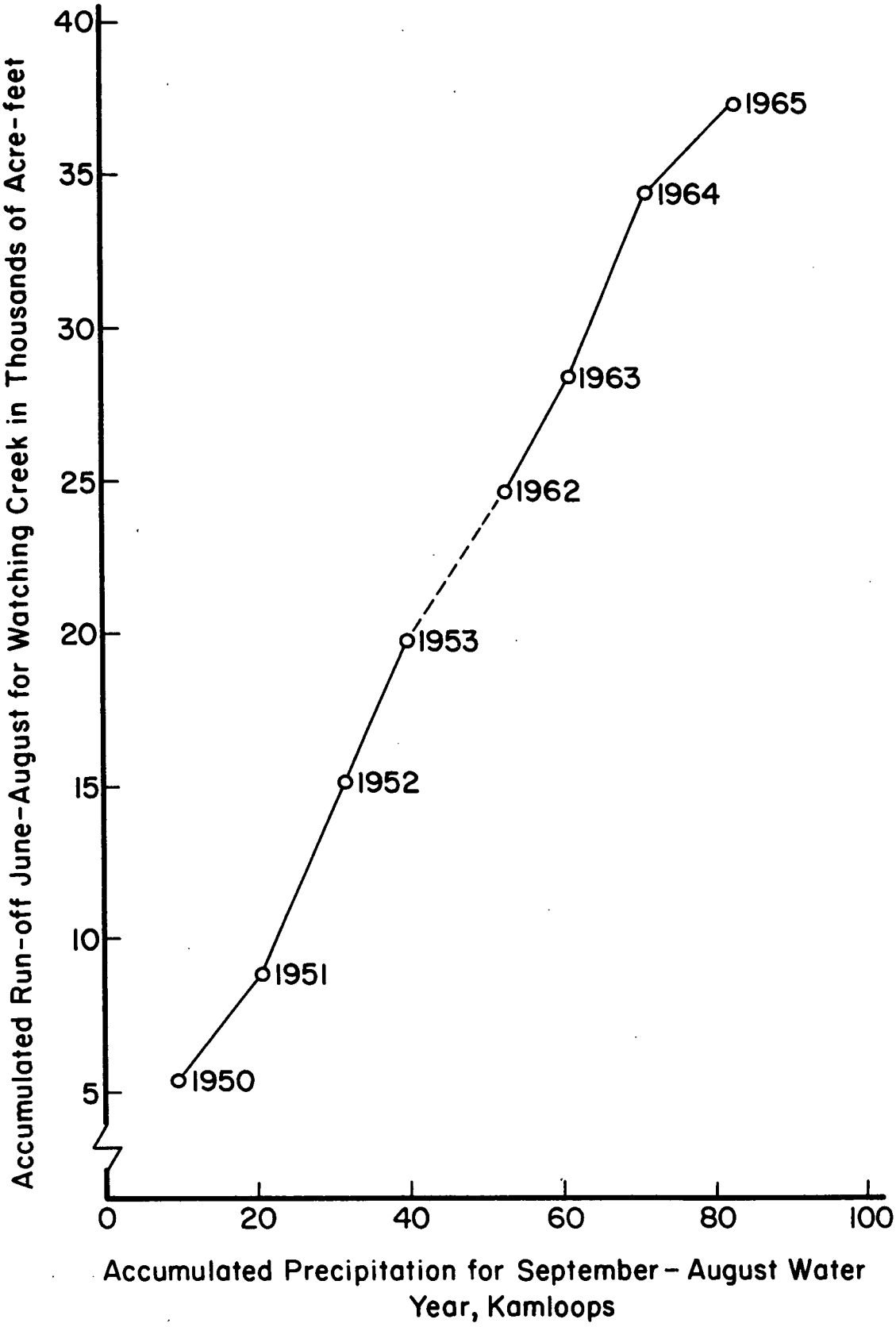


Fig. 15. Mass curve of runoff from Watching Creek over precipitation at Kamloops, 1950–1953 and 1962–1965

was related to the precipitation which began the previous September.

Fig. 15 does not indicate any change in the runoff-precipitation relation between the two periods, i.e., the total amount of spring and summer runoff is the same in the two periods, as indicated in Fig. 14.

Maximum and minimum June flows plotted over the year of occurrence (Fig. 16) does not indicate a trend. A line joining the mean for each period does show that the average maximum June flow has been greater, and the average minimum June flow less in the 1962-1965 period. The increased maximum flow is consistent with numerous studies (Bates and Henry 1928, Hoover and Shaw 1962, Hoyt and Troxell 1934, Reinhart et al. 1963), but the decreased minimum flow is not. Rothacher (1965a) reported increased minimum flows during late summer months after logging.

Mean June-August flows do not show any trend, but the average mean flow is lower for the 1962-1965 period. This also would be expected especially as the month of May, in which peak flows most often occur, is not included.

Minimum June-August flows plotted over time (Fig. 17) does not indicate a trend, but the average minimum June-August flow is greater for the 1962-1965 period than for the pre-logging period. This difference, even though very small (4.8 against 4.1 c.f.s.), is unexpected, particularly in view of the apparent trends indicated by the other graphs. The minimum June-August flows are actually minimum August flows because it was in August that they always occurred.

With records as scanty as were available for this watershed and with treatment, i.e., logging, being carried out on only a small part of

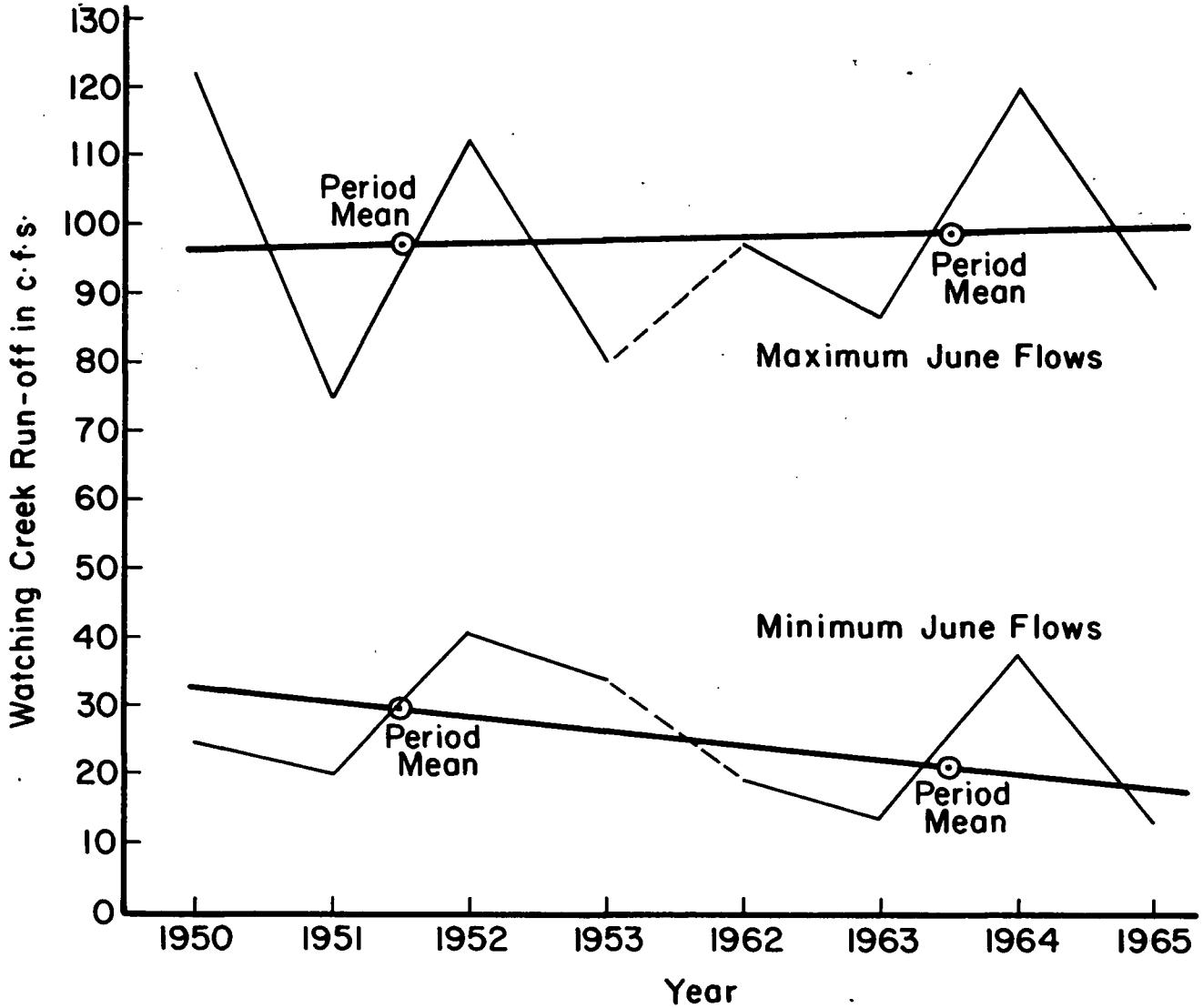


Fig. 16. Maximum and minimum June flows from Watching Creek, 1950–1953 and 1962–1965, with means for each period

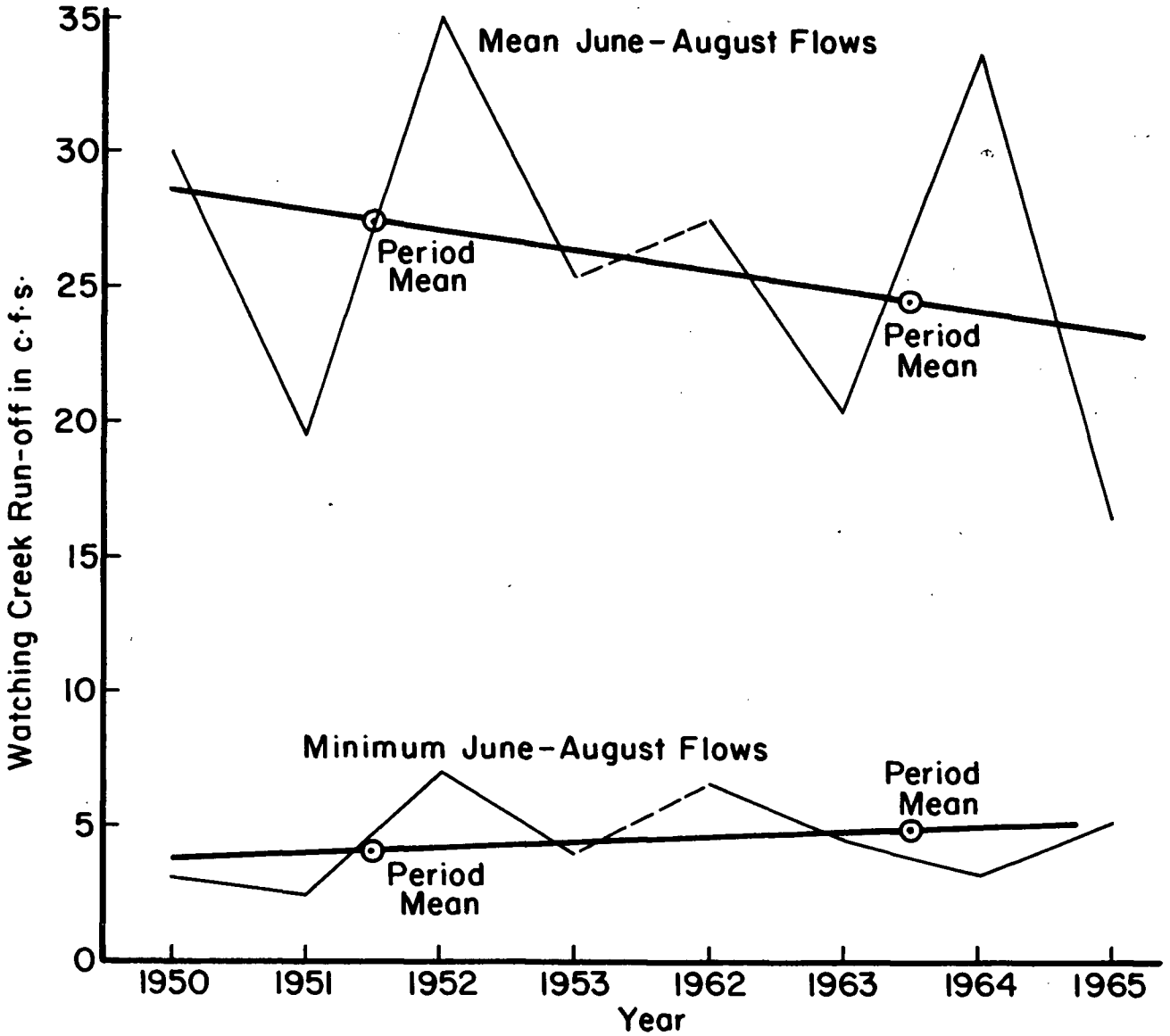


Fig. 17. Mean and minimum June–August flows from Watching Creek, 1950–1953 and 1962–1965, with means for each period

the watershed, and over a comparatively long period (10 years), little confidence can be placed in the apparent trends in maximum and minimum flows.[1] This must be the conclusion even though the trends are generally consistent with those found in other investigations.

This study points out to an even greater degree than the preceding study (Windermere-Sinclair Creek watersheds) the limitations of an analysis of logging effects on streamflow where the watersheds have not been carefully chosen and where streamflow data have been discontinuous and for short periods.

5. HYDROLOGIC STUDIES ON THE UNIVERSITY OF BRITISH COLUMBIA RESEARCH FOREST

In 1966, a project was begun on the University of British Columbia Research Forest, near Haney, B.C., to study the hydrology of a small, forested watershed. References used in this brief outline of the project are Coulthard (1966a, 1966b) and IHD (1965b, 1967).

The objectives of the study are (1) to determine a qualitative water balance of the 50-acre basin, (2) to calibrate three small watersheds

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[1]The difference between the means of minimum June flow for the periods 1950-1953 and 1962-1965 was tested using Students t-test (Snedecor 1956). The means were 29.65 c.f.s. (1950-1953) and 20.95 c.f.s. (1962-1965) and the probability of a value of t greater than the calculated t was 0.28. Therefore the means for the two periods cannot be accepted as different. The data are too fragmentary to warrant any further statistical analysis.

in the same region on a quantitative basis, and (3) to evaluate the effects of management and conservation practices on water yield, water quality, and erosion. A companion study to be carried out on the same watershed has as its objectives (1) the determination of annual and per-storm runoff values, (2) the correlation of precipitation amount and intensity with "time of concentration" (i.e., the time required for water to flow from the most remote point on the watershed, in time of flow, to the outlet (Frevert et al. 1955)), peak discharge, and total runoff, and (3) the evaluation of the runoff coefficient, C, in the rational formula, $Q = CiA$ (where Q is the peak runoff rate in c.f.s, i is the rainfall intensity in inches per hour for a duration equal to the "time of concentration", and A is the watershed area in acres.

The watershed, generally on the west side of the Coast Mountains, has hilly to gently rolling topography and is surrounded by mountainous terrain. Compact till overlays the bed rock to a depth of two to three feet. About one-third of the watershed was logged in 1966 as a windfall-salvage operation. The remainder has a forest cover of 80-90-year old Douglas fir, hemlock, and red cedar.

A reinforced concrete dam with a 120° V-notch weir and level recorder was constructed in 1966 on the stream draining the basin. Rain gauges and evaporimeters were established at three different altitudes on the watershed along with a hygrothermograph and evaporation pan at the lowest station. Meteorologic and hydrometric data are now being collected for analysis. Project coordinator is Prof. T.L. Coulthard, Department of

Agricultural Engineering, University of British Columbia, Vancouver, B.C.

6. OTHER WATERSHED STUDIES IN BRITISH COLUMBIA

Trapping Creek Representative Basin

Trapping Creek is a tributary of the West Kettle River, and its basin is in a narrow, forested mountain valley near McCulloch, B.C. The overall objective of this study is to gain an understanding of the groundwater flow system in the Interior Plateau of British Columbia, and in particular to determine how groundwater moves between the more humid high Interior Plateau uplands and the more arid, deep intermontane valleys.

The Trapping Creek watershed was established as an IHD-approved representative basin in 1965. The coordinator of the project is Dr. I.C. Brown, Water Resources Branch, Canada Department of Energy, Mines and Resources. References for this outline of the project are Brown (1966), Hobson (1966), and IHD (1967). The study is concentrated at present on measuring the groundwater flow systems near the outlet of the valley. The development of methods of studying these factors is an important part of the project.

Instrumentation consists of stream-gauging stations, recording precipitation gauges, snow courses, anemometers, soil moisture units, and piezometric installations. Four reversed refraction profiles were surveyed in 1966 by hammer refraction seismograph at the confluence of Trapping Creek and the West Kettle River.

Serpentine and Nicomekl Representative Basins

The objective of the representative basins of Serpentine and Nicomekl Creeks is to study the groundwater flow system in a small drainage basin in the Lower Fraser Valley. The coordinator of the project, which was established in 1965, is Dr. I.C. Brown, Water Research Branch, Canada Department of Energy, Mines and Resources.

The two watersheds are about 20 miles east of Vancouver, in an area of complex surficial geology, high rainfall, considerable relief, grading into the Fraser delta dyked areas (IHD 1965b, 1967).

Okanagan Study Basin - Carrs Landing

The Carrs Landing representative basin, established in 1965, is a small watershed with no visible surface runoff, between Okanagan and Kalamalka Lakes. The project coordinator is Mr. H.I. Hunter, Water Investigations Branch, Water Resources Service, B.C. Department of Lands, Forests, and Water Resources. References to the project are Hunter (1966) and IHD (1965b, 1967).

The objective of the Carrs Landing project is to observe the components of the hydrologic cycle with special emphasis on soil moisture and ground water to improve runoff forecasting and for application to agriculture in British Columbia. Instrumentation includes rain gauges, precipitation storage gauges, hygrothermographs, evaporation pans, "Ogopogo" evaporimeter, anemometer, access tubes for soil moisture measurement with the neutron probe, resistance units for soil moisture determination, snow stakes and courses, and observation wells.

Mass Balance of Woolsey, Place, and Sentinel Glaciers

In 1965, a program was initiated by the Glaciology Section of the Department of Mines and Technical Surveys to determine the mass flux, heat and energy budgets of Woolsey Glacier, near Revelstoke, and Place Glacier, near Pemberton, and to relate these parameters to meteorological parameters. Project coordinator is Dr. I.C. Brown, Water Research Branch, Canada Department of Energy, Mines and Resources. Information on this study was obtained from IHD (1967), Østrem (1966a, 1966b), and Stanley (1966).

In 1966, Sentinel Glacier was added to the program in British Columbia. These three glaciers, along with Peyto and Ram River Glaciers in Alberta, form an east-west transect across the Canadian Cordillera and were selected to cover a wide range of climatic conditions. These glaciers have clearly defined catchment areas, are small enough to be examined by small field parties, and have relatively good access.

Snow accumulation and ablation, meteorological parameters, and run-off are measured. Analysis of data taken during the first season of measurement (1965) indicated a somewhat negative budget for Woolsey Glacier (i.e., the glacier had a net loss of mass for the year), and an extremely negative budget for Place Glacier.

Watershed Management Theses, University of British Columbia

Several studies have been carried out by students at the University of British Columbia for B.S.F. theses. Jackson (1948) examined the influence of forests on floods in British Columbia. Parchomchuk (1965) described, with particular reference to forestry, some of the factors

influencing streamflow in the interior wet belt of the province. His study was carried out on Noisy Creek near Enderby. Parchomchuk reported that after a storm, sediment in a stream flowing through a cut-over was much greater than in a stream flowing through an uncut area. Water temperatures and storm runoff peaks were higher in the stream from the cut-over.

Anderson (1962) studied the influence of the forest on the hydrologic cycle in the Upper Similkameen River. Carter (1961) discussed watershed management problems in the Okanagan Valley.

Vancouver and Victoria Municipal Watersheds

This section does not describe watershed studies that have been conducted on the Vancouver and Victoria municipal watersheds because none have been carried out, but it does consider the possibilities of watershed studies on the two areas.

Teller (1963) evaluated the forested municipal catchments of the Douglas-fir region from the point of view of multiple use. Both the Vancouver and Victoria watersheds were included in the evaluation which pointed out the differences in management of the two areas. In the past, the policy of the Greater Vancouver Water District has been one of no logging, although a salvage operation was begun in 1962 (Greater Vancouver Water Dist. 1963). However, the watershed is now under sustained yield forest management. Travel on the Vancouver watershed has been restricted as well. On the other hand, the Greater Victoria Water District has carried out logging on its watershed, averaging 9.2 million f.b.m. per year (Homer-Dixon 1966). High-lead logging on the watershed has been

carried out by the Water District itself to ensure protection of the watershed. Forest management on the watershed has been described by Weatherby (1961). The watershed is crossed at one end by a public road and by the Canadian National Railway. Limited hunting has been permitted in an attempt to reduce high deer populations which cause a great deal of damage to young seedlings.

The Vancouver watershed is 144,640 acres in size, much of which is leased from the Crown in the right of the province. The Victoria watershed is 34,000 acres and is owned outright by the city of Victoria and the three surrounding communities (Saanich, Oak Bay, and Esquimalt). The ownership has, no doubt, influenced the management policies on each watershed. While at present there is little recreational use of either watershed it is likely that increasing populations with more leisure time will force the opening of the areas for recreation. The Greater Vancouver Water District has now recognized the value of managing the watershed for forest crops as well as water and was granted a Tree Farm Licence in 1967.

The point is, that here are two large areas offering many advantages for watershed research, one of which is the presently restricted use of the areas. Ideally, hydrologic data should be gathered for sub-basins on which little disturbance has yet taken place so that knowledge will be gained of the hydrologic behaviour of such watersheds and as a basis with which to compare behaviour after intensive use.

The Greater Victoria Water District considers one of its functions to be the providing of suitable areas on which other agencies may carry

out their research (Homer-Dixon 1966). The Victoria watershed has been used for research by the University of British Columbia for gravitation studies, and by the Pacific Naval Laboratory and both the federal and provincial forestry departments. No research has been carried out on streamflow or sediment production on the area, however. The Greater Vancouver Water District would also be willing to cooperate with agencies wishing to carry out research on the watershed (Blakeny 1965).

Both the Vancouver and Victoria watersheds are well located in that they are close to the universities in the two cities as well as to the headquarters of those government departments that are involved with managing the natural resources of the province. The University of British Columbia, the B.C. Forest Service, and the Water Resources Service should seriously consider conducting hydrologic investigations on these watersheds.

7. WATERSHED RESEARCH NEEDS IN BRITISH COLUMBIA

Watershed research needs in British Columbia differ little from any other areas, although the range of needs may be greater because of the extreme variations in climate and physiography. Research, especially in the United States, has provided information on the relation of climate, vegetation, and water, but transposition of research results from one region to another is hazardous because of differences in climate, vegetation, soils, and geology. Therefore, research must be carried out in British Columbia to obtain knowledge of the relations of climate, vegetation, soils and water in various regions of the province. Research carried out in other countries and other parts of Canada should provide

guidelines for a watershed research program in British Columbia.

As Haddock (1963) pointed out, one of the greatest needs in British Columbia is an awareness of watershed values. This should lead to the recognition of watershed problems and to designation of problem areas. This would be similar to the designation of problem areas given in this thesis, but should be a finer breakdown, delineating smaller areas.

The main watershed management needs in British Columbia concern improving the yield and timing of runoff, reducing the probability and severity of local floods, and reducing erosion.

Research should be carried out in those regions where it appears from past research that vegetation is pertinent to the watershed problem. Research should be directed toward evaluating the effects of different forest cover arrangements(including species, density, and cutting method) on water yield and timing. Greater research effort should be concentrated on those areas where forest treatment has a greater effect.

Research should include studies of snowpack management by forest-cover manipulation for increased yield, prolonged runoff and reduced peak flows, and studies of differences between species of transpiration rates, consumptive use, and energy exchange.

Experimental watersheds are the customary method of investigating the relation of water yield, timing, and quality to land use. The problem associated with experimental watersheds is the application of results to larger areas. Generally, it has not been possible to prescribe a specific treatment to achieve a specific result. In spite of this, and although

there is an increasing emphasis on basic research into hydrologic behaviour, the experimental watershed will continue to be an important research tool in this field. One reason for this is that there is not an adequate substitute to integrate all the complex relations of climate, vegetation, soil, and geology on a particular area.

The experimental watershed provides a hydrologic laboratory on which investigations in various fields of hydrology are facilitated. Individual studies are not carried out in isolation but as part of integrated research into several aspects of hydrologic behaviour.

In view of the preceding paragraphs, it is recommended that watershed research in British Columbia be carried out mainly on experimental watersheds. In Chapter IV, four broad watershed management regions were designated, the Coastal, Peace River, Interior, and Columbia Mountains. The minimum watershed research program requires that at least two experimental watersheds be established, one in the Interior where water deficits range from four to 12 in., and one in the Coastal region where the water deficit is zero. These two regions are at opposite ends of the range of watershed problems encountered in British Columbia.

There is still the difficulty of extrapolating research results to the region of which the experimental watershed is representative. Research is needed into the means of extrapolating these results to the larger region. Even more difficult is the transposition of results from the experimental watersheds to the other two regions of the province.

After calibration, the experimental watershed should receive treatment

selected to fit the forest and watershed conditions and the watershed problems associated with the area. Studies should not be limited to only the treatment effect on runoff but should include basic research into the interaction of climate, vegetation, soil, and water.

Research is needed into the combinations of soil, climate, vegetation, and topography which present the greatest erosion hazards. A means of estimating the erosion hazard would be particularly valuable to field staff of the B.C. Forest Service in protecting watersheds during logging and road construction.

Research into the economics of water yield, timing, and quality improvement through forest management should be carried out to aid in establishing watershed management goals. Much can be done along these lines with presently available data. Information should be gathered on current water values for domestic, industrial, irrigation, and recreational uses, and on costs of improving water yield, timing, and quality. The costs of sediment removal for various water uses should be compared to costs of reduced sediment production on the watershed.

These are the minimum requirements of a watershed research program for British Columbia. If greater resources could be directed to the program, the Columbia Mountains should receive priority and an experimental watershed established there. Flood and erosion control as well as water yield increase would be important objectives of research in this region.

The Canada Department of Forestry and Rural Development has assumed the responsibility for project planning and coordination of three experimental watersheds in the East Slopes (Alberta) Watershed Research Program. This department should probably accept similar responsibility for experimental

watersheds in British Columbia. The total program should be guided by representatives of each of the agencies involved in research or support of the program. Cooperating agencies should include the federal departments of Transport (Meteorological Branch) and Energy, Mines and Resources (Water Survey of Canada and Water Quality and Engineering); the provincial departments of Lands, Forests, and Water Resources (Water Resources Service and Forest Service) and Agriculture (Soil Survey Branch); and the University of British Columbia.

CHAPTER VIII. SUMMARY AND CONCLUSIONS

Investigations of the past 25 years have provided quantitative evidence of the influence of forests on the hydrologic cycle. Forests may be managed to affect the quantity and timing of runoff, and water quality. The objectives of such management may be to increase available water or to reduce flood hazard and erosion.

There has been little research in watershed management in British Columbia until 1965, when several projects were begun under the IHD program. The transposition of results of investigations carried out in other regions to British Columbia is often not valid because of differences in climate, vegetation, soils, geology, and physiography. Research must be carried out in British Columbia to determine what forest management practices may contribute to the solution of water problems in the different regions of the province.

The difficulty associated with experimental watersheds is the application of research results to larger areas. Research must go beyond the classic experimental-watershed approach to understand the processes involved. These fundamental studies may often be best carried out on research watersheds, however, where they may be integrated with other studies and the overall objectives of the research.

In spite of the hazards associated with transposing research results to other areas, there are results that do have application and should be applied. This has been done in this thesis with erosion control information being related to British Columbia. Another example is the use of

research results from other areas to indicate what range of results might be expected in this province. This has been done in this thesis in constructing a rainfall interception model which may be refined as local information becomes available.

A greater degree of coordination of the various water studies in British Columbia should be obtained in order that duplication be avoided and that the research results from one project may be more quickly available to other investigators. This would be a legitimate undertaking of the IHD committees, both national and provincial. Where projects are integrated and carried out on the same area both would benefit.

The water resources of British Columbia are more than sufficient to satisfy any foreseeable demand for water in the province, although there are regions of the province where water shortage is a present problem.

There is some validity to the view that even water in excess of British Columbia's needs should not be diverted to other parts of Canada and the United States but should be retained to attract industry to the province. Factors other than water are required by industry, however, and such factors as proximity to supplies and markets may outweigh the advantage of water supply. Abundant water supply may not attract industry to the province, at least not to the extent that proponents of a no-diversion water policy foresee.

On the other hand, revenue from exported water would provide capital which may be used for the industrial growth of the province. A policy toward water export should not be fixed until a study has been made of the economic implications of both alternatives, an inventory of the resource

has been made, and present and future needs have been estimated.

Because of the great number of federal and provincial agencies involved in administering the water resource, coordination is sometimes lacking, resulting in duplication and omission. It is the responsibility of the provinces to manage their own resources, and this has been a major factor in the passive role played by the federal government in water resource management. Cooperation between the provinces is necessary because of the nature of the water resource, but this is sometimes missing.

Therefore, the federal government must take a more active leadership role to coordinate management of the water resource and to bring provincial governments together for consultation. Provincial agencies must be more aware of water-resource problems and must be willing to cooperate with the federal government and the other provinces.

The B.C. Water Resources Service is the logical provincial agency in which to vest authority for management and development of the provincial water resource. Because of increased rate of industrial growth and proposed water diversion schemes the Water Resources Service must increase staff to carry out its function. Economists, forest hydrologists, and regional planners are needed as well as engineers and hydrologists.

Greater coverage by meteorologic and hydrometric stations is necessary in British Columbia to provide knowledge to properly administer the resource. Publication of data dealing with climate and water resources should be assumed by the two federal agencies most closely associated with data gathering, the Meteorological Branch and the Department of Energy, Mines and Resources. The time lag between collection and publication should

be kept to a minimum.

There are many examples of accelerated erosion in British Columbia traceable to logging and road building. Erosion often goes unnoticed although it results in site deterioration, lowered water quality, and property damage. The B.C. Forest Service often includes watershed-protection clauses in timber-sale contracts, but these are not always enforced due to a lack of both awareness of erosion and adequate field staff.

The practice of referring timber-sale applications to the B.C. Water Rights Branch and water users such as irrigation districts is recommended. But this cannot take the place of adequate watershed management training of Forest Service personnel. Greater emphasis must be placed on watershed protection in courses given by the B.C. Forest Service Training School, and periodic refresher courses should be given to field staff, especially Forest Rangers.

The staff of the B.C. Forest Service has increased very little in the past 10 years although the forest industry has greatly expanded. Field staff, especially, must be increased to provide the inspection and enforcement necessary for proper watershed protection.

To aid management, areas with similar watershed problems and priorities should be grouped into regions. The water resources of British Columbia were examined and four watershed-management regions (Coastal, Peace River, Interior, and Columbia Mountains) were delineated on the basis of climatic factors, water needs, and flood and erosion potential. Forest-management practices were recommended that would contribute to attaining the objectives of water-resource management in each region. In the Coastal region and the Peace River region the objective of forest management with regard to watershed problems should be to reduce peak

flows. Flood control should be given top priority in the Columbia Mountain region, with water-yield increase also receiving attention. In the Interior region, increasing water yield is the primary objective. In all regions, careful attention should be paid to minimising erosion caused by logging and road construction.

With existing records and transposing the results of watershed research carried out in other regions, Tree Farm License No. 9 in the Okanagan Valley was used to demonstrate the effect of forest management on water yield and timing. An increase of five per cent in water yield can be attributed to changing from no use of the timber products of the area to utilization under the present forest management. A further five per cent increase could be realized by substituting for present management, one based on financial rotations and consideration of water as an important secondary product.

Statistical calibration of the Windermere and Sinclair Creek watersheds in the East Kootenays was presented, and the effect of logging on streamflow from Watching Creek near Kamloops was analysed graphically. Water balance and other studies were presented for Terrace Creek watershed on Tree Farm License No. 9. Other watershed research in British Columbia was reviewed and research needs discussed. A comprehensive watershed-research program was recommended, to begin with intensely-instrumented experimental watersheds in the Coastal and Southern Interior Regions of the province.

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APPENDIX I. METEOROLOGICAL OBSERVATIONS ON TERRACE-ESPERON CREEK WATERSHED

Table A1. Daily precipitation at Meteorological Stations Nos. 1, 2, and 3 on the Terrace-Esperon Creek Watershed for the period June 23 - September 30, 1966 (Source: recording tipping-bucket rain gauge charts)

Date (1966)		Precipitation in inches		
		Met. station No. 1	Met. station No. 2	Met. station No. 3
June	23	0.09	0.02	0.03
	24	-	-	-
	25	-	-	-
	26	0.11	0.08	0.02
	27	0.07	0.06	0.12
	28	0.10	0.02	0.06
	29	-	0.01	-
	30	0.01	-	-
July	1	0.14	0.07	0.14
	2	0.25	0.20	0.25
	3	0.45	0.34	0.38
	4	-	-	-
	5	0.72	0.64	0.64
	6	-	-	-
	7	-	-	-
	8	-	-	-
	9	-	-	-
	10	0.13	0.02	0.02
	11	-	-	0.28
	12	0.04	-	-
	13	-	0.01	-
	14	-	-	-
	15	-	-	0.02
	16	0.10	0.04	0.04
	17	-	-	-
	18	0.19	0.06	0.30
	19	-	-	-
	20	-	-	-
	21	-	-	-
	22	-	-	-
	23	-	-	-

Table A1 continued

Date (1966)		Precipitation in inches		
		Met. station No. 1	Met. station No. 2	Met. station No. 3
July	24	0.39	0.21	0.36
	25	0.43	0.18	0.35
	26	-	-	0.08
	27	-	-	-
	28	-	-	-
	29	-	-	-
	30	-	-	-
	31	-	-	-
Aug.	1	-	-	-
	2	-	-	-
	3	0.06	0.02	-
	4	0.18	0.20	0.52
	5	-	-	-
	6	-	-	-
	7	0.08	-	0.03
	8	-	-	-
	9	-	-	0.04
	10	0.15	-	0.06
	11	-	-	-
	12	0.47	0.41	0.34
	13	0.25	0.08	0.11
	14	0.06	0.04	0.04
	15	-	-	-
	16	-	-	-
	17	-	-	-
	18	-	-	-
	19	-	-	-
	20	-	-	-
	21	-	-	-
	22	-	-	-
	23	-	-	-
	24	-	-	-
	25	-	-	-
	26	-	-	-
	27	0.06	0.03	0.10
	28	-	-	-
	29	0.55	0.36	0.35
	30	0.01	0.01	0.01
	31	-	-	-

Table A1 continued

Date (1966)	Precipitation in inches		
	Met. station No. 1	Met. station No. 2	Met. station No. 3
Sept. 1	-	-	-
2	-	-	-
3	-	-	-
4	-	-	-
5	-	-	-
6	-	-	-
7	0.02	0.02	0.02
8	-	-	-
9	0.02	0.01	0.02
10	0.08	0.07	0.08
11	0.05	0.06	0.05
12	0.03	0.03	0.05
13	-	-	-
14	-	-	-
15	0.03	0.02	0.02
16	-	-	-
17	0.08	0.06	0.06
18	0.01	-	0.02
19	-	-	-
20	-	-	-
21	-	-	-
22	0.08	0.03	0.06
23	-	0.03	0.08
24	-	-	-
25	-	-	-
26	-	-	-
27	-	-	-
28	0.04	0.01	-
29	-	-	0.01
30	-	-	-

Table A2. Weekly precipitation for Meteorological Stations Nos. 1, 2, 3; for the open site; and for different distances from the bole of a tree in the forest site; for the period June 17 - October 13, 1966, on the Terrace-Esperon Creek watershed[1]

Period (1966)	Precipitation in inches										
	Meteorological stations			Open site	Forest site						
					Distance from tree bole in feet						
	No. 1	No. 2	No. 3		1	3	6	10	15	21	35
June 17-June 23	n.m.[2]	n.m.[2]	n.m.[2]	0.23	-	Tr[3]	0.03	0.11	0.12	0.17	0.16
June 24-June 29	0.28	0.17	0.20	0.25	-	-	Tr[3]	0.04	0.13	0.22	0.18
June 30-July 7	1.57	1.25	1.41	1.66	0.35	0.67	0.77	1.30	1.27	1.39	1.41
July 8-July 14	0.17	0.03	0.30	0.13	Tr[3]	Tr[3]	Tr[3]	0.01	0.02	0.08	0.10
July 15-July 21	0.29	0.10	0.36	0.13	0.06	0.10	0.06	0.06	0.13	0.24	0.19
July 22-July 28	0.82	0.39	0.79	0.78	0.24	0.39	0.30	0.14	0.39	0.60	0.57
July 29-Aug. 4	0.24	0.22	0.52	0.24	-	Tr[3]	0.01	0.03	0.04	0.12	0.19
Aug. 5-Aug. 11	0.23	-	0.13	0.21	-	0.02	0.01	0.01	0.04	0.07	0.11
Aug. 12-Aug. 18	0.78	0.53	0.49	0.76	0.06	0.17	0.13	0.16	0.35	0.54	0.63
Aug. 19-Aug. 25	-	-	-	-	-	-	-	-	-	-	-
Aug. 26-Sept. 1	0.62	0.40	0.46	0.55	0.03	0.15	0.20	0.18	0.15	0.25	0.43
Sept. 2-Sept. 8	0.02	0.02	0.02	0.02	-	-	Tr[3]	Tr[3]	Tr[3]	0.02	0.02
Sept. 9-Sept.15	0.21	0.19	0.22	0.19	-	-	Tr[3]	0.06	0.15	0.19	0.19
Sept.16-Sept.22	0.17	0.09	0.14	0.18	-	Tr[3]	Tr[3]	0.01	0.06	0.12	0.11
Sept.23-Sept.29	0.04	0.04	0.09	0.03	-	-	-	-	-	Tr[3]	0.01
Sept.30-Oct. 6	n.m.[2]	n.m.[2]	n.m.[2]	0.40	0.02	0.05	0.03	0.02	0.06	0.20	0.26
Oct. 7-Oct. 13	n.m.[2]	n.m.[2]	n.m.[2]	0.02	-	Tr[3]	Tr[3]	Tr[3]	0.01	0.01	0.01
June 17-Oct. 13	n.m.[2]	n.m.[2]	n.m.[2]	5.78	0.76	1.55	1.54	2.13	2.92	4.22	4.57
June 24-Sept.29	5.44	3.43	5.13	5.13	0.74	1.50	1.48	2.00	2.73	3.84	4.14

[1]Rain-gauge locations are described in the Chap. VII.

[2]Not measured.

[3]Trace.

Table A3. Snow survey measurements for Okanagan Valley snow courses for 1966 and averaged for the length of record [1]

Snow Course	No.	Elevation in feet	Year of record	Water equivalent of snow in inches[2]					
				Feb. 1	Mar. 1	Apr. 1	May 1	May 15	June 1
Lower Esperon	164	4,270	1966	5.9	9.0	11.0	6.2	0.4	-
Middle Esperon	163	4,580	1966	8.5	11.0	13.6	6.8	0.4	-
Upper Esperon	162	5,290	1966	10.2	14.5	19.2	15.6	6.4	0.4
McCulloch	4	4,200	1966	4.6	6.0	5.0	0.9	-	-
McCulloch	4	4,200	average[3]	4.9	6.4	6.6	2.8	0.8	-
Bouleau Creek	31	5,000	1966	NM[4]	NM[4]	9.5	6.9	NM[4]	-
Bouleau Creek	31	5,000	average[3]	6.1	9.7	11.9	7.2	4.4	-
White Rocks Mt.	70	6,000	1966	NM[4]	18.1	22.0	NM[4]	NM[4]	-
White Rocks Mt.	70	6,000	average[3]	NM[4]	16.7	18.8	NM[4]	NM[4]	-

[1]Source: B.C. Dept. Lands, Forests, and Water Resources 1966. Snow Survey bulletin. Hydrology Div., Water Investigations Br., B.C. Water Resources Service (published each year on Feb. 1, Mar. 1, Apr. 1, May 1, 15, June 1).

[2]The dates on which the snow survey measurements were made were not always as indicated in the column head but were within several days of this date.

[3]The average values given are for the length of the record period for each station. The length of record varies between stations and even between dates of measurement for individual stations.

[4]NM - snow survey was not conducted on these dates.

Table A4. Evaporation from Ogopogo evaporimeters from June 10 to October 28, 1966, at Meteorological Station No. 1, Terrace-Esperon Creek watershed

Week Ending		Amount of evaporation			
		Evaporimeter LA133 (cc.)	Evaporimeter LA105 (cc.)	Average of LA133 and LA105 (cc.)	Average of LA133 and LA105 (inches)
June	17	184	-	184.0	1.93
	24	163	-	163.0	1.71
	30	-	-	-	-
July	8	123	130	126.5	1.32
	15	161	161	161.0	1.69
	22	171	160	165.5	1.73
	29	172	176	174.0	1.83
Aug.	5	216	233	224.5	2.35
	12	157	155	156.0	1.64
	19	143	146	144.5	1.51
	26	210	218	214.0	2.24
Sept.	2	98	132	115.0	1.21
	9	205	255	230.0	2.41
	16	-	159	159.0	1.68
	23	173	178	175.5	1.84
	30	54	54	54.0	0.56
Oct.	7	120	119	119.5	1.25
	14	50	48	49.0	0.51
	21	87	75	81.0	0.85
	28	38	21	29.5	0.30

Table A5. Evaporation from Ogopogo evaporimeters from June 10 to October 28, 1966, at Meteorological Station No. 2, Terrace-Esperon Creek watershed

Week Ending	Amount of evaporation			
	Evaporimeter LA164 (cc.)	Evaporimeter LA166 (cc.)	Average of LA164 and LA166	
			(cc.)	(inches)
June 17	190	165	177.5	1.86
24	175	164	169.5	1.77
30	159	149	154.0	1.62
July 8	112	123	117.5	1.23
15	175	183	179.0	1.88
22	154	162	158.0	1.66
29	161	161	161.0	1.69
Aug. 5	248	232	240.0	2.52
12	165	164	164.5	1.72
19	157	154	155.5	1.63
26	245	240	242.5	2.54
Sept. 2	106	108	107.0	1.12
9	167	163	165.0	1.73
16	129	116	122.5	1.30
23	126	124	125.0	1.31
30	73	73	73.0	0.77
Oct. 7	94	87	90.5	0.94
14	50	53	51.5	0.53
21	68	69	68.5	0.72
28	24	23	23.6	0.24

Table A6. Evaporation from Ogopogo evaporimeters from June 10 to October 28, 1966, at Meteorological Station No. 3, Terrace-Esperon Creek watershed

Week Ending	Amount of evaporation			
	Evaporimeter LA163 (cc.)	Evaporimeter LA136 (cc.)	Average of LA163 and LA136	
			(cc.)	(inches)
June 17	178	177	177.5	1.86
24	168	169	169.5	1.77
30	154	153	153.5	1.61
July 8	124	122	123.0	1.29
15	183	181	182.0	1.91
22	159	162	160.5	1.68
29	169	168	168.5	1.87
Aug. 5	224	220	222.0	1.33
12	143	160	151.5	1.59
19	133	154	143.5	1.50
26	198	272	235.0	2.47
Sept. 2	98	116	107.0	1.12
9	140	183	161.5	1.69
16	105	130	117.5	1.23
23	108	134	121.0	1.27
30	64	82	73.0	0.77
Oct. 7	82	107	94.5	0.99
14	55	55	55.0	0.57
21	69	64	66.5	0.70
28	31	19	25.0	0.26

APPENDIX II. CALIBRATION OF WINDERMERE CREEK WITH SINCLAIR CREEK

Table A7. Sum of squares and products for annual discharge in area-inches from Windermere Creek (Y) and Sinclair Creek (X), 1961-1965

SX	63.04	SY	41.20		
$\bar{x}$	12.61	$\bar{y}$	8.24		
SX^2	808.4394	SY^2	343.4210	SXY	523.1757
$(SX)^2/n$	794.8083	$(SY)^2/n$	339.4880	SXSY/n	519.4496
Sx^2	13.6311	Sy^2	3.9330	Sxy	3.7261

Table A8. Partial analysis of covariance for period of calibration of Windermere Creek (Y) with Sinclair Creek (X)

Source	Degrees of freedom	Corrected squares and products			b	Degrees of freedom	Errors of estimate	
		Sx^2	Sxy	Sy^2			Sum squares	Mean square
Period 1	4	13.6311	3.7261	3.9330	.2734[1]	3	2.9145[2]	0.9715

[1] b = regression coefficient = Sxy/Sx^2 = 3.7261/13.6311 = 0.2734

[2] Sum squares = $Sy^2 - (Sxy)^2/Sx^2$ = 3.9330 - $(3.7261)^2$/13.6311 = 2.9145

Correlation coefficient, $r = \sqrt{(Sxy)^2/(Sx^2)(Sy^2)}$ = 0.5089

Regression equation: $\hat{Y} = \bar{y} + b(X-\bar{x})$

$= 8.24 + 0.2734\ (X-12.61)$

$= 4.79 + 0.2734X$

From Kovner and Evans (1954),

$$d = sy.x^2 / \frac{n.n_2}{n.+n_2} \left[\frac{1}{F\left(1+\frac{F}{n_1+n_2-2}\right)} \right] = 1.37 \text{ area-inches}$$

where d = the smallest significant difference between discharge from Windermere Creek before and after logging, in area-inches

$sy.x^2$ = variance of estimate, 0.9715

n_1, n_2 = length of calibration and treatment periods, respectively, in years

F = variance ratio

Table A9. Monthly water balance calculated by Thornthwaite's method using climatic data for McCulloch, B.C. (elevation 4,100 ft.), and observed runoff from Terrace Creek for the water year October 1965 - September 1966

Component	Values for the components of the water balance in centimeters												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
Precipitation	5.59	6.43	8.31	7.57	6.45	5.87	4.72	6.12	7.42	4.75	3.94	4.83	72.00
Actual evapo-transpiration	2.85	-	-	-	-	-	2.32	6.63	8.70	10.05	6.27	5.24	42.06
Calculated runoff	-	-	-	-	-	-	11.72	14.97	3.25	-	-	-	29.94
Observed runoff from Terrace Creek	0.16	0.16	0.16	0.16	0.16	0.20	6.56	13.12	3.56	1.42	0.25	0.07	25.98