# EFFECTS OF CLEARCUT TIMBER HARVESTING ON ANNUAL WATER YIELDS IN THE CARNATION CREEK WATERSHED, BRITISH COLUMBIA

by

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## ABSTRACT

Changes in annual water yield after clear-cut timber harvesting are investigated at Carnation Creek on the west coast of Vancouver Island, British Columbia. The paired basin method was used to determine annual, seasonal and monthly changes in water yield between treated basins H (12 ha) and J (24 ha) and control sub-basins C (145 ha) and E (265 ha). Water yield increased 20% and 28% at H and J watersheds, respectively and was matched by corresponding decreases in evapotranspiration. Water yield increases were lowest the first year after harvesting and peaked six years later. Wet season (October - March) water yields increased 20% at H watershed and 25% at J watershed while dry season (April-September) increases were 14% at H watershed. Increases in annual water yield after timber harvesting are attributed to reduced evapotranspiration and interception losses allowing more water for streamflow. These findings support results reported from studies in the Pacific northwest region and provide quantitative information on the effects of clear-cut timber harvesting on the west coast of Vancouver Island.

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## ACKNOWLEDGEMENTS

I was once asked to describe my experience of graduate school metaphorically and naturally I turned to sailing. For as in sailing, it is not the destination that is so important, but how it is reached. Weather, tides and currents are constantly changing and sails need to be trimmed to stay under control. In competitive sailing, it is a combination of crew work, knowledge and awareness of changing conditions and discerning information fed by the crew which ensures successful completion of the race. The relationship between the skipper and the crew is vital to the success of the passage and is symbiotic at times. The crew provides information and opinions about conditions to the skipper and the skipper must make decisions which ensure safety to the crew, the boat and which will help achieve the desired goal. On this journey, the thesis is my sailing vessel and the committee is crew. The ultimate responsibility has been mine, but the destination could not have been reached without the support of my committee and many others. The passage has been marked by changing crew members, different ports of call, and was drydocked for 12 months. But as with every boat, she continued to sail, finally reaching home port. It is with flying sails I wish to acknowledge the following people.

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*Dedicated to*

| | |
|---|---|
| G.B. Dupuis | 1931-1990 |
| L.C. Sullivan | 1902-1993 |

*There's not a day goes by, you're not in my thoughts.*
*Thanks for believing.*

# CHAPTER 1
# INTRODUCTION

## 1.1 Introduction

Large-scale clearcut timber harvesting has strong visual and physical impacts on the environment. Images come to mind when hearing the words "clearcut logging": vast tracts of land littered with stumps and logging slash, scarred hillsides ribboned with logging roads, road-related slides, logging-related torrented creeks and gullies. These images are easy to visualize because we have seen them on posters, in magazines, or we may have experienced them first-hand, but perhaps most important, they represent what is most tangible - the impact on the physical environment.

The impacts from removing forest cover on the physical environment affect many different components linking a forest ecosystem; wildlife, habitat, vegetation and soils. Different forest types will support different lifeforms and different foodchains, but all have one thing in common: dependency on water.

Many logging related impacts are driven by the hydrologic regime in the region. In the Pacific Northwest region of the United States and the southwest coast of British Columbia, specifically the west coast of Vancouver Island, high rainfall and steep terrain combine to create a dynamic hydrologic environment. Shallow soils and relatively impermeable bedrock allow creeks to respond quickly to precipitation inputs. These climatic and physiographic characteristics are an integral part of this environment. Land-use changes made to this system ultimately affect changes in water yield, the total runoff from a drainage area through surface channels and by groundwater flow. Water yields vary directly with precipitation on an annual basis, as evapotranspiration is less variable than precipitation (Hetherington, 1987).

The most common and accepted method for determining changes in water yield from timber harvesting and other land use changes is the paired basin method (Hewlett, 1971). This method assumes that the hydrologic relationships observed between two basins in the past will continue into the future, unless some change is made on one of the basins (Hewlett, 1971). The control basin serves as a climatic standard, against which experimental results can be assessed.

Much of our understanding of forest hydrology in British Columbia comes from observations and data collected from paired basin studies around the world. Although different climates and regions produce different results, the processes that act on these areas are similar. It has been well documented that removal of forest cover results in increased water yields due to reduced evapotranspiration and interception losses allowing more available water to enter the stream channel (Bosch and Hewlett, 1982). Increased water yields may effect the physical characteristics of a stream channel and lead to downstream effects on fisheries resources, water supply and other consumptive/non-consumptive uses.

The majority of forest hydrology research in the Pacific Northwest has been concentrated in the coastal regions of western Washington and Oregon states. Only a limited amount of forest hydrology research has been conducted in coastal British Columbia watersheds (Golding, 1988). Research completed in the Okanagan region of the province describes the effects of removing timber on annual water yields (Cheng, 1980). Regional differences in climate between coastal and interior areas preclude meaningful comparisons between timber harvesting and hydrologic relationships. Climate is perhaps the most significant factor as a larger percentage of precipitation falls as snow in the interior and this results in a very different hydrologic response than is expected from a rain-dominated hydrologic environment. Difficulties in transferring hydrologic relationships are not limited to regional differences, but can also apply from basin to basin in one region depending on runoff processes in a watershed (Pilgrim, 1983).

## 1.2 Research Objectives

The purpose of this research is to evaluate the hydrologic impact of timber harvesting on annual, seasonal and monthly water yields in Carnation Creek, British Columbia. The goal of the research is to quantify and explain the changes in annual water yields from clearcut timber harvesting focusing on forest hydrologic processes. Many studies have examined the impacts of timber harvesting and provided quantitative information on annual yields, but few have attempted to examine the hydrologic response with respect to the forest hydrologic cycle.

In order to accomplish this goal, three main objectives were identified:

Objective 1: to establish pre-harvest relationships between water yield and precipitation variables for each of four sub-basins

Objective 2: to quantify any post-harvest changes in annual water yield for each treated sub-basin

Objective 3: to evaluate changes in annual water yield relative to timber harvesting and changes to the forest hydrologic cycle

Based on these objectives, a research hypothesis was developed which states that the removal of timber increases water yields within a basin due to more water being available for streamflow. This hypothesis was further broken down into specific research hypotheses stating individual forest hydrology processes:

- Increases in annual water yield can be attributed to reduced evapotranspiration and interception losses allowing more water to be available for streamflow.

- Increases in annual water yield will occur throughout the year, with the greatest increases occuring in winter months due to higher precipitation and saturated soils requiring less moisture to recharge, thereby allowing more water to be available for streamflow.

- Increases in annual water yields will be largest immediately post-harvest with a decrease in water yields occurring over time as regrowth of vegetation occurs.

## 1.3 Research Significance

Due to the limited amount of existing quantitative information on timber harvesting-water quantity relationships in the province of British Columbia, this research will provide a regional context for timber harvesting effects on annual water yields in coastal British Columbia. This research will also provide an opportunity for comparison with results from other studies conducted in the Pacific Northwest region, where the majority of research has been completed and inferences have been made.

At the same time, this study will supply needed quantitative information on the hydrologic response of a west-coast stream to clearcut timber harvesting. Foresters and planning staff are now required to assess streams within each cutblock as part of the permitting process. Field experience has lead many of the decisions in the past without a complete understanding of process to direct them. On the assumption that Carnation Creek is representative of a west coast Vancouver Island stream, data that come out of this research may be applied to neighbouring watersheds such as the Carmanah, Walbran, and other west-coast creeks. An understanding of the hydrology and processes which influence annual water yields may direct resource managers in the decision-making process.

Finally, the focus of this research is on forest hydrology processes. It is hoped that an understanding of these processes as they relate to land-use changes and the subsequent impact on annual water yield will supplement and complement past research.

## 1.4 Thesis Outline

Chapter 2 presents a review of literature covering forest hydrology processes, the effect of timber harvesting on the hydrologic cycle and the resulting impact on annual water yields. Previous studies reporting results from timber-harvesting impacts on water yields are addressed in context of the Pacific Northwest experience.

Chapter 3 provides a detailed description of the study area followed by an introduction to the Carnation Creek Experimental Watershed Project and review of preliminary analyses conducted prior to this research.

In Chapter 4, methods for analysing the hydrometerological data are described and results are presented in Chapter 5. This includes analysis on annual, seasonal and monthly data.

Discussion of results is presented in Chapter 6. Research hypotheses are reviewed with a focus on alterations to the forest hydrology system and the resulting influence on annual water yields. Chapter 7 summarizes research findings and concludes the thesis.

# CHAPTER 2
# RESEARCH BACKGROUND

## 2.1 Introduction

Removing the forest cover from a watershed changes the quantity, timing and distribution of water movement. The direct effect of clearcutting on the forest hydrologic cycle also varies regionally with climate. In British Columbia, the hydrologic response of a watershed is dependent upon whether or not the runoff is generated by rainfall, rain on snow, or spring snowmelt. An understanding of the hydrologic response of a creek requires an understanding of the physical processes which influence water yields. The purpose of this chapter is threefold: first, to introduce the history of watershed research studies in British Columbia; second, to review forest hydrologic processes which influence water yields and third, to discuss the impact of timber harvesting on these processes with a focus on watershed studies conducted in the Pacific Northwest region.

## 2.2 Research History

Basin-scale forest hydrology studies in British Columbia began in 1969 with the establishment of a paired basin experiment in the Jamieson (3 $km^2$) and Elbow (1.2 $km^2$) basins in the Vancouver municipal water-supply area. The focus of that study was to describe the effects of forest management practices by the Greater Vancouver Water District on streamflow regimes (Golding, 1988). The intent was to develop a set of forest management guidelines designed to protect water resources in the municipal drainage basins. The research conducted in this watershed focused on seasonal storm peaks.

In 1970, the Carnation Creek Experimental Watershed Project was established to determine the effects of clearcut logging on west-coast fisheries resources (Scrivener, 1987). The study objectives were fourfold: to understand ecological and physical processes influencing salmon and trout populations; to determine the effect of clearcut logging and forestry practices on these processes; to provide continuous input for resource management strategies; and to communicate the results of these investigations to the scientific/technical community and the general public (Chamberlin, 1987). A more detailed research background is presented in Chapter 3.

In 1970, the paired basin method also was used to assess streamflow changes after clearcut logging in Camp Creek (33.9 km$^2$), located between Penticton and Kelowna, in the interior of British Columbia. Mature lodgepole pine had been significantly affected by the mountain pine beetle and clearcutting was used to salvage the infested trees and, as a preventive measure, to bring the pine beetle epidemic under control (Cheng, 1989). Changes in annual and monthly water yields and annual peak flows were examined as a component of this study.

Basin size and scale are considerations in watershed studies with respect to measurement error and the ability to extrapolate experimental results from small to large watersheds. Cheng's study provided results from logging a watershed greater than 10 km$^2$ and contributed additional knowledge complementing results from smaller watershed experiments.

After a severe forest fire in the area west of Salmon Arm in September 1973, a study was initiated to describe the hydrologic effects of the fire. Pre- and post-burn streamflow characteristics of Palmer Creek (18.1 km$^2$) were analysed. This research investigated seasonal and monthly water yields and annual peak flows. The study was based on the paired basin method and provided an opportunity to learn about the hydrologic effects of forest fire for the interior of the province (Cheng, 1980).

## 2.3 Hydrologic Processes

The hydrologic cycle comprises several processes by which water in its different states moves from the atmosphere to the land to the ocean and back to the atmosphere (Figure 2.3-1). In the cycle, radiant energy is absorbed in the process of evaporating water from the ocean. Pressure and temperature gradients produce wind currents which carry this moist air over continents. Water vapour cools as it rises, condenses, and when conditions are favourable, some of the moisture falls back to earth in the form of either rain or snow. Some of this moisture is intercepted by vegetation and re-evaporated back to the atmosphere, while the remainder falls to the ground (Dunne and Leopold, 1978). Water reaching the ground surface may be absorbed into the soil by the process of infiltration, where it is either stored or percolates through the soil matrix into the stream channel or groundwater aquifer. Water remaining in the soil may be re-evaporated to the atmosphere or utilised by trees through the process of transpiration. However, not all water reaches the stream channel through the soil matrix. When rainfall intensity is greater than the infiltration capacity of the soil or when the infiltration rate exceeds rainfall intensity, water will reach the ground surface and run downslope in a process called overland flow.

### 2.3.1 Precipitation

Forest hydrology systems can be divided into two main categories: rain-dominated and snow-dominated (Harr, 1979). Where annual runoff closely follows annual precipitation, the system is usually assumed to be dominated by rain. Where most of the precipitation falls during the winter season but the major runoff occurs in the spring, the system is dominated by snow (Harr, 1979).

Precipitation is the controlling factor in the hydrologic cycle of a region. The characteristics of a precipitation regime include the size and intensity of individual

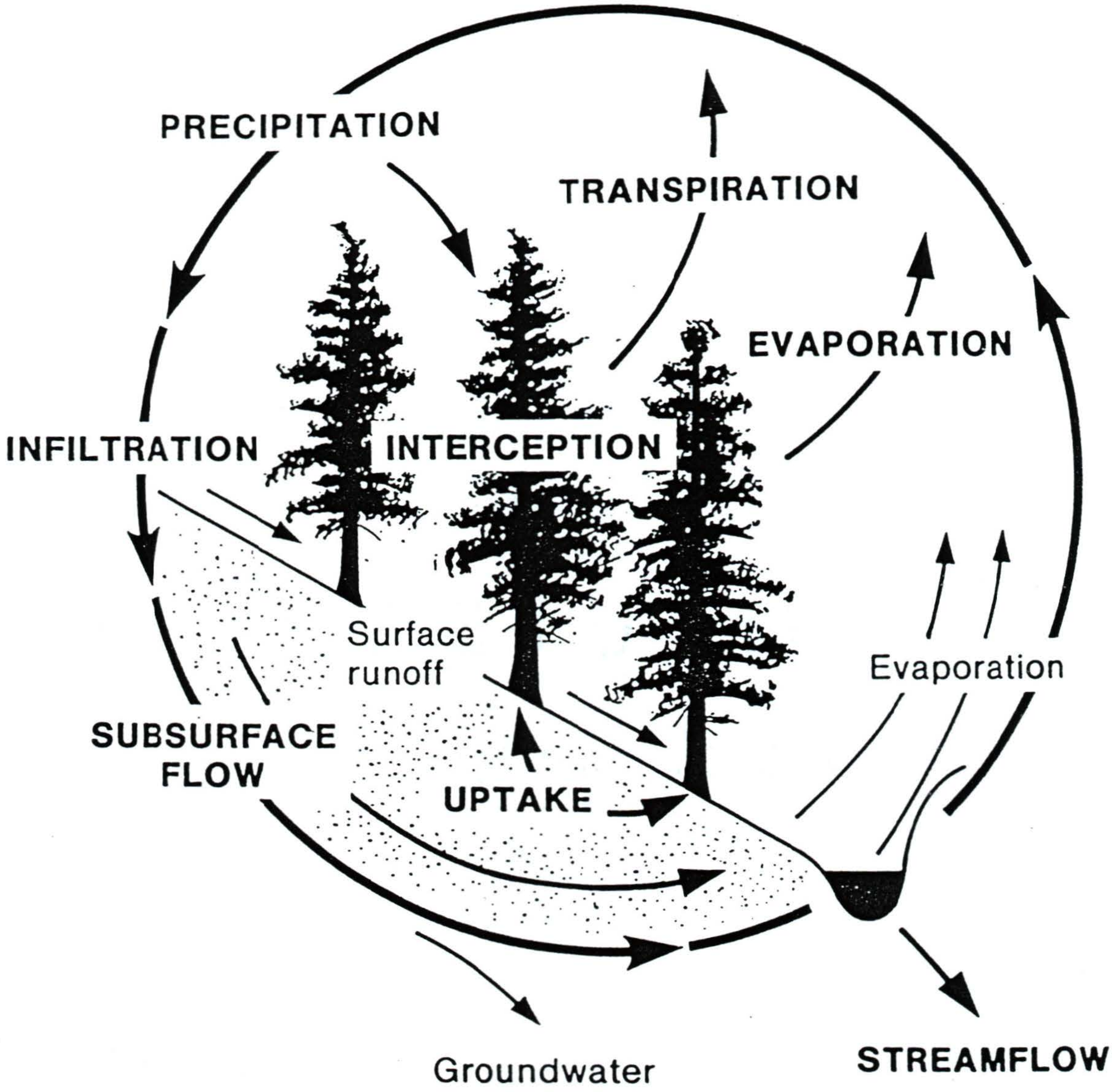

Figure 2.3-1 Diagram of the hydrologic cycle (Hetherington, 1987)

storms, storm duration, relative amounts of precipitation received by the ground surface and frequency of occurrence. These characteristics determine the amount of runoff that occurs over a drainage basin. The actual amount of precipitation that becomes runoff is largely influenced by the type of ground cover and interception characteristics of that ground cover, soil and bedrock type.

### 2.3.2 Interception

Interception is the amount of precipitation that is caught by vegetation or surface cover and evaporated back to the atmosphere (Dunne and Leopold, 1979). By intercepting precipitation, forest canopies reduce the amount and change the timing of rain and snow reaching the ground surface, thereby altering its distribution. The amount of annual precipitation intercepted by forest stands is usually assumed to be approximately 20-30% (Harr, 1979). The exact amount, however, is dependent on the precipitation regime, and secondly, by the nature of the vegetation cover including type, density and form.

Annual interception values will vary with seasonal storm characteristics. Hetherington (1981) states the amount of interception is dependent upon storm size and may range from less than 5% for prolonged winter rainfall, to nearly 100% for light summer rains. Rothacher (1963) found that for summer storms of 25 mm, 50 mm and 90 mm, interception losses totalled 5 mm (20%), 10 mm (20%) and 16 mm (18%) respectively. Interception losses during winter rainy periods were less than in the summer. For storms of 50-100 mm, 100-150 mm and greater than 200 mm, interception losses averaged 6-12 mm (12%), 7-10 mm (7%) and 9 mm (5%) respectively. Ford and Deans (1978) report that interception losses in a Sitka Spruce plantation accounted for 30% of annual precipitation, decreasing to 15% during the winter period.

Pearce and Rowe (1980) state that the frequency and duration of canopy wetness influences the water yield of forested areas. In regions of high precipitation, interception can account for 60-70% of total evaporative loss. In regions with annual precipitation greater than 1500 mm, water yield changes following timber harvesting are likely to be dominated by changes in interception loss. Alternately, in regions with annual precipitation less than 700-800 mm, water yield changes are likely to be a function of seasonal soil moisture losses.

The interception of precipitation in forested areas is also determined by the type and density of trees. Conifer stands in British Columbia have been reported to intercept more rainfall on a seasonal basis than mixed forest stands in Alberta and hardwoods in Quebec (Hetherington, 1987). Interception values of summer rainfall reported in these regions are 57%, 37% and 8% respectively. Interception of precipitation has been measured extensively in old-growth forests of Douglas-fir (Harr, 1979). In the H.J. Andrews Experimental Forest in Oregon State, Rothacher (1963) measured an annual interception of 46 cm over a 1-year period, with an annual precipitation of 213 cm (22%). Krygier (1971; in Harr, 1979) measured 28 cm of interception, when annual precipitation was 100 cm (28%) in a study of second-growth Douglas-fir.

Interception is also dependent on crown closure and the storage capacity of the forest canopy. A stand of trees will be described as open or closed depending on the density of the trees and the subssequent cover created by overlapping branches. Where stand density is low, the canopy will generally be more open than a higher density stand which would have a closed canopy. Lower interception values are reported for more open stands (Hetherington, 1981). Gash et al. (1980) measured rainfall interception from two Sitka Spruce forests where stand densities differed by 20%. Gash observed higher interception losses in the closed stand (11% vs 7%).

The storage capacity of the canopy is the quantity of water that is held on the leaves, branches and bark. It is dependent on the physical characteristics of the tree and the surrounding climatic environment. Conifers can hold an average of 0.2 cm of rainfall, ranging from 0.05 - 0.9 cm (Helvey and Patric, 1965).

Significant differences between coniferous and deciduous form strongly influence interception values. Dunne and Leopold (1978) report median canopy interception for coniferous and deciduous forest as 22% and 13% of gross precipitation. Coniferous trees intercept more rainfall because they have constant foliage throughout the year. Leaf form also contributes to interception differences. Broad-leaved trees allow for the formation of larger water droplets which overcome surface tension and drop to the ground surface. Needle-leaved trees hold water droplets apart on or between individual needles that do not fall off so easily (Dunne and Leopold, 1978).

### 2.3.3 Fog drip

Interception is not restricted to precipitation only. Harr (1979) states that in some local areas, interception of clouds or fog may increase precipitation. Fog drip is the result of fog water being horizontally transported by prevailing winds and intercepted by trees. Water droplets coalesce on branches and leaves forming larger droplets which fall to the ground under the canopy. The net effect of fog drip is the supply of additional water to the underlying soil and ground cover. When such moisture added to the canopy exceeds the amount of intercepted water a particular tree can hold, canopy precipitation results. In some parts of the world, this 'precipitation' may be substantial and harvesting the stand would eliminate a source of moisture, possibly offsetting expected water yield increases from reduced evapotranspiration losses (Ingwersen, 1985).

Isaac (1946) found that annual precipitation augmented by fog interception and drip under the forest canopy near the Oregon Coast was 2520 mm, 520 mm more than in the open. Azevedo and Morgan (1974) reported fog drip beneath Douglas-fir during a 46-day rainless period during summer in coastal northern California that ranged up to 425 mm. Additional fog drip measurements during rainless periods include 52 mm beneath a sheltered redwood tree (Oberlander, 1956) and 57 mm per month beneath exposed knobcone pine in southern California (Vogl, 1973; in Harr, 1982).

Harr (1982) reported a small decrease in annual water yields from two 25% patch-logged watersheds on the Fox Creek experimental watersheds, located on the Bull Run Municipal Watershed 40 km east of Portland, Oregon. The expected result was an increase in annual water yield of 100 to 150 mm. Instead, a decrease of <20mm was observed. In addition, the number of low flow days increased during many post-harvest years at Fox Creek, suggesting that summer low flows decreased after harvest. Harr hypothesizes that reduction of fog interception and drip is a possible cause of the lack of increase in annual yield and for the increases in number of low flow days at Fox Creek. Fog is common at the 840-1070 m elevation at Fox Creek and observations made by field crews reported precipitation under the forest canopy when no concurrent precipitation was recorded in rain gauges.

Harr (1982) subsequently also reported that net precipitation under the forest canopy at Fox Creek totalled 1739 mm during a 40-week period, 29% more than reported in the adjacent clearcut areas. When expressing data on a full water year basis, Harr suggested fog drip could have added 882 mm of water to total precipitation. The implications of his research suggest that cutting of stands which had contributed substantial amounts of fog drip to annual precipitation, will alter the amount of precipitation, offsetting reductions in evaporative losses, thereby reducing net water yield (Harr, 1982).

A further study of fog drip, water yield, and timber harvesting in the Fox Creek watershed by Ingwersen (1985) reports recovery water yields (6-13 years post-harvest). In the context of the fog drip phenomenon, he suggests that after 5 to 6 years of vegetation recovery, the form of vegetation usually has high foliar surface area which likely intercepts significant amounts of water including windblown fog. These vegetation species are not subject to re-interception loss and water likely reaches the ground surface. Therefore, a slow increase in water yields would result from re-introduced fog drip 'precipitation' and reduced water consumption from recovery vegetation.

### 2.3.4 Throughfall

Some of the precipitation, fog and cloud water intercepted by the forest canopy moves through the canopy to the ground. This water, known as throughfall, penetrates the canopy directly or drips from leaves, twigs and branches (Dunne and Leopold, 1978). This process delivers water to the forest floor.

Rothacher (1963) found storm size to be one of the most important factors influencing variation in throughfall in both the summer and winter. Average throughfall during the summer period was reported to be 76%, although he notes that the amount is subject to extreme variation associated with point sampling and variation in distribution of storm size.

In comparison, Rothacher also found that winter storms which occurred as continuous rainy periods of several weeks duration resulted in very high throughfall percentages. The relationship between gross precipitation and throughfall proved quite variable, and was attributed to characteristics of typical winter storms. Storms which exceeded 200 mm resulted in throughfall nearly equalling or exceeding amounts received in the open.

Crown density was also found to be associated with variations in summer throughfall. Generally, the denser the foliage, the greater its interception storage. Density refers not only to the top canopy, but also to the lower layers (Dunne and Leopold, 1978). The mean throughfall was related to mean density for the study area plots and regressed with a correlation coefficient of 0.87.

### 2.3.5 Evapotranspiration

Evapotranspiration is the term used to refer to the total loss of moisture from the soil and open water by evaporation and water loss from plants by transpiration. Harr (1979) notes that because so little energy is available for evaporation from soil under a dense forest canopy, most evapotranspiration is derived from transpiration.

Evapotranspiration rates vary according to vegetation type and duration of moistness (Hetherington, 1987). Transpiration rates from temperate coniferous and broadleaved forest can reach 0.8 mm/hr, with midday summer values of 0.3 mm/hr. Evapotranspiration is highest for conifers and broad-leaved evergreen species (25-55%) and lowest for broad-leaved deciduous species and from some broad-leaved evergreen species of *Eucalyptus* (10-35%) (McNaughton and Jarvis, 1983). The highest reported estimates of daily transpiration rates by individual trees in Canada are 16 litres/day for lodgepole pine in Alberta (Swanson, 1975) and 24 litres/day for young Douglas-fir in B.C. (Black et al. 1980). Higher rates are due to more extensive root systems, longer periods of transpiration and greater evaporation of intercepted precipitation (Calder, 1982). Evapotranspiration should be high in the coniferous forests of the Pacific Northwest region because of mild climates, frequent rainstorms, dense vegetation and the high degree of interception typical in conifer forest types.

The relative amounts of water transpired and evaporated over a year depend on the proportion of time that the canopy is wet (McNaughton and Jarvis, 1983). When the canopy is wetted by frequent small storms, evaporation of intercepted water is by far the larger evaporative component of the water balance and may be up to 2.5 times the loss through transpiration. These losses are smaller when the canopy is wetted by a few large storms. Where rainfall is seasonal, the largest losses of water take place when the rainfall is most prevalent (in the winter).

The frequency and average duration of canopy wetness are important determinants of the relative importance of interception and transpiration in the total evaporation from forest cover. Areas with high precipitation and high numbers of rain days show that evaporation of intercepted water can be 70% of the total evaporation (Pearce and Rowe, 1980).

The evaporation rates of intercepted water from the forest can reach as high as 0.9 mm/hr when the canopy is drying out after rainfall, but they are more commonly about 0.2 mm/hr at the low saturation deficits and net radiation levels that occur during rainfall (McNaughton and Jarvis, 1983). Transpiration rates are also determined by climatic factors and by physiological controls by the trees. Under conditions of limited soil moisture, the stomata of the leaf will close and slow down the rates of transpiration. Root depth is also a consideration because under these same conditions, plants with shallow root systems will transpire at rates below the potential evapotranspiration rate. Under conditions of abundant water supply/soil moisture, plants and trees will transpire at rates close to potential evapotranspiration rates. The deeper root systems will allow trees to transpire at higher rates because of higher moisture availability. As a result, however, soil moisture will deplete at a faster rate also (Dunne and Leopold, 1978).

Evaporation from the soil may increase after clearcut harvesting, but dry summers combined with wet, humid winters in the Pacific Northwest should result in relatively low soil evaporation rates after clearcut harvesting (Rothacher, 1970). Transpiration losses to the atmosphere are reduced after harvesting and are not matched by increased evaporation, the result being that soils remain wetter and more water is available for streamflow and groundwater recharge.

Transpiration losses are dependent on the amount of forest that is cut. Forest harvesting reduces transpiration losses in proportion to the reduction in stand density, with clearcutting causing the greatest net decrease. Evaporation from the exposed ground surface will increase but will still remain much less than the decrease in transpiration (Hetherington, 1981). Partial cutting will begin to reduce transpiration after more than 20% of the basal area is cut (Douglass, 1967). The root systems of remaining trees compensate partially for the removal of trees up to this level of cut. Slash burning will further reduce transpiration losses by destroying ground vegetation.

The reduced evapotranspiration losses will result in higher soil-moisture levels during the growing season. As the available storage capacity for soil water is decreased, a shorter soil-recharge phase for a storm of a given size and intensity results. Higher soil-moisture conditions may lead to increased runoff yield and runoff rate.

### 2.3.6 Water yield

Hibbert (1967) reviewed results from 39 catchment experiments throughout the world that studied the effects of logging on water yield and made the following generalizations:

1. Reduction in forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

In his review, Hibbert found that the first year response of water yield to forest harvesting ranged from 34 mm to more than 450 mm of increased streamflow. This large range reflects the diverse nature of the results and the complexity of the causal factors. Hibbert notes that the practical upper limit of yield increase appears to be about 4.5 mm/yr for each percent reduction in forest cover, but most treatments produce less than half this amount.

Bosch and Hewlett (1982) updated the review of basin experiments and noted that the impacts of logging on water yield and evapotranspiration from these studies support the first two generalizations summarized by Hibbert. However, the third generalization made by Hibbert has subsequently proven to be unfounded. All 94 basin experiments, with the exception of perhaps one, resulted in the increase of water yield with a decrease in forest cover or a decrease in water yield with increasing cover. From this review, it was found that there was a decreasing influence on water yield with forest type in this order; coniferous forest, deciduous hardwood, brush and grass cover. Values that were reported for changes in annual water yield with a 10% change in cover for the above forest types are: 40 mm, 25 mm and 10 mm respectively.

Changes in water yield are dependent on several factors: precipitation regime, forest type, proportion of forest cleared, basin size, soil moisture, soil type and depth. Water yield changes are greatest in regions of high precipitation but are shorter lived due to the rapid regrowth of vegetation. Therefore, in drier regions, changes in water yield tend to be more persistant because of the slow recovery of vegetation (Bosch and Hewlett, 1982).

Several studies conducted in the rain-dominated precipitation regime of coastal North America support the findings of Hibbert (1967) and Bosch and Hewlett (1982) (Figure 2.3-2). Rothacher (1970) found an increase in annual water yield of over 30% in a coastal Oregon watershed, with a mean annual precipitation of 230 cm and mean annual streamflow of 145 cm. Keppeler and Ziemer (1990) found post-harvest increases in Northwestern California of 7 to 34% of total annual flow volume after 67% of the timber volume was harvested. Harr (1979) reported increases in annual water yield of up to 62 cm after timber harvesting in six experimental watersheds in western Oregon and Washington.

The distribution of precipitation throughout the year has important influences on seasonal and annual increases in water yield changes. Approximately 75-85% of annual precipitation in the Pacific Northwest Region occurs in the winter period (October-March), mostly in the form of rain (Harr, 1983; Hetherington, 1982; Mahacek-King and Shelton, 1987). The largest increases in annual yields have been reported to occur during this period for watersheds in western Oregon. Lower transpiration rates combine with wetter soils requiring less moisture for recharge to allow a larger proportion of the precipitation to go to water yield (Harr, 1976). Harr also found summer increases to be small in absolute terms, but large in relative terms.

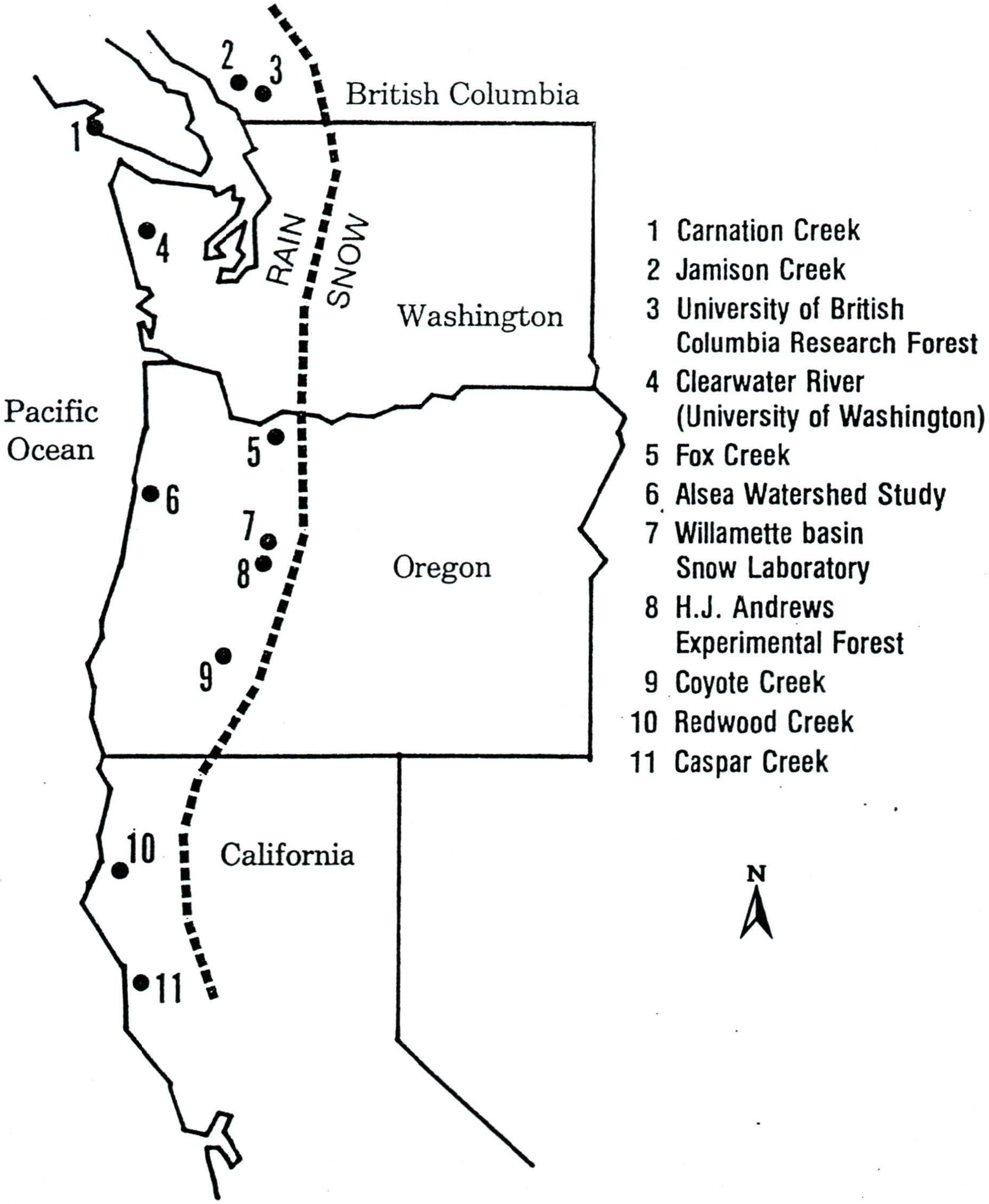

Figure 2.3-2 Research and experimental watersheds in the Pacific Northwest region (Harr, 1979)

Variation in precipitation from year to year influences the size of water yield increases after harvesting. The largest increases are expected to occur in the first post-harvest year. They may, however, be associated with precipitation maximums. Rothacher (1970) observed the largest annual water yield increase at H.J. Andrews was 56 cm higher than expected three years after harvesting and was related to two extreme runoff events.

Increases in water yield roughly conform to the proportion of forest cover removed (Rothacher, 1970). Data from patchcut and clearcut watersheds confirm that increases caused by vegetation removal are roughly proportional to the area cleared. Bosch and Hewlett (1982) give a hypothetical example where mean annual precipitation equalling 18 mm will result in an increase of 6 mm if one third the area is cleared. They also report, however, that reductions in forest cover of less than 20% apparently cannot be detected by measuring streamflow.

# CHAPTER 3
# RESEARCH LOCATION

## 3.1 Introduction

Descriptions of the physical and climatic nature of the Carnation Creek watershed are presented in this chapter. An overview of the Carnation Creek Experimental Watershed Project is included followed by a review of a preliminary analysis conducted on annual water yields 10 years post-harvest.

## 3.2 Study Area

The Carnation Creek watershed drains into Barkley Sound (48°54'N, 125°01'W) on the west coast of Vancouver Island (Figure 3.2-1). It is a small west-draining basin (9.5 km$^2$) with a mean elevation of 450 m, ranging from sea level (at the mouth of the creek) to about 880 m. Three named (C, J, and H) and three unnamed tributaries descend directly into or onto and across a short distance of flood plain before entering Carnation Creek (Hartman and Scrivener, 1990). Three other tributaries flow parallel to the main channel in the floodplain before joining the creek.

Topography in the watershed is steep and variable with side-slope gradients ranging between 40% to 80%. The valley walls are interrupted by bluffs and rock outcrops (Hartman and Scrivener, 1990). The main stream meanders through a wide valley bottom (Hetherington, 1982) (Table 3.2-1). Soils in the watershed have developed largely from the decomposition of local rock that has moved a short distance through glaciation and subsequent colluvial action (Oswald, 1982). Slope soils, underlain by impervious bedrock of volcanic origin, are composed of gravelly loam to loamy sand

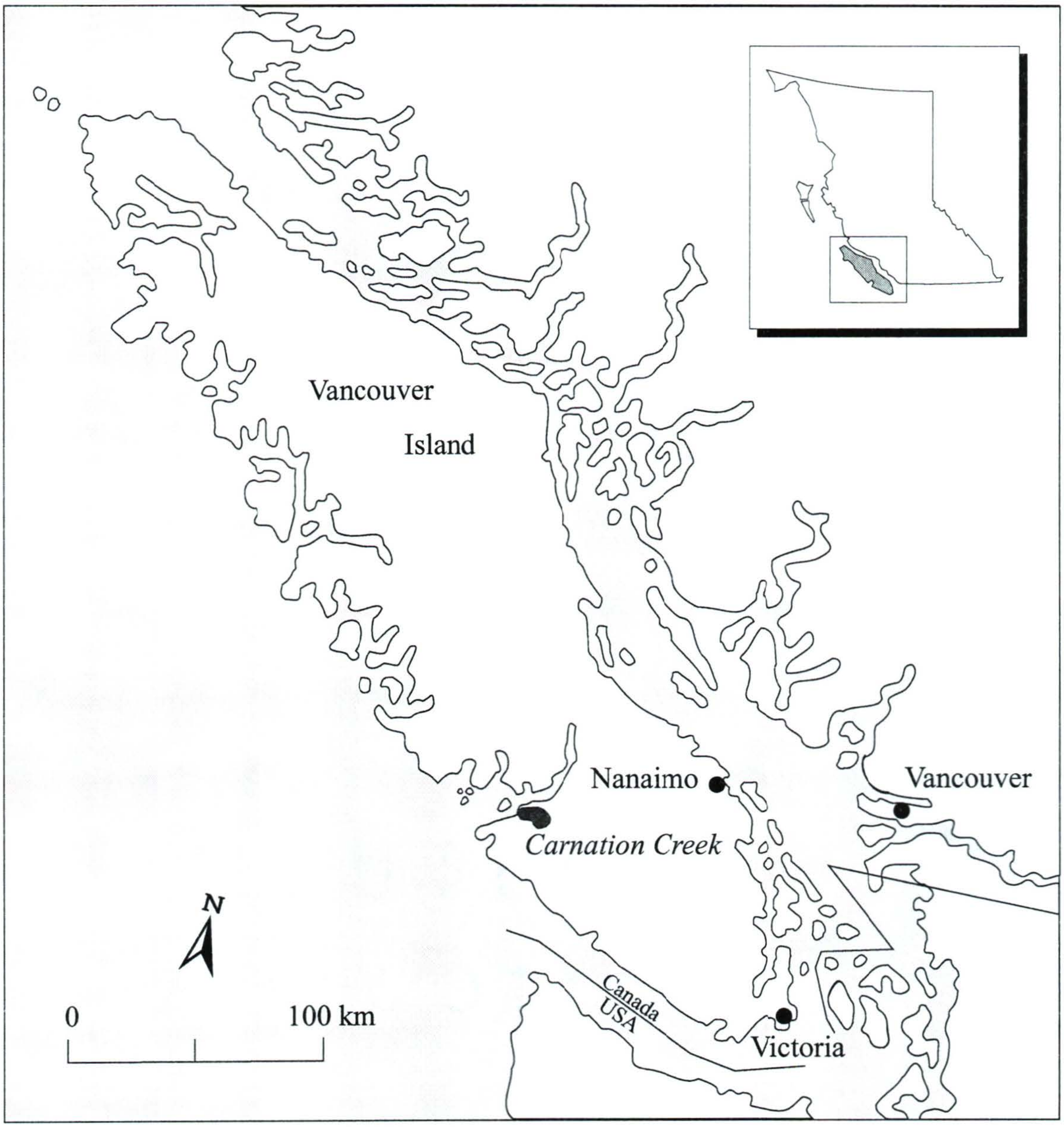

Figure 3.2-1 Location of the Carnation Creek watershed, British Columbia

Table 3.2-1 Watershed characteristics of Carnation Creek sub-drainages

| BASIN | MEAN ANNUAL RAINFALL (cm) | MEAN ANNUAL WATER YIELD (cm) | ELEVATION (m) | ASPECT | AREA (ha) |
|---|---|---|---|---|---|
| C | 324 | 198 | 30-880 | N | 145 |
| E | 384 | 300 | 180-825 | W | 265 |
| H | 321 | 233 | 140-200 | SE | 12 |
| J | 274 | 198 | 10-325 | SE | 24 |

with a moderately thick organic layer. They are classified as Ferro-humic Podzols (Oswald, 1973). Most sites have shallow soils (average depth 70 cm), that are highly permeable and remain moist year-round. Flood plain soils are composed of gravel, alluvial sands, lenses of sandy-clay and organics (Hetherington, 1982).

The climate of Carnation Creek is strongly influenced by prevailing westerly winds from the Pacific Ocean and by the local topography. This combination of factors results in mild, wet winters and cool, dry summers. Annual precipitation ranges from 200 cm to greater than 480 cm. Mean monthly precipitation ranges from 18 cm to over 52 cm, with over 75% of the precipitation occurring between October and March (Hetherington, 1982). Orographic lifting influences precipitation variation within the watershed, although frequent frontal storms during winter are the driving mechanism for precipitation to occur.

Carnation Creek lies within the Coastal Western Hemlock Biogeoclimatic Zone (Hartman and Scrivener, 1990). Before harvesting began in the drainage, vegetation included western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), amabilis fir (*Abies amabalis*), Douglas-fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*). Predominant shrubs in the watershed included salal (*Gaultheria shallon*), salmonberry (*Rubus spectabilis*), stink currant (*Ribes bracteosum*), and four species of *Vaccinium*.

## 3.3 Carnation Creek Experimental Watershed Project

The Carnation Creek Experimental Watershed Project was initiated in 1970 to study the impacts of clearcut logging on west-coast fisheries resources (Scrivener, 1987). The project consisted of three phases: pre-harvest calibration, harvesting and a post-harvest period. The pre-harvest calibration period lasted four years during which baseline data were collected to establish the biological and physical status of the basin. This period also included right-of-way falling and road building (Tables 3.3-1a and 3.3-1b). Harvesting began in 1976 when 41% of the basin was logged as thirteen cutblocks over a period of six years (Figure 3.3-1). Three different streamside treatments were designed. An undisturbed streamside treatment left a portion of the creek with a variable-width strip of deciduous vegetation and merchantable trees along the banks. An intense streamside treatment involved felling timber away from or across the stream channel and yarding to roadside landings. Streambanks and large debris in the channel were damaged. A careful streamside treatment left minor vegetation along the stream with the majority of the timber felled away from the stream. The post-harvest period was originally scheduled to last from 1981 to 1986. The study period was extended and is currently ongoing.

After harvesting, the cutblocks received a variety of silvicultural treatments (Dryburgh, 1982). Cutblocks were planted or allowed to restock naturally. Hartman and Scrivener (1990) summarize the post-harvest forest regeneration conditions. Three years post-harvest, three distinct layers of trees, shrub/herb and forb/moss had reappeared. Planted conifers (1 m in height) and red alder (2 m), salmonberry (0.6 m) and ferns were in existance. Five years post-harvest, planted conifers were 2 m tall and shrub cover ranged from 17 to 43%. Ten years post-harvest, vegetation cover (tree/shrub/forb) had recovered to 80-90% of the ground surface of Carnation Creek, which was equivalent to pre-harvest coverage.

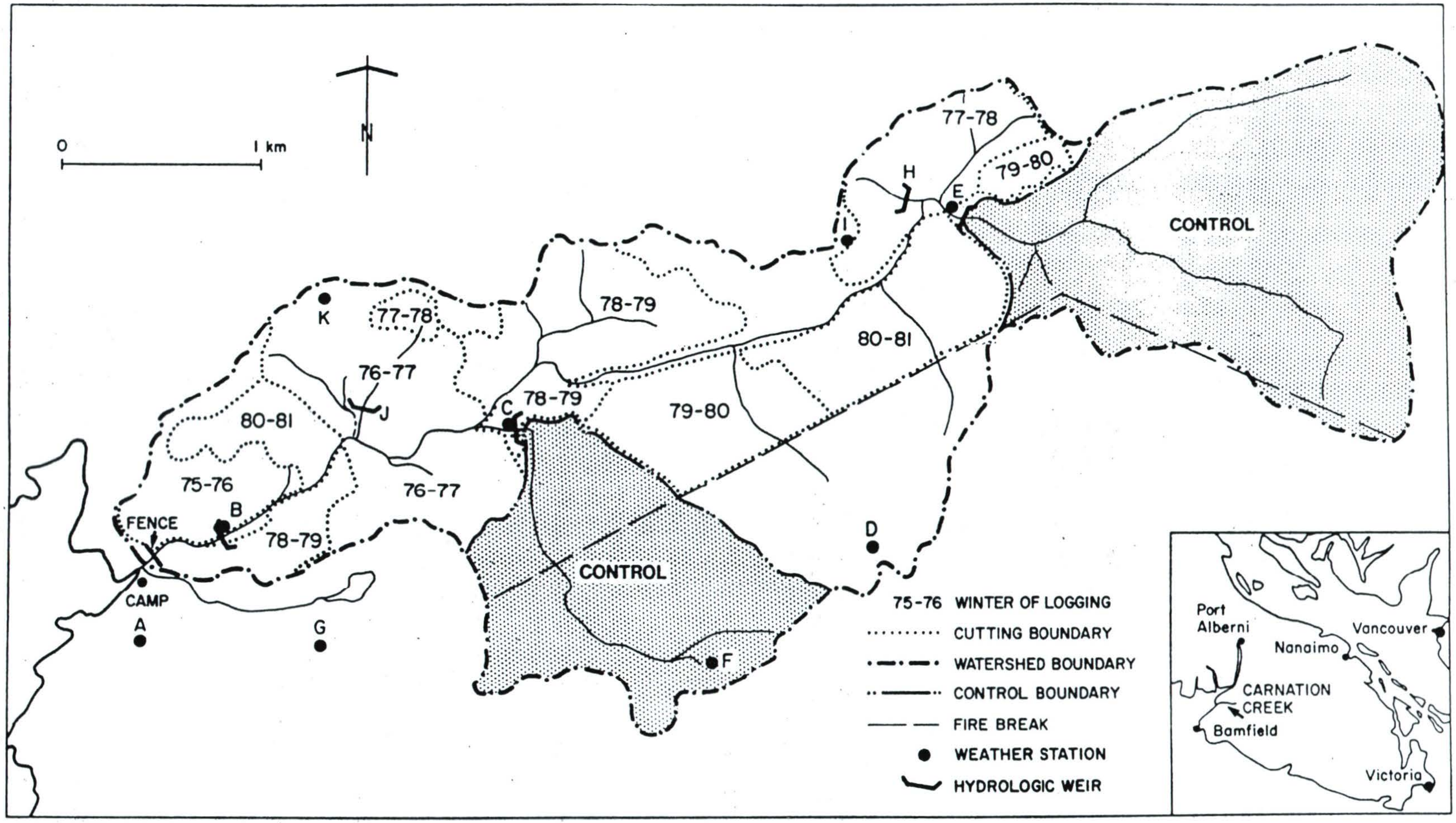

Figure 3.3-1 Hydrometeorologic stations and timber harvesting cutblocks in the Carnation Creek watershed (Hetherington, 1982)

Table 3.3-1a Carnation Creek forestry treatment history in H watershed

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pre-road | ▨ | ▨ | ▨ | | | | | | | | | | | | | |
| Right of way | | | ▨ | | | | | | | | | | | | | |
| Road | | | ▨ | ▨ | ▨ | | | | | | | | | | | |
| Falling | | | | | | ▨ | | | | | | | | | | |
| Yarding | | | | | | ▨ | | | | | | | ▨ | | | |
| Burn | | | | | | | ▨ | | | | | | | | | |
| Plant | | | | | | | | ▨ | | | | | | | | |
| Water Year | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |

Table 3.3-1b Carnation Creek forestry treatment history in J watershed

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pre-road | ▨ | ▨ | ▨ | | | | | | | | | | | | | |
| Right of way | | | ▨ | | | | | | | | | | | | | |
| Road | | | ▨ | ▨ | ▨ | | | | | | | | | | | |
| Falling | | | | | ▨ | ▨ | | | | | | | | | | |
| Yarding | | | | | ▨ | ▨ | | | | | | | | | | |
| Burn | | | | | | ▨ | ▨ | | | | | | | | | |
| Plant | | | | | | ▨ | ▨ | ▨ | | | | | | | | |
| Water Year | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |

### 3.4 Review of Preliminary Analysis

Data collection at Carnation Creek was initiated in 1971 and is ongoing. Streamflow data were collected from 5 sites within the watershed (Figure 3.3-1). Continuous records of water levels were collected throughout the period of record using Stevens water-level chart recorders (Hartman and Scrivener, 1990). Stage-discharge curves were used to convert water levels to streamflow. Data from the Stevens chart recorder were digitized by the Department of Fisheries and Oceans and by Water Survey of Canada.

Preliminary analyses have been conducted on annual water yields from all weirs and quantitative comparisons of post-harvesting data to pre-harvesting data have been completed to 1987 (Hartman and Scrivener, 1990; Hetherington, 1982). These analyses identified increases in annual water yield from H watershed of 16% and 9% relative to control watersheds C and E, respectively. Watershed J yielded 24% more water from water years (October - September) 1976 to 1986 relative to watershed C. Post-harvest results between watersheds J and E were not available.

Changes in water yield measured at B weir (main stream) were variable and more difficult to detect (Hartman and Scrivener, 1990). Decreases in annual water yield from B weir of 14.8 and 24.5 cm occurred in relation to control watersheds C and E, respectively, during the logging period. Increases in annual water yield of 23.5 cm in relation to watershed C and 1.0 cm in relation to watershed E were observed after logging. The accuracy of low flows at B weir was questionable because of the problem of bedload movement downstream and dewatering the channel, subsequently affecting water level measurements at B weir (Hetherington, *personal communication*, 1993).

These increases in annual water yield have been attributed to reduced transpiration and interception losses from timber harvesting. The assumption was that these changes left more water available for streamflow (Hartman and Scrivener, 1990).

Decreases in annual water yield at B weir were initially attributed to reduced fog interception (fog drip) by the forest canopy (Hetherington, 1982). This interpretation was, however, subsequently discounted (Hetherington, 1987).

Precipitation data are available for 12 sites within the watershed (Table 3.4-1). Data were collected using M.S.C. tipping bucket (recording), Belfort weighing (recording), Sacramento, and standard measuring rain gauges (Hartman and Scrivener, 1990). Data from Sacramento storage gauges were collected weekly for low-elevation stations and monthly for high-elevation stations. Sixteen additional stations were installed for water year 1989-90 to assess areal variations in precipitation (Hetherington, *personal communication*, 1991).

Table 3.4-1 Long-term precipitation stations in the Carnation Creek watershed

| STATION | PERIOD OF RECORD | ELEVATION (m) |
|---|---|---|
| A | 1971-1989 | 55 |
| B | 1971-1989 | 8 |
| C | 1972-1989 | 27 |
| D | 1972-1989 | 685 |
| E | 1972-1989 | 150 |
| F | 1971-1989 | 450 |
| G | 1972-1989 | 120 |
| H | 1976-1989 | 150 |
| I | 1972-1989 | 315 |
| K1 | 1975-1983 | 305 |
| K2 | 1978-1989 | 290 |
| L | 1982-1989 | 640 |

Precipitation data from Station A, the principal weather station for the project, were published by Environment Canada, Atmospheric Environment Service. Total monthly precipitation at this station was approximately five times greater from the period November to March than from June to August. Mean minimum monthly precipitation was approximately 7 cm for summer months (July-August) and the mean maximum monthly precipitation was over 40 cm for winter months (November-March). Unpublished results are available from a preliminary kriging analysis conducted on the data from the sixteen additional stations (Hetherington, *personal communication*, 1992).

# CHAPTER 4
# METHODS

## 4.1 Introduction

The methods used in preparing and analysing the Carnation Creek data sets are described in this chapter. Data sets used in the analysis included precipitation, interception, evapotranspiration, water yield, air temperature, solar radiation and potential evapotranspiration (PET). Data available on an annual, seasonal and monthly basis include precipitation, water yield, air temperature, solar radiation and PET. Annual and seasonal totals for precipitation and water yield were summed from monthly values. Annual and seasonal values are available for interception and annual values only for evapotranspiration. Annual water yield is expressed on a water year basis (October 1-September 30). Seasonal water yields are divided into wet (October 1-March 31) and dry (April 1-September 30) periods.

The analysis of water yields was based on the paired basin method which compares a treated watershed to a control watershed (Hewlett and Pienaar, 1973). Comparisons are made between treated sub-basins H and J and control sub-basins C and E within the Carnation Creek watershed. The period of interest for this data set is 1972-1989. Pre-harvest data exist for water years 1972-1975 for H watershed and for the period 1974-1975 for J watershed. The post-harvest period is 1978-1988 for H and J watersheds. Problems with C weir during water year 1989 precluded the use of these data in the analysis.

Analysis of water yields was excluded for B weir, which would present results on the effects of timber harvesting 40% of the entire watershed. Problems with gravel movement at the weir limited the accuracy of summer low flow measurements (Hetherington, *personal communication*, 1993). Excluding B weir data from the analysis maintains a method consistent with that of the paired basin experiment.

Annual water yields were analysed to determine the effect of timber harvesting on a yearly basis. Seasonal and monthly water yields were analysed to gain an understanding of when the expected changes in annual water yield take place throughout the year.

Forest hydrology processes are dependent on many different climatic factors which have seasonal variations. Few studies in the Pacific Northwest (Harr, 1979; Rothacher, 1970) have investigated annual yields at the seasonal and monthly level.

In collecting and preparing data for analysis, it is important to recognize the limitations of the data set. In this study these exist because the present analysis was not part of the original study objectives. Determining the number and location of precipitation and stream gauging stations is dependent on the purpose of a study and the cost of installing and maintaining the network. At Carnation Creek, the primary purpose of the study was to evaluate logging impacts on fisheries resources. Therefore, the hydrometeorological data collected were for that purpose.

## 4.2 Precipitation

Precipitation data were collected from eight stations in operation since 1972. Of these, three are low elevation stations and five are mid- to high-elevation stations. Although the network density is high for the basin (Linsley et al., 1988), the distribution and period of record are unbalanced. The majority of stations are located in the lower third of the basin, while a few of the higher elevation stations were installed at a later date (K1, K2, and L, respectively).

Sacramento gauge data were used in the analysis because they represented a more accurate catch when precipitation at higher elevations fell as snow. Annual precipitation totals were adjusted for most years by Hetherington (*personal communication*, 1993) to account for snowfall accumulations. However, annual values were not adjusted for stations A, C, G, I, K1, and K2 for 1971-72, 1978-89, and 1979-80 for all stations. Station D values were left unchanged for 1973-74, 1975-76, 1979-80 and 1990-91 while those for remaining years were replaced by station C values multiplied by 1.17. Station E data were left unchanged for all years except 1974-75 and 1977-78. Station F data were replaced with station C values multiplied by 1.24 except for 1973-74, 1975-76, 1977-78, 1979-80 and 1982-83. All values for station L were replaced with adjusted station F totals multiplied by 1.09 (Hetherington, *personal communication*, 1993). Precipitation is reported in centimetres (cm) as depth over the watershed.

Statistical tests were performed on the precipitation data to determine whether there were differences between pre-harvest and post-harvest periods. As control watershed E is geomorphologically difference from control watershed C, a paired t-test was conducted to determine whether the mean difference is statistically different from zero.

### 4.2.1 Estimating missing data at station L

The period of record for station L begins in 1982, which is the shortest period of record (7 years) of the long-term climate stations in Carnation Creek. Monthly precipitation for station L was estimated for water years 1972-1981 using station C data. Measurements collected at station C are considered reliable (E. Hetherington, *personal communication*, 1993) and were not changed or adjusted for the 17-year period of record.

The following method was used to estimate the missing data:

- data from stations C and L were compared during the period 1982-1989 when both stations were in operation
- mean monthly precipitation was calculated for stations C and L for each month for the 8-year period
- as the data gap for the period of interest was so large (1972-1981), the mean monthly precipitation for this period at station C was calculated to determine how the monthly means for each time period compared (1972-1981 to 1982-1989)
- monthly precipitation for 1972-1981 at station L was then estimated by dividing the monthly station C precipitation value for the water year in question by the mean monthly station C value when both stations were in operation (1982-1989)
- the station C value was then multiplied by the mean monthly value for station L when both stations were in operation (1982-1989)

Example:

$$\text{October 1972 } (L_{est}) = \frac{\text{October 1972 (C)}}{\text{October 1982-1989 (C)}} * \text{October 1982-1989 (L)}$$

$$(L_{est}) = \frac{5.33}{31.81} * 42.08$$

$$(L_{est}) = 7.05$$

### 4.2.2 Monthly precipitation

To account for the underestimation of monthly precipitation due to the lack of snow measurement and wind effects, monthly values at station F were adjusted for months in which snow fell (November-March).

Monthly values for station F were left unchanged for 1973/74, 1975/76, 1977/78-1979/80 and 1982/83. The rest were replaced by the following method:

- for each year, the months with no snow were summed
- this value was subtracted from the adjusted annual precipitation value giving the estimated winter precipitation (November-March)

- the actual precipitation which fell during November-March was summed and subtracted from the estimated value giving an estimated amount of snowfall
- the estimated snowfall was divided by the number of months in which snow fell (5), assuming the amount of undercatch is consistent from year to year, and added to each month

### 4.2.3 Isohyetal analysis

Mean annual precipitation was estimated for each sub-basin (C, E, H, and J) using the isohyetal method. Additional precipitation data collected during 1989-90 were used to define the areal pattern. Average precipitation over the sub-basins was determined by drawing, on a map of the watershed, lines of equal precipitation (isohyets) based on existing station locations, precipitation amounts and the additional 1989-90 results. The average precipitation for each sub-basin was then calculated by measuring the area between isohyets, using a manual planimeter. This value was multiplied by the average precipitation between isohyets, and then dividing the sum of these products by the total area (Gray, 1970). This method is considered to be the most accurate technique of averaging precipitation over an area (Linsley et al., 1988) and takes into account orographic effects.

### 4.2.4 Double-mass analysis

Double-mass analysis was performed on the precipitation data to identify any changes in precipitation catch. The analysis compared the accumulated annual precipitation from the Sacramento base stations within the watershed with the concurrent accumulated values of mean precipitation from a group of surrounding regional climate stations. Changes in catch detected by this analysis are shown by a break in slope on a graph which can be the result of change in exposure, instrumentation or observer error (Chow, 1964) (Figure 4.2-1). A paired t-test was performed on the climate station data to determine if the mean difference between regional climate stations and stations in the Carnation Creek watershed were significantly different from zero.

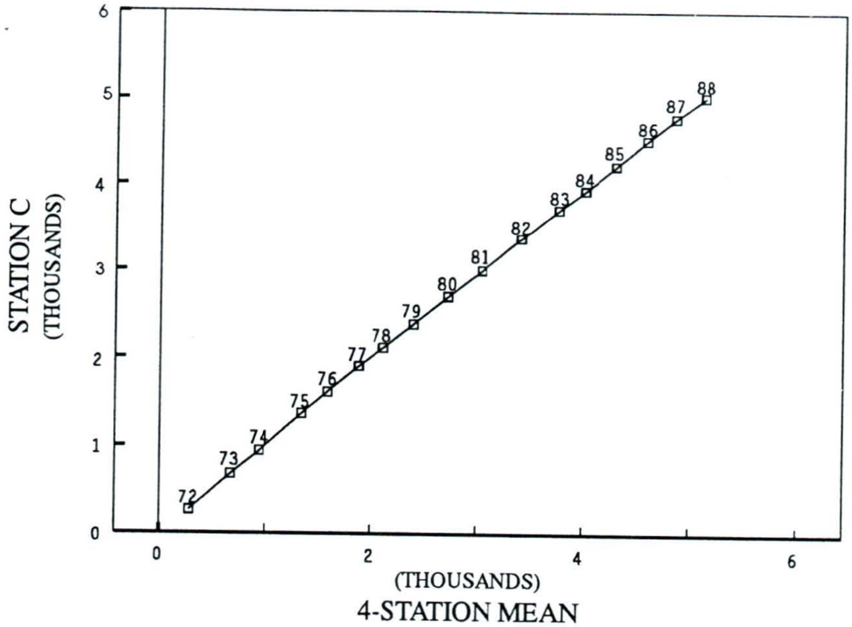

Figure 4.2-1 Double mass analysis comparing Station C to four-station mean, 1972-1988

Four regional climate stations monitored by Environment Canada were selected for this analysis based on proximity to the watershed and similar precipitation patterns (Figure 4.2-2). Cumulative values from regional stations were plotted on the X axis against the cumulative value of the specific watershed precipitation station on the Y axis. Some deviation along the mean line was expected, therefore, a paired t-test was performed on these data sets to determine if precipitation patterns and breaks in slope were significantly different. The regional climate stations used in the analysis were Ucluelet, Bamfield, Pachena Point, and Carmanah Point.

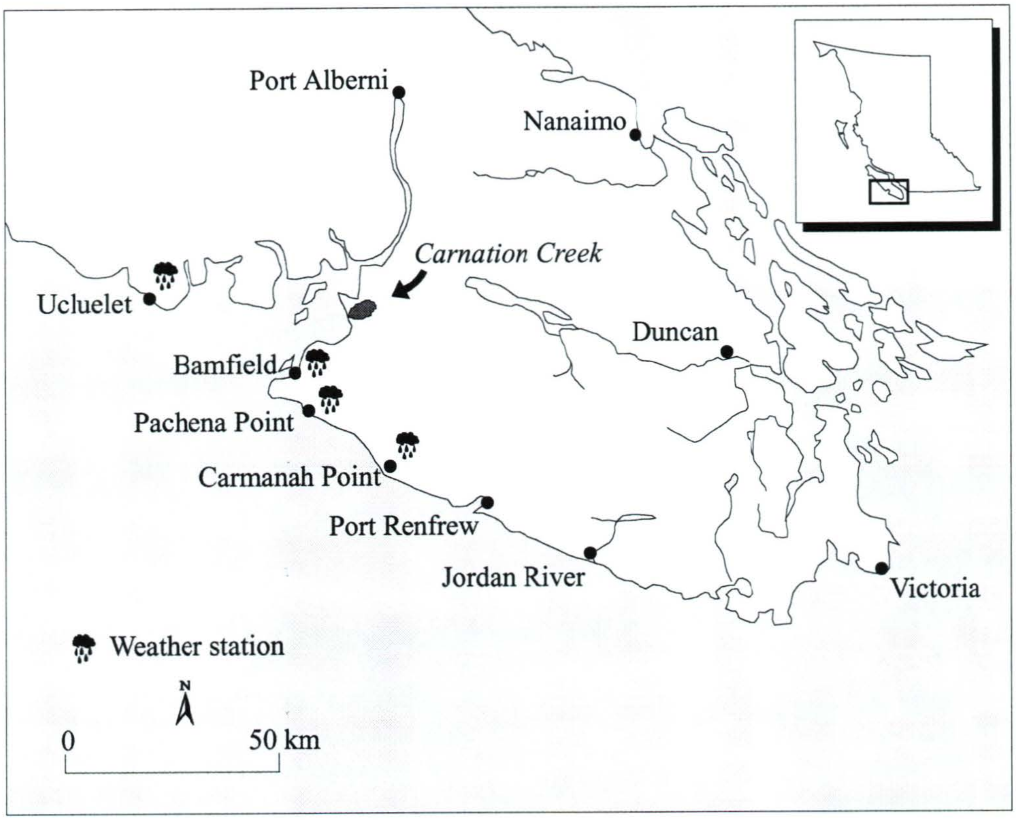

Figure 4.2-2 Regional climate stations

### 4.2.5 Precipitation-water yield relationships

To establish pre-harvest and post-harvest precipitation-water yield relationships between control and treated watersheds, line graphs of precipitation and water yield were plotted and overlain to compare temporal patterns on an annual and seasonal basis. Linear regression analysis was performed on annual and seasonal pre-harvest and post-harvest data and plotted to compare differences between the watershed treatments.

## 4.3 Interception and Fog Drip

Interception data were collected by E. Hetherington at a study site near station G. Two specially constructed trough rain gauges were placed under the forest canopy, three more standard type gauges were located in an adjacent clearcut, and one standard gauge was situated in a forested opening. All of the gauges were located at approximately 175 m on the same north-facing slope. Data were collected on a weekly basis from 1983-1989.

The interception data collected were separated into two periods:

- times when precipitation in the open was greater than precipitation under the canopy (assuming no fog drip)
- times when precipitation in the open was less than or equal to precipitation under the canopy (fog drip occurrence)

Fog drip was assumed to have occurred when precipitation under the canopy was greater than precipitation in the open. The difference between precipitation measured in the open and precipitation measured under the canopy represents net interception.

### 4.4 Evapotranspiration

Mean annual evapotranspiration was computed for each sub-basin for all years using the water budget method. This method computed evapotranspiration as the difference between mean basin precipitation and annual water yield. This water budget method assumes the change in water storage in a basin over the period of interest is negligible (Linsley et al., 1988). Based on this assumption, evapotranspiration was not investigated on a monthly or seasonal basis.

A regression equation was developed for the pre-harvest calibration period for annual evapotranspiration using data from weirs H and J as the dependent variables and data from weirs C and E as the control or independent variables. The regressions were developed using four observations for variables C, E, and H; and two observations for J. Post-harvest changes in evapotranspiration were calculated as the difference between the estimated and observed values. These values were then compared and evaluated to corresponding changes in annual water yields.

### 4.5 Water Yield

Water yield data were collected from five hydrologic stations, four in operation since 1972 and one (J weir) since 1975. Weirs were sited at the mouths of each main tributary and the mainstem. This network is suitable for the objectives of the study as all major sub-drainages have been monitored.

Monthly water yields were summed by water year (October-September) for weirs C, E, H, and J and all years (1972-1988) to develop an annual value. Wet and dry season water yields were developed by summing monthly water yields October-March and April-September, respectively. Water yields were reported as runoff values (cm) over the watershed to allow comparisons between sub-drainages within the basin.

Regression analysis was used to establish pre-harvest calibration equations for annual, seasonal, and monthly water yields using data from weirs H and J as the dependent variables and data from weirs C and E as the control or independent variables. The calibration regressions used data from water years 1972-1975 for all weirs except J weir where calibration regressions used data from 1974 and 1975. Water yield for water year 1974 at J weir was derived from measurements taken on J creek by Dr. Eugene Hetherington prior to the establishment of J weir (Hetherington, *personal communication*, 1995).

For each water yield variable, the regression equation was used to compute what the predicted water yield would have been in the treated basins had the timber not been harvested. The difference between the observed and predicted water yields was calculated and the results were then evaluated relative to changes in forest cover.

Statistical tests were conducted on the data to determine whether changes in water yield were significant. As timber harvesting was expected to increase annual water yields, a one-tailed t-test was performed on the difference of means to determine if pre-harvest and post-harvest runoff values are statistically different from zero. Paired t-tests were run on the data to determine whether water yields at control watershed E were statistically different from water yields at control watershed C. This test was also applied to the treated watersheds, H and J, relative to C. The significance of the regression models was also tested using an F test. As the F statistic is the ratio of explained to unexplained variance, higher F ratios will indicate higher proportions of explained variance (Shaw and Wheeler, 1985).

### 4.6 Climatic Variables

Other climatic variables collected during the period of interest included air temperature and solar radiation. These variables were used in the calculation of potential evapotranspiration.

Air temperature and solar radiation data were collected between water years 1972 and 1990. Air temperature was measured at four sites in the watershed (stations A, C, D, E) (Figure 3.2-1). Mean monthly values were developed from daily measurements and averaged to create annual and seasonal means. Solar radiation was measured at one site in the watershed, station A. Mean monthly values were calculated from daily totals and summed for annual and seasonal totals.

Potential evapotranspiration data were provided by Dr. Eugene Hetherington. Annual potential evapotranspiration values were derived using the Priestly-Taylor equation with estimates of evaporation of intercepted rainfall for rainy days (Spittlehouse and Black, 1981). Station A meteorological data (air temperature, solar radiation, relative humidity) were used to compute daily transpiration. Daily interception evaporation losses were derived using a relationship developed from rainfall interception data collected near Station G. Annual totals were calculated by summing the daily values. These variables were plotted as line graphs and used as additional interpretation tools in evaluating post-harvest changes in annual water yields.

# CHAPTER 5
# RESULTS

## 5.1 Introduction

Observations made from comparisons of the hydrometeorological data from harvested and control watersheds are included in this chapter. Hydrometeorological data include precipitation, interception, evapotranspiration and annual water yield. Other climatic variables investigated were air temperature, solar radiation and potential evapotranspiration (PET). Spatial and temporal variations in the data are examined on an annual, and where not restricted by data limitations, seasonal and monthly basis.

## 5.2 Precipitation

### 5.2.1 Isohyetal analysis

Mean annual basin precipitation and the spatial variation within each sub-basin were derived from the isohyetal map (Figure 5.2-1). This analysis shows mean annual basin precipitation of 324 cm, 384 cm, 321 cm and 284 cm for sub-drainages C, E, H and J respectively.

Precipitation gradients appear to be strongly influenced by orographic uplift within the watershed. Mean annual precipitation ranges from approximately 285 cm near the mouth of the creek to over 400 cm at the eastern boundary of the watershed. The watershed has a relatively wide valley bottom below 100 m elevation, where mean annual precipitation does not exceed 290 cm. Within each sub-basin, spatial variations indicate a general trend of increasing precipitation with increasing

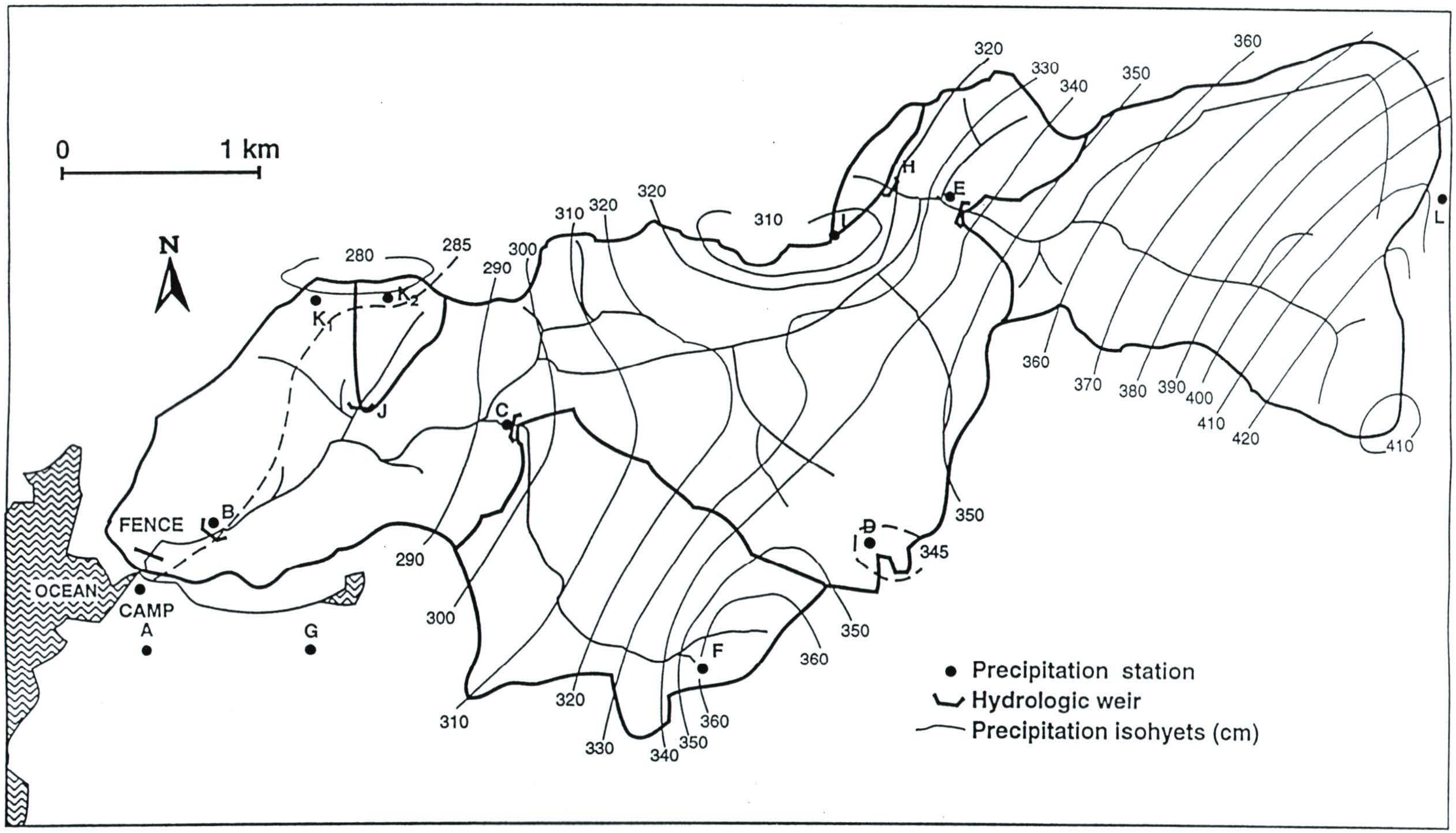

Figure 5.2-1 Isohyetal map of the Carnation Creek watershed

elevation. The exceptions to this, as noted in Section 5.2.1, are pockets of lower precipitation along ridges where it is likely that wind effects have altered the catch. C and E watersheds have steep slopes, extending up to 800 m, and show a clear orographic effect. H and J watersheds do not exhibit a strong precipitation-elevation relationship. This is likely due to the small elevation range in H and wind effects in J watershed where raindrop trajectories are spread as wind accelerates over ridges.

Average basin precipitation was determined for annual, seasonal and monthly basis using ratios developed from data for rain gauges representing each of the sub-basins and basin mean annual values derived from the isohyetal map (Table 5.2-1). Although the isohyetal analysis was not carried out on seasonal and monthly precipitation data, the assumption was made that similiar precipitation patterns would be exhibited for these time periods as storm processes affecting the watershed throughout the year are similar (Maunder, 1968).

Table 5.2-1 Precipitation ratios developed from isohyetal analysis

| WATERSHED | EQUATION |
|---|---|
| C | 0.60(C) + 0.40(F) |
| E | 0.20(E) + 0.80(L) |
| H | 0.50(E) + 0.50(I) |
| J | 0.95(C) |

Mean annual basin precipitation derived from the isohyetal analysis was highest in water year 1975 for all sub-drainages. The lowest amount of precipitation occurred in water year 1978 for all sub-drainages except H, which showed minimum basin precipitation in water year 1984.

Mean seasonal precipitation for all sub-basins reflected October-March influences on annual precipitation as maximum and minimum values also occurred in water years 1975 and 1978. Precipitation maximums for all sub-drainages appear to be driven by October and November values as almost 40% of annual and 50% of wet season maximums occur in these months.

Precipitation minimums are the result of consistently low rainfall between October-March, with the exception of above average precipitation in February, 1978. Dry season precipitation maximums, although not reflected in annual totals, occur in water year 1980 for all sub-basins where April and June totals account for 55-58% and 83-88% of seasonal maximums and means, respectively. Precipitation minimums occurred in water year 1981 (C and J) and 1988 (E and H). Monthly precipitation in all sub-drainages follows the temporal distribution as shown in Figure 5.2-2.

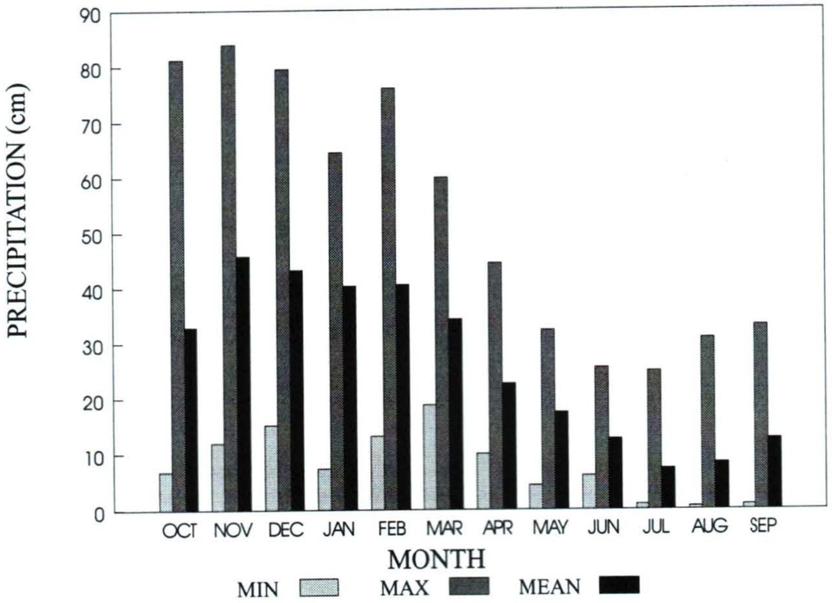

Figure 5.2-2 Mean monthly precipitation in H watershed, 1972-1988

### 5.2.2 Double-mass analysis

Regional weather stations used in the analysis exhibited the same temporal distribution of precipitation as stations in the watershed. Observations from this analysis indicated no significant shifts in gauge catch at Carnation Creek stations as compared with regional stations for the period of record, as illustrated by the example in Figure 4.2-1. Although some deviation existed along the mean line, a paired t-test indicated no significant difference between precipitation values. Therefore, the data were used without further adjustments.

### 5.2.3 Annual precipitation

Mean annual precipitation estimated from measured catch throughout the watershed was approximately 300 cm ranging from a minimum precipitation of 125 cm at Station K1 in 1978 to an estimated maximum precipitation of 530 cm at Station L in 1975. Spatial variations in precipitation are due to differences in site location and elevation.

Precipitation generally increases with elevation although in the Carnation Creek watershed, wind effects appear to be alter this relationship. This climatic effect is best illustrated by three pairings of weather stations in the watershed. Station D (elev. 685 m), the highest elevation station located on the top of Mt. Blenheim, recorded lower amounts of precipitation than Station E (elev. 150 m), located in the valley. Station I (elev. 315 m), also located on a ridge, has historically measured lower precipitation than Station E (elev. 305 m). The third pair of stations is K1 (elev. 305 m) and K2 (elev. 290 m), where K1 recorded less precipitation than K2, which was located in a more sheltered site at a slightly lower elevation (Hetherington, *personal communication*, 1993).

The temporal distribution of annual precipitation and precipitation means for both pre-harvest and post-harvest periods are shown in Figures 5.2-3 and 5.2-4. The temporal distribution varied throughout the period of interest with all stations in the watershed

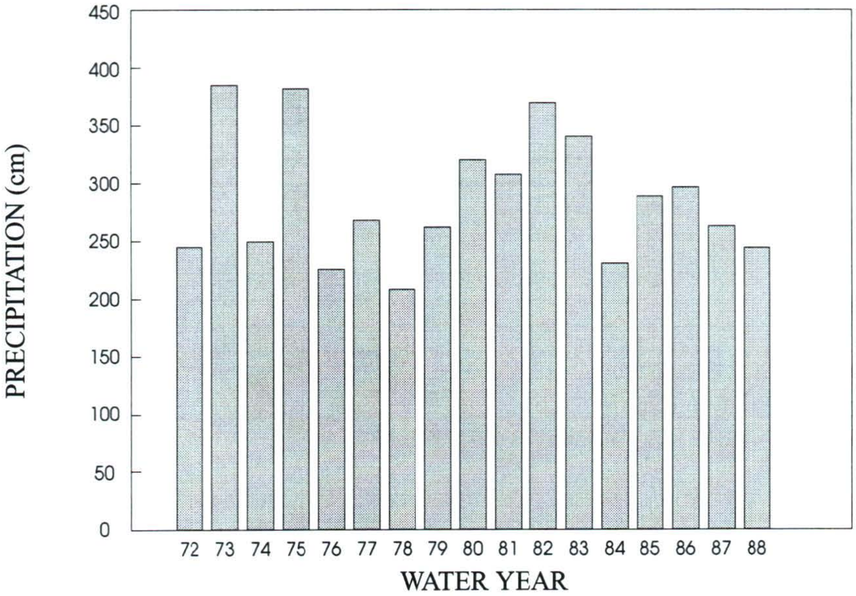

Figure 5.2-3 Mean annual precipitation for Station A, 1972-1988

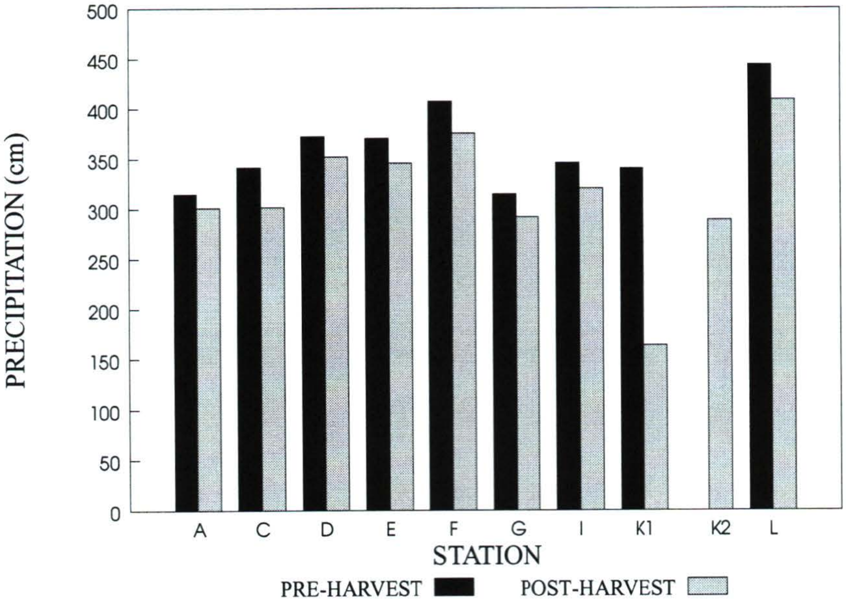

Figure 5.2-4 Mean annual precipitation for climate stations in the Carnation Creek watershed during pre-harvest and post-harvest periods

exhibiting similar temporal variations as shown by Station A. Pre-harvest precipitation annual means are 5-13% higher than post-harvest precipitation annual means, primarily due to higher than normal precipitation during water years 1973 and 1975 (Figure 5.2-4). Pre-harvest precipitation was found to be significantly higher than post-harvest precipitation in all four sub-basins.

### 5.2.4 Seasonal precipitation

All stations in the watershed showed similar temporal variations in monthly precipitation from which seasonal values were derived (Section 4.1). Therefore, a subset of stations was chosen to facilitate discussion. Stations chosen are those representing each of the treated and control sub-basins and having a period of record of 18 years with the exception of Station L. These include Stations C, F, L, I and E.

Seasonal precipitation is broken into two periods: a wet season from October-March and a dry season from April-September (Harr et al., 1979). Approximately 75% of annual precipitation occurred during the wet season (Figure 5.2-5). Maximum and minimum precipitation for all stations occurred in pre-harvest water year 1975 and post-harvest water year 1978, respectively.

The remaining 25% of annual precipitation falls during the April-September dry season. Mean dry-season precipitation was 80 cm ranging from a minimum of 50 cm at station C in 1981 to a maximum of 130 cm at Station L in 1980. Maximum dry-season precipitation occurred in 1980 for all stations, while the minimum occurred in both 1981 and 1988. Spatial variations in precipitation follow patterns as described under Section 5.2.1. Variation between stations in the wet season is greater than in the dry season.

Temporal distributions of precipitation differ between seasons. Wet-season precipitation closely follows that of annual precipitation as described above. Figure 5.2-6 shows the yearly distribution of dry-season rainfall during the period of interest

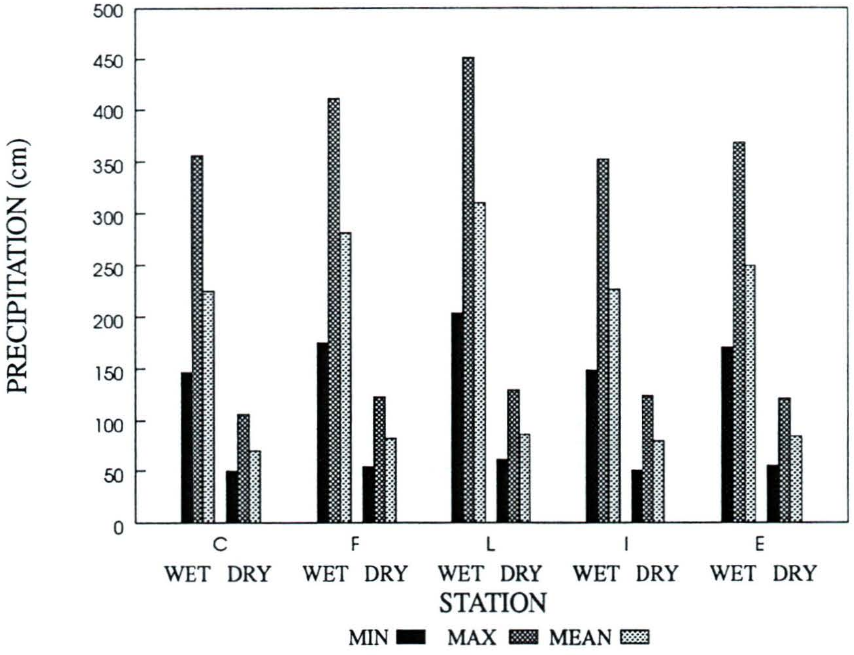

Figure 5.2-5 Minimum, maximum and mean seasonal precipitation for five climate stations in the Carnation Creek watershed

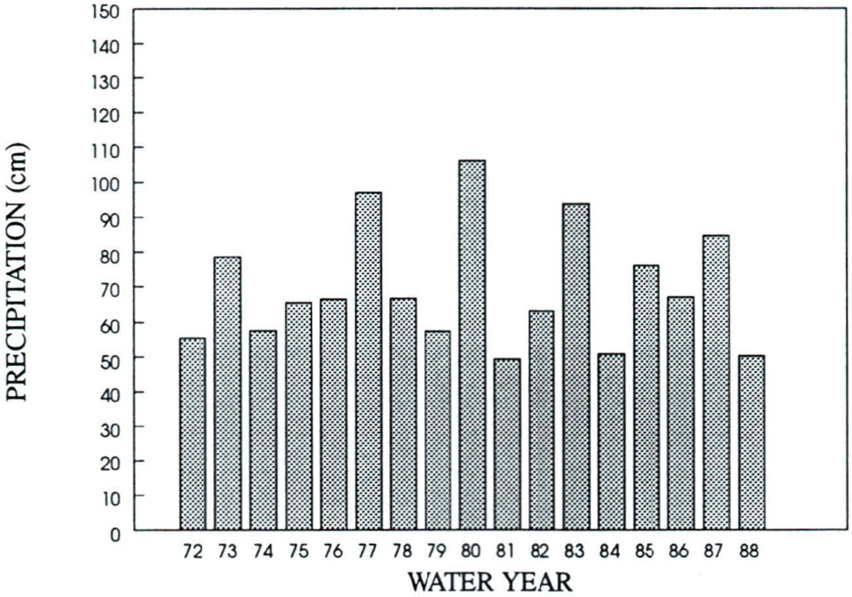

Figure 5.2-6 Temporal variation in dry season (April-September) precipitation at Station C, 1972-1988

was more variable. Cyclical trends are closer together with higher than average rainfall occurring every two or three years. Differences were observed seasonally between pre-harvest and post-harvest periods. Mean rainfall was 13-19% higher during the October-March pre-harvest period, while dry-season precipitation was 13-20% higher during the post-harvest period (Figure 5.2-7). Both wet- and dry-season precipitation values are statistically significant.

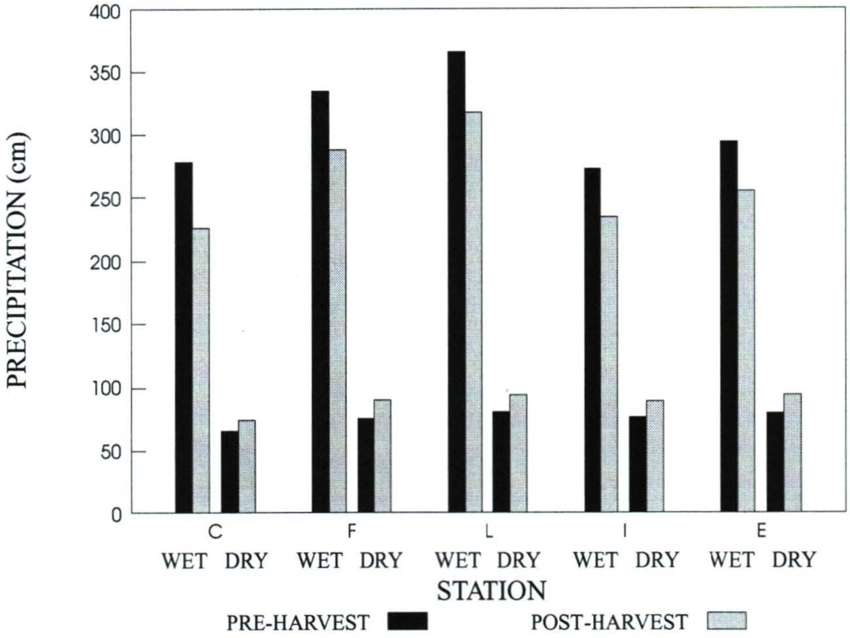

Figure 5.2-7 Mean seasonal precipitation for five climate stations in the Carnation Creek watershed during pre-harvest and post-harvest periods

### 5.2.5 Monthly precipitation

Annual and seasonal totals are based on monthly precipitation values. November, December and January account for 42% and over 50% of mean annual and wet-season precipitation, respectively. In comparison, June, July and August account for only 8% of annual and 35% of dry-season precipitation.

Minimum monthly precipitation values generally occur in July and maximums in November at lower elevations and in December at higher elevations. Adjusted maximum monthly precipitation of 105 cm occurred in November at station F (1975) and minimum monthly precipitation of 0.30 cm in July at Station E (1988). Mean monthly precipitation ranges from 5 cm in July to 62 cm in December for all stations.

### 5.2.6 Precipitation-water yield relationships

#### 5.2.6.1 Annual precipitation and water yield

Precipitation and water yields were closely related in all sub-basins as characterized by the two wet (1973, 1975) and two dry (1972, 1974) pre-harvest years (Figure 5.2-8). Mean annual water yields were 69% of precipitation for C, H and J watersheds compared to 78% for E watershed. The water yields at E basin are significantly higher than the water yields at the other basins.

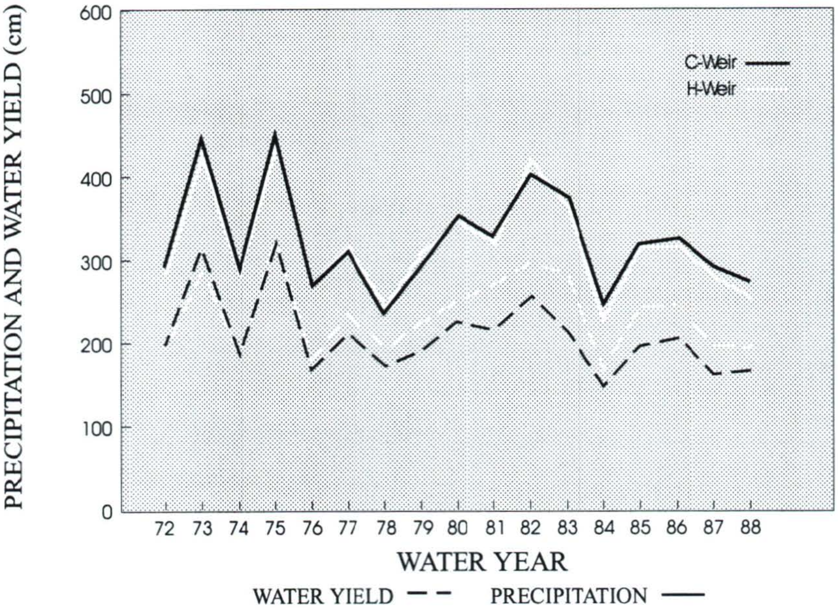

Figure 5.2-8 Temporal distribution of annual precipitation-water yield in C and H watersheds, 1972-1988

Annual precipitation and water yield were most similar between C and H watersheds. Differences in water yield were observed between control C-weir and treated H-weir during the post-harvest period. In the pre-harvest period, precipitation was similar in both C and H watersheds and this was reflected in the water yields recorded at the respective weirs. However, after harvesting, although precipitation remained similar in these watersheds, water yields at H weir were higher than at C weir.

Regression analysis of precipitation and water yield conducted on pre-harvest and post-harvest periods for both control and treated watersheds supports this difference (Figures 5.2-9 and 5.2-10). J-weir also exhibited a similiar pre-harvest precipitation-water yield pattern to C-weir. Differences in water yields were observed during the post-harvest period in this basin as shown by Figures 5.2-11 and 5.2-12.

### 5.2.6.2 Seasonal precipitation-water yield

The temporal distribution of precipitation and water yield differed between seasons, although during both seasons, runoff as a percentage of precipitation increased after harvesting. The wet-season temporal distribution of precipitation and water yield corresponded to the annual distribution for all sub-basins. Conversely, the dry-season distribution was variable throughout the period of interest as illustrated by H watershed (Figure 5.2-13). Post-harvest water yields at H weir increased from 74% to 82% in the wet season and from 53% to 58% in the dry season.

Wet-season precipitation levels in J watershed were lower than in C watershed for the period of interest, although water yield values are almost identical between the two basins (figure 5.2-14). Changes in water yields at J-weir become evident when the pre-harvest and post-harvest wet-season water yield regression relationships for C and J weirs are plotted (Figure 5.2-15). Runoff as a percentage of precipitation increased by 9% during the post-harvest period in J watershed. The dry-season patterns of precipitation and water yield were similar to temporal patterns at C and H watershed. Post-harvest runoff increased from 49% to 63% of precipitation.

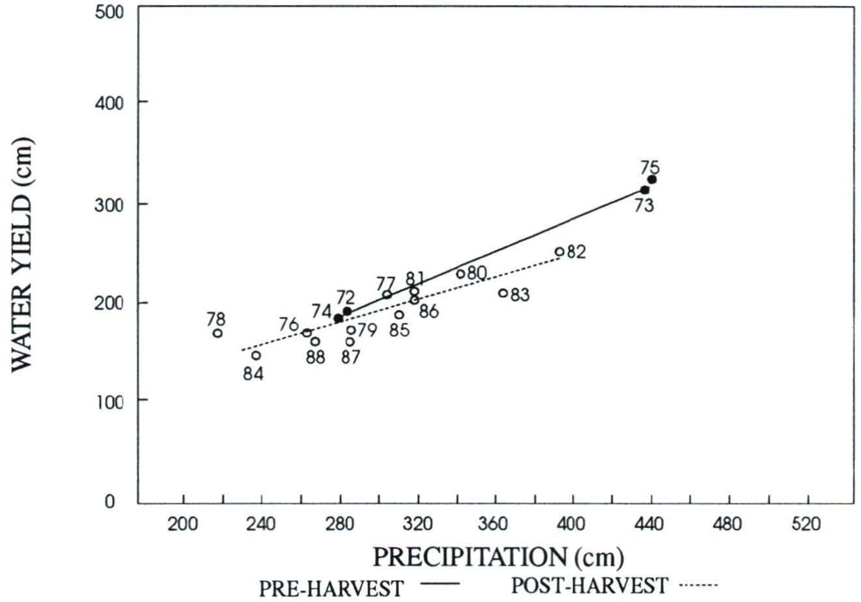

Figure 5.2-9 Pre-harvest and post-harvest relationship between mean annual precipitation and water yield in C watershed, 1972-1988

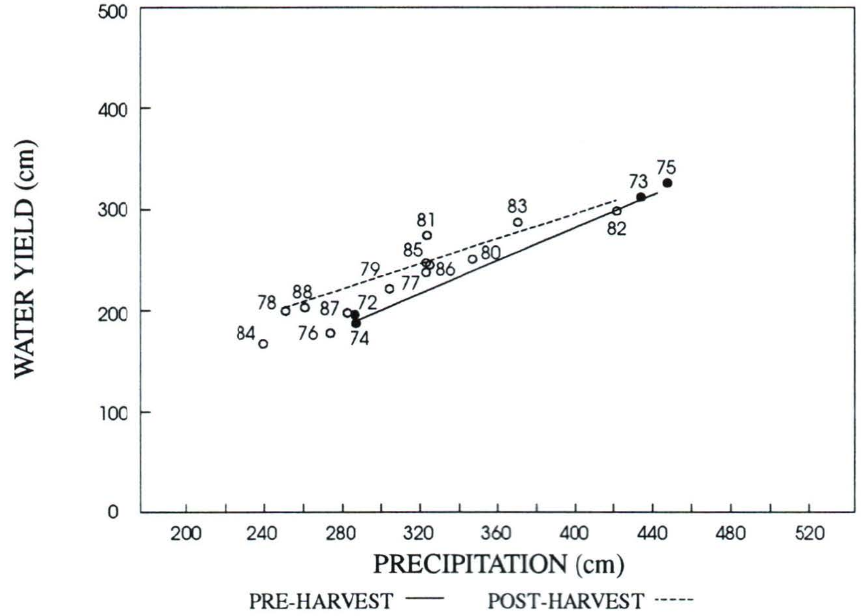

Figure 5.2-10 Pre-harvest and post-harvest relationship between mean annual precipitation and water yield in H watershed, 1972-1988

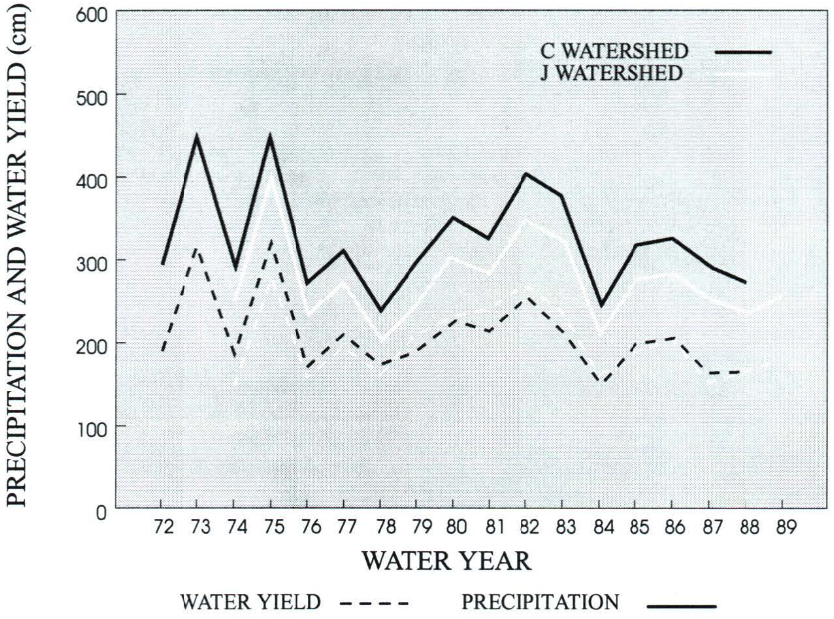

Figure 5.2-11 Temporal distribution of annual precipitation and water yield in C and J watersheds, 1972-1988

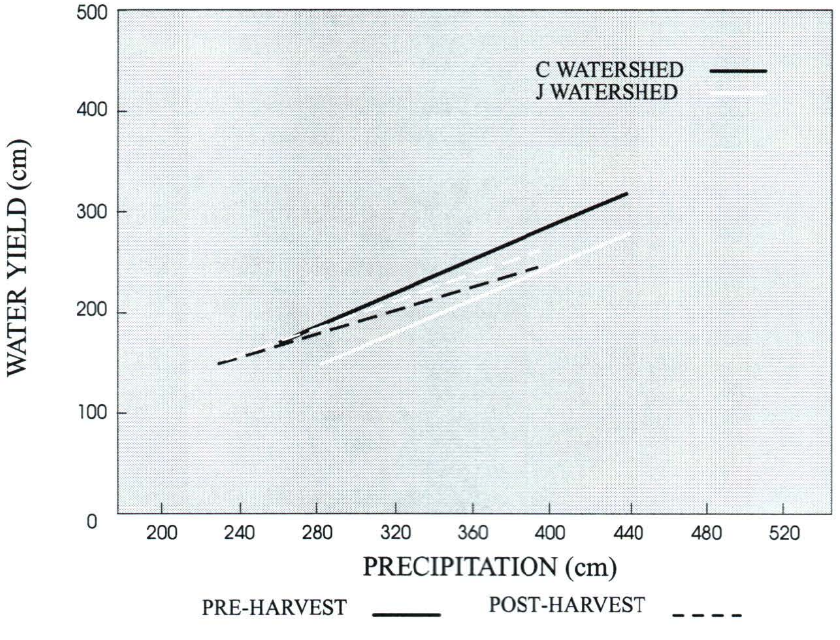

Figure 5.2-12 Pre-harvest and post-harvest relationship between mean annual precipitation and runoff in C and J watersheds, 1972-1988

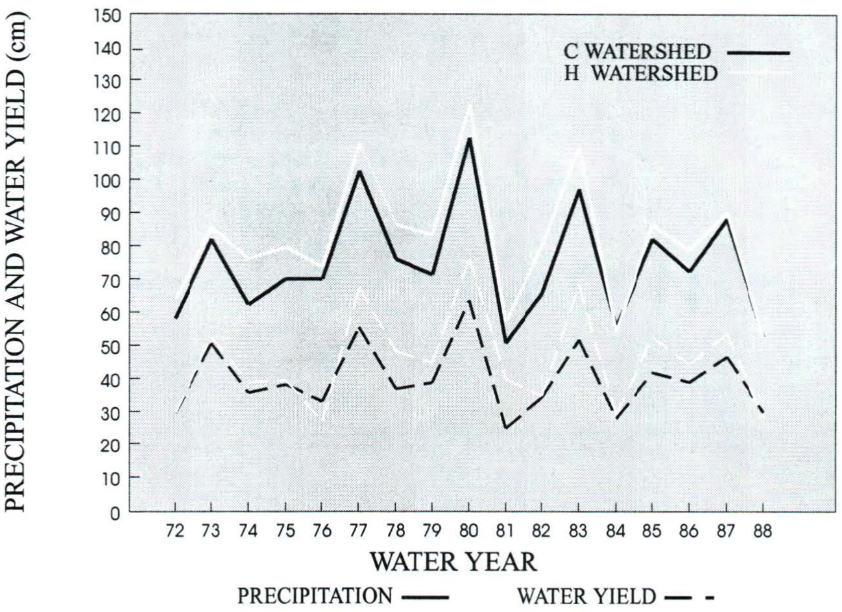

Figure 5.2-13 Temporal distribution of dry season precipitation-streamflow in C and H watersheds, 1972-1988

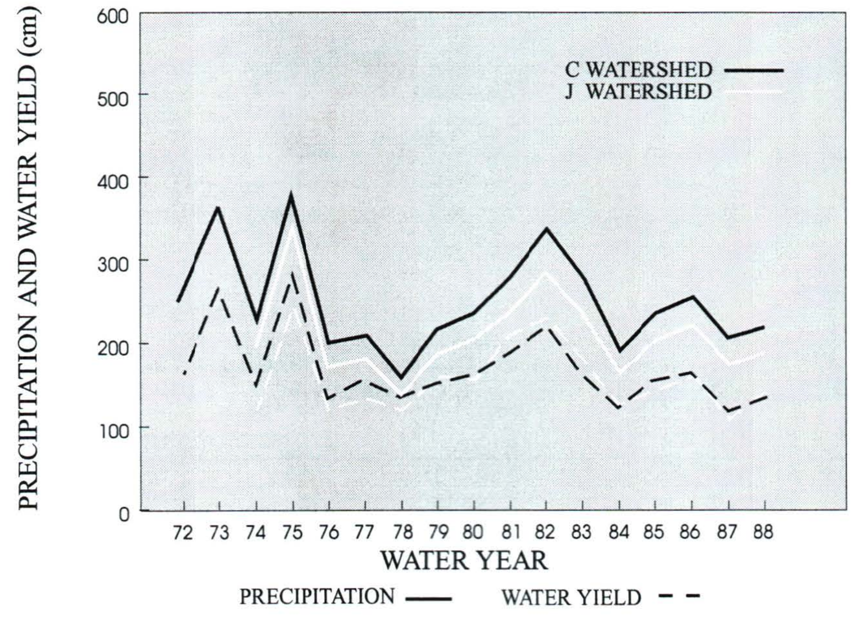

Figure 5.2-14 Temporal distribution of wet season precipitation-streamflow in C and J watersheds, 1972-1988

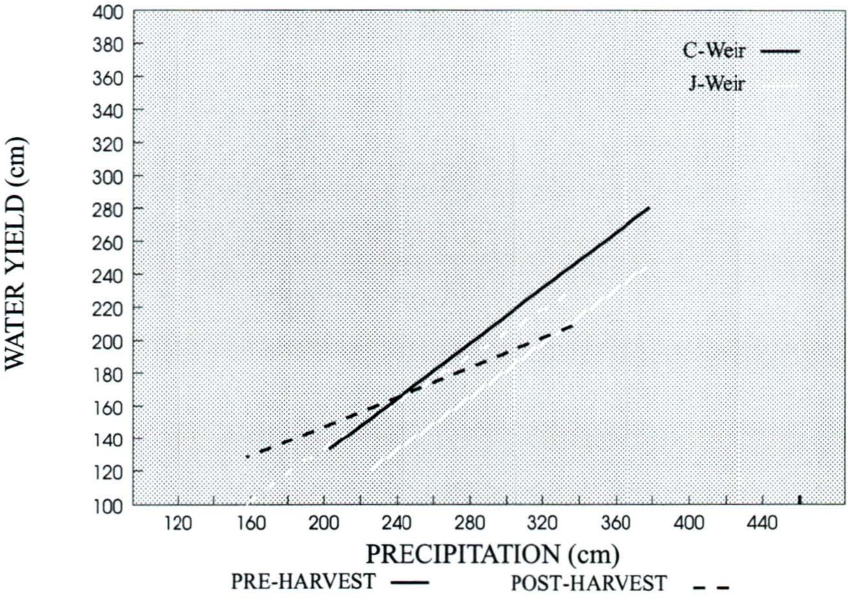

Figure 5.2-15 Pre-harvest and post-harvest relationships between mean wet season precipitation and runoff in C and J watersheds, 1982-1988

## 5.3 Interception

Interception data, collected between 1982 and 1989, have been summarized into annual and seasonal totals. Estimated mean vertical interception for periods where precipitation in the open was greater than precipitation measured under the canopy ranges from 27% in 1982 to 38% in 1987, with an overall mean of 32%. Seasonal interception was lower during the October-March wet season, with a mean of 27% ranging from 22% in 1982 to 36% in 1987. Temporal distribution of wet-season interception values paralleled annual distribution. Estimated average dry season (April-September) interception was 1.5 times the wet season value, at 44%. Maximum dry season interception was 59% in 1982, with a minimum value of 34% in 1986.

Fog drip values estimated from interception data (for periods when precipitation under the canopy was greater than precipitation in the open) ranged from 8-17% with an annual average of 11.5%. Minimum and maximum values occurred in 1985 and 1987, respectively.

The addition of fog drip reduces the net interception loss. When mean fog drip (11.5%) is subtracted from mean vertical interception loss (32%), the outcome is a net interception loss of 20.5%.

## 5.4 Evapotranspiration

Annual basin evapotranspiration values reported are, a) estimates obtained by subtracting annual water yield from annual precipitation for each sub-basin, and b) computed potential evapotranspiration calculations for dry-weather transpiration and wet-weather evaporation of intercepted precipitation, as described in Section 4.3. Observations from regression analysis conducted on evapotranspiration estimates focus on C watershed. Data from E watershed suggest different meteorological conditions. Correlations between H and J watersheds for both pre-harvest and post-harvest periods are weak.

### 5.4.1 Basin evapotranspiration

Annual basin evapotranspiration determined by the water budget method varied considerably (Figure 5.4-1). Evapotranspiration in C watershed followed the same temporal distribution as annual precipitation and water yield throughout the period of interest, with mean annual values of 115 and 120 cm for pre-harvest and post-harvest periods, respectively.

Pre-harvest evapotranspiration estimates in E watershed are lower by 26-30% (mean=81 cm) when compared to the other sub-drainages. Mean post-harvest evapotranspiration was 24% lower (62 cm) than pre-harvest water years in E watershed and estimates for the period of interest do not follow the temporal pattern defined by C watershed.

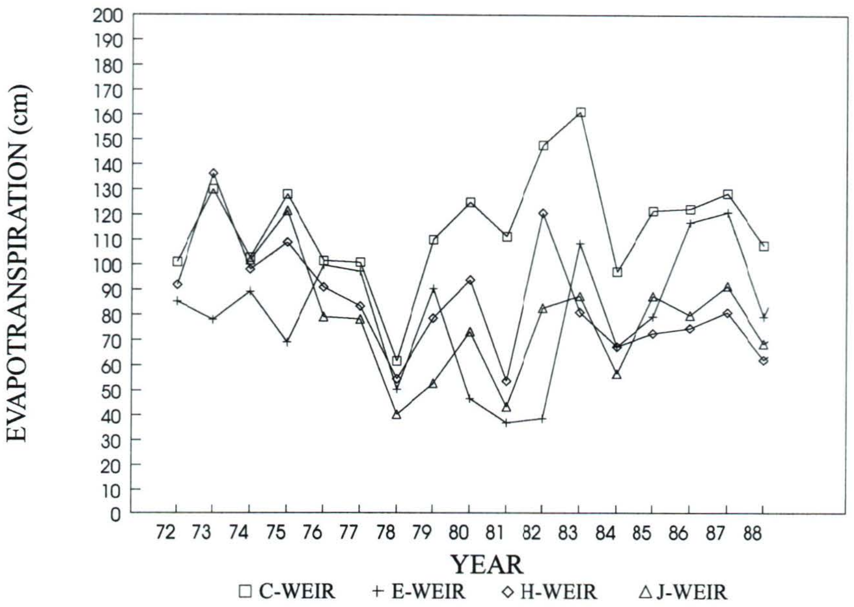

Figure 5.4-1 Mean annual evapotranspiration for sub-basins in the Carnation Creek watershed

Annual evapotranspiration values for treated H and J watersheds reflect the temporal distribution of rainfall and water yield for pre-harvest years. Mean annual evapotranspiration for this period was 109 and 112 cm for H and J watersheds, respectively. Post-harvest estimates were 26 and 44% lower. Although post-harvest evapotranspiration is lower in the treated watersheds, the temporal distribution of evapotranspiration throughout this period corresponds to the pattern for the control C watershed.

Pre-harvest evapotranspiration relationships established between control and treated watersheds were strongest between control C and treated H and weakest with any pairing with E watershed (Table 5.4-1). The post-harvest evapotranspiration relationships were strongest between control C and treated J. The regression analysis conducted on the evapotranspiration data clearly illustrates the reductions in evapotranspiration throughout the post-harvest years (Figures 5.4-2 and 5.4-3). During this period, evapotranspiration is lower and the difference is statistically significant at the 95% confidence limit in both treated watersheds. Although post-harvest evapotranspiration estimates fall below the pre-harvest calibration for E watershed, comparisons are not reported because post-harvest correlations were weak.

Table 5.4-1 Regression equations for annual evapotranspiration during pre-harvest and post-harvest periods for all sub-basins in the Carnation Creek watershed

| PERIOD | WATERSHED | EQUATION | $r^2$ | NO. OF OBS. |
|---|---|---|---|---|
| Pre-harvest | C-H | 1.05(C) - 12.5 | 0.71 | 4 |
| | E-H | -1.02(E) + 190.7 | 0.21 | 4 |
| Post-harvest | C-H | 0.49(C) + 22.09 | 0.49 | 6 |
| | C-J | 0.56(C) + 3.83 | 0.62 | 11 |
| | E-H | -0.04(E) + 83.15 | 0.003 | 6 |
| | E-J | 0.28(E) + 47.63 | 0.14 | 8 |

Decreases in evapotranspiration were observed for all post-harvest water years in both treated watersheds, except in 1978 for H watershed. Losses were greatest in water years 1983 and 1981 for H and J watersheds, respectively, with smallest decreases occurring one year post-harvest (Figures 5.4-4 and 5.4-5). Mean annual evapotranspiration losses during the first six years of the post-harvest period were estimated to be 29% and 45% less than the pre-harvest values for H and J watersheds, respectively. During the 1984-1988 post-harvest period, evapotranspiration losses increased to 34% for H watershed and decreased to 31% for J watershed (Tables 5.4-2 and 5.4-3).

Post-harvest decreases in annual evapotranspiration for H watershed closely correspond to post-harvest increases in annual water yield for most water years (Table 5.4-2). Exceptions are 1978 and 1982 when the difference between evapotranspiration losses and water yield increases were 19 cm and 23 cm, respectively. Regression analysis conducted on J watershed data were strongest with decreases in evapotranspiration corresponding directly to increases in annual water

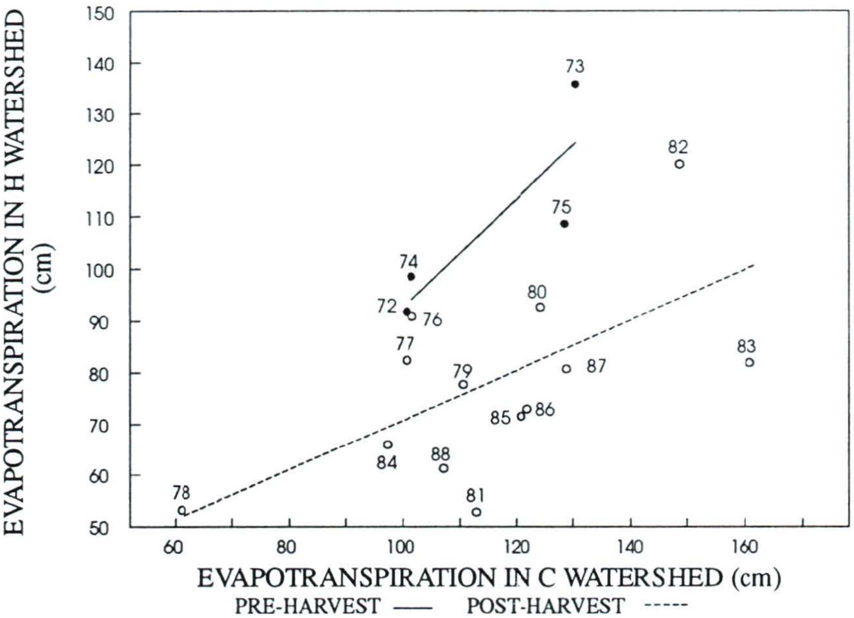

Figure 5.4-2 Relationship between annual evapotranspiration for control watershed C and treated watershed H for pre-harvest and post-harvest periods

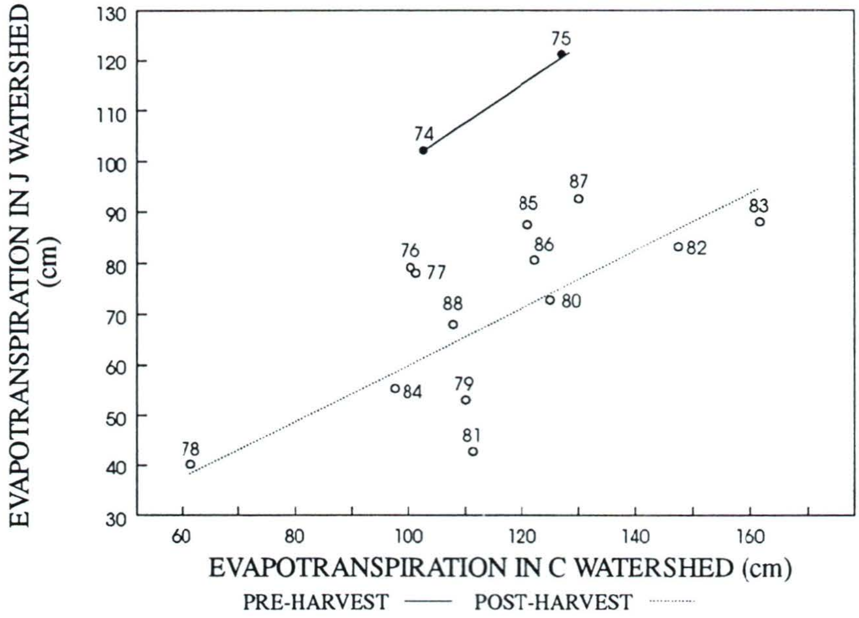

Figure 5.4-3 Relationship between annual evapotranspiration for control watershed C and treated watershed J for pre-harvest and post-harvest periods

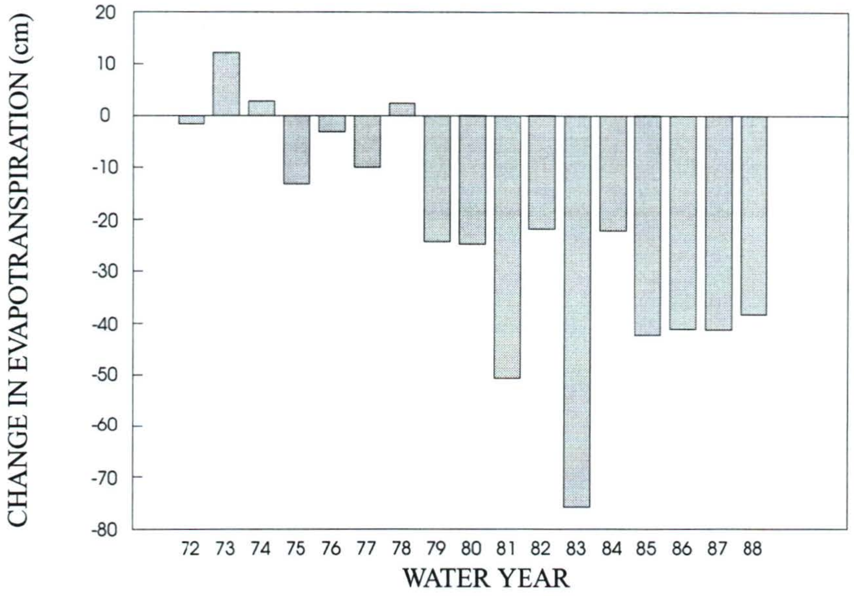

Figure 5.4-4 Changes in annual evapotranspiration at H watershed, 1972-1988

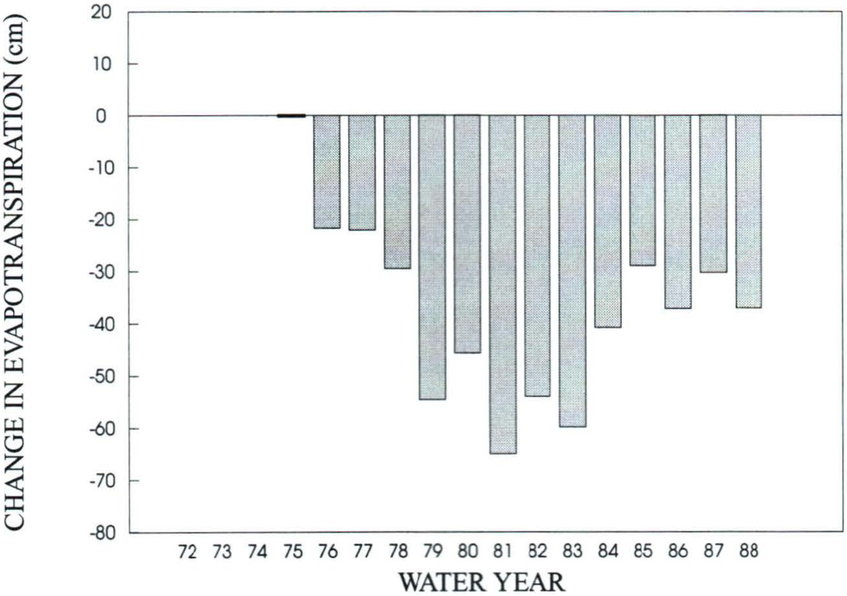

Figure 5.4-5 Changes in annual evapotranspiration at J watershed, 1972-1988

Table 5.4-2 Annual evapotranspiration losses in H watershed during the post-harvest period

| YEAR | ANNUAL LOSS (cm) | ANNUAL LOSS (%) |
|---|---|---|
| 1978 | 2.4 | 4.5 |
| 1979 | -24.3 | 24 |
| 1980 | -24.8 | 21 |
| 1981 | -50.6 | 48 |
| 1982 | -21.8 | 15 |
| 1983 | -75.7 | 48 |
| 1984 | -22.1 | 25 |
| 1985 | -42.4 | 37 |
| 1986 | -41.2 | 35 |
| 1987 | -41.3 | 34 |
| 1988 | -38.3 | 38 |
|  | MEAN LOSS (cm) | MEAN LOSS (%) |
| 1978-83 | -32.5 | 29 |
| 1984-88 | -37.1 | 34 |
| 1978-88 | -34.6 | 33 |

yield. The reductions also correspond to the temporal distribution of precipitation and water yield with the smallest decrease occurring one year after harvesting and the largest decreases occurring six years later (Table 5.4-3).

### 5.4.2 Potential evapotranspiration

Annual potential evapotranspiration computed from meteorological data at Station A averaged 135 cm, ranging from 104 cm in 1978 to 199 cm in 1983. Minimum and maximum values correspond to minimum and maximum precipitation years. Potential evapotranspiration averaged 140 cm during the pre-harvest period but decreased to 137 cm during the 1978-1983 post-harvest period and to 132 cm during the 1984-1988 post-harvest period. Temporal variation in potential evapotranspiration throughout the period of interest is variable, with highest values calculated for water years 1975, 1983, and 1987 (Figure 5.4-6).

Table 5.4-3 Annual evapotranspiration losses in J watershed

| YEAR | ANNUAL LOSS (cm) | ANNUAL LOSS (%) |
|---|---|---|
| 1978 | -29.5 | -42 |
| 1979 | -54.7 | -51 |
| 1980 | -45.7 | -38 |
| 1981 | -65.0 | -60 |
| 1982 | -54.0 | -40 |
| 1983 | -59.9 | -41 |
| 1984 | -40.8 | -42 |
| 1985 | -28.9 | -25 |
| 1986 | -37.2 | -32 |
| 1987 | -30.3 | -25 |
| 1988 | -37.1 | -35 |
|  | MEAN LOSS (cm) | MEAN LOSS (%) |
| 1978-1983 | -51.5 | -45 |
| 1984-1988 | -34.9 | -31 |
| 1978-1988 | -39.6 | -35 |

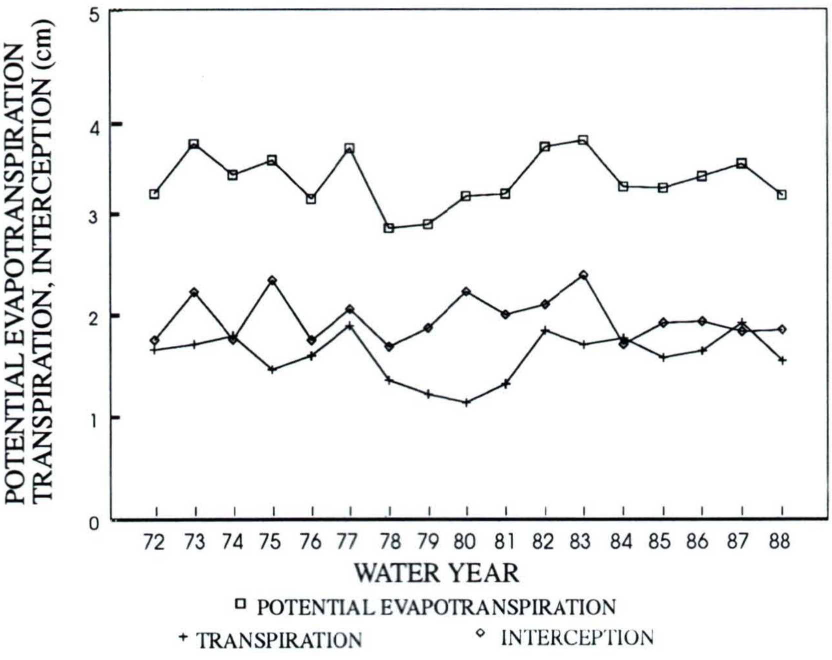

Figure 5.4-6 Temporal variation in annual evapotranspiration at Station A, 1972-1988

Annual interception loss alone averaged 72 cm during the period of interest, ranging from 61 cm in 1978 to 87 cm in 1983. Interception losses averaged 74 cm during the pre-harvest period, increasing slightly to 75 cm during the 1978-1983 post-harvest period and decreasing during the 1984-1988 post-harvest period. The temporal pattern of annual interception follows that of annual precipitation and subsequently annual water yield (Figure 5.4-6).

Annual transpiration alone ranged from 42 cm in 1980 to 71 cm in 1987 and averaged 59 cm during the period of interest. Transpiration averaged 61 cm and decreased to 53 cm between 1978-1983 and increased to 62 cm between 1984-1988. The temporal variation during the period of interest varies minimally except between 1978 and 1982 (Figure 5.4-6).

### 5.4.3 Comparison of Et and PET

Potential evapotranspiration was originally defined by Thornthwaite (1944) as "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation." This definition has been modified over time to account for different ground surfaces but maintains the dependence on available moisture. With this in mind, potential evapotranspiration is expected to be greater than evapotranspiration estimates from precipitation and streamflow for the sub-basins. The results indicate this with the exception of C weir in 1980, 1982, and 1985, and H weir in 1973.

This finding may be explained in part by the location of Station A relative to the Carnation Creek watershed. Station A is situated closer to the water and at a lower elevation than most of the watershed. This suggests that the climatic conditions and, therefore, evapotranspiration rates at this site may differ from other locations within the watershed. Therefore values of potential evapotranspiration computed from data at Station A may not model conditions for all years elsewhere in the watershed.

The computed potential evapotranspiration values are closest to the evapotranspiration values, estimated from precipitation and streamflow, in C watershed for the period of interest. Pre-harvest potential evapotranspiration values are closest to evapotranspiration estimates for H and J watersheds during the post-harvest period. The temporal distribution of potential evapotranspiration closely follows evapotranspiration estimates for C, H, and J watersheds.

## 5.5 Water Yield

The evaluation of water-yield changes after timber harvesting involved the establishment of pre-harvest regression relationships between each of the control watersheds (C and E) and each of the treated watersheds (H and J) (Table 5.5-1). Pre-harvest calibration water years are 1972-1975 for H-weir and 1974-1975 for J-weir. Road building in H watershed occurred in 1976 and, as it constituted neither a fully treated or fully non-disturbed condition, was not included in the calibration period. Right-of-way falling and road construction in J watershed began in the spring of 1975. As the calibration period required a minimum of two years pre-harvest monitoring, the period of road construction was automatically included. However, as falling and road construction disturbed only 4.5% of the watershed, it was assumed to have had a minimal impact on water yields.

Observations made from regression analysis conducted on water yield data focus on comparisons with C weir. E weir water yields are probably not as accurate as those for C, H, and J weirs due to limitations in accuracy of low flow measurements (Hetherington, *personal communication*, 1994). Results from the paired t-test indicate that water yields at E weir are statistically different from water yields at C weir at the 95% confidence limit. Therefore, the results from E weir were mainly used to support results involving comparisons with C weir.

Table 5.5-1 Regression equations for annual, seasonal and monthly water yields during the calibration period for H watershed using control watershed C, Carnation Creek

| TIME PERIOD | EQUATION | $r^2$ | NO. OF OBSERVATIONS |
|---|---|---|---|
| Annual | 0.93(C) + 14.29 | 0.95 | 4 |
| Oct-Mar (wet) | 0.95(C) + 7.14 | 0.94 | 4 |
| Apr-Sep (dry) | 1.06(C) - 0.51 | 0.98 | 4 |
| October | 1.09(C) - 1.76 | 0.99 | 4 |
| November | 1.00(C) + 1.33 | 0.97 | 4 |
| December | 1.28(C) - 14.12 | 0.87 | 4 |
| January | 1.19(C) - 9.02 | 0.95 | 4 |
| February | 0.89(C) + 1.85 | 0.94 | 4 |
| March | 0.45(C) + 15.29 | 0.99 | 4 |
| April | 0.89(C) + 2.30 | 0.99 | 4 |
| May | 1.22(C) - 1.99 | 0.83 | 4 |
| June | 1.00(C) + 0.50 | 0.99 | 4 |
| July | 1.12(C) - 0.68 | 0.99 | 4 |
| August | 1.29(C) - 1.32 | 0.98 | 4 |
| September | 1.14(C) - 0.58 | 0.99 | 4 |

### 5.5.1 Annual water yield

**H watershed**

Changes in annual water yield were observed for H-weir during the 1978-1983 post-harvest period after 90% of the watershed was harvested. For these six post-harvest years, the observed annual water yield was higher than and statistically different from the values predicted by the calibration model (Figure 5.5-1). Increases in annual water yield ranged from 16.6 cm in 1978 to 72.7 cm in 1983, with a mean increase of 41.9 cm (20%) (Figure 5.5-2). Increases were greatest in water years 1983 and 1981 (53.8 cm) with the lowest increase of 16.6 cm occurring in the first post-harvest year (Table 5.5-2).

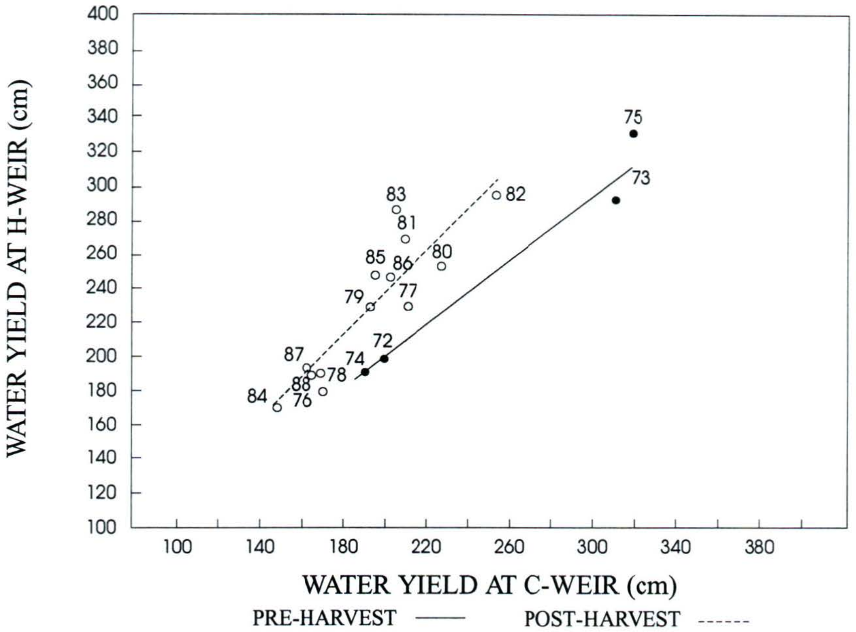

Figure 5.5-1 Relationship between annual water yields for control watershed C and treated watershed H for pre-harvest and post-harvest periods

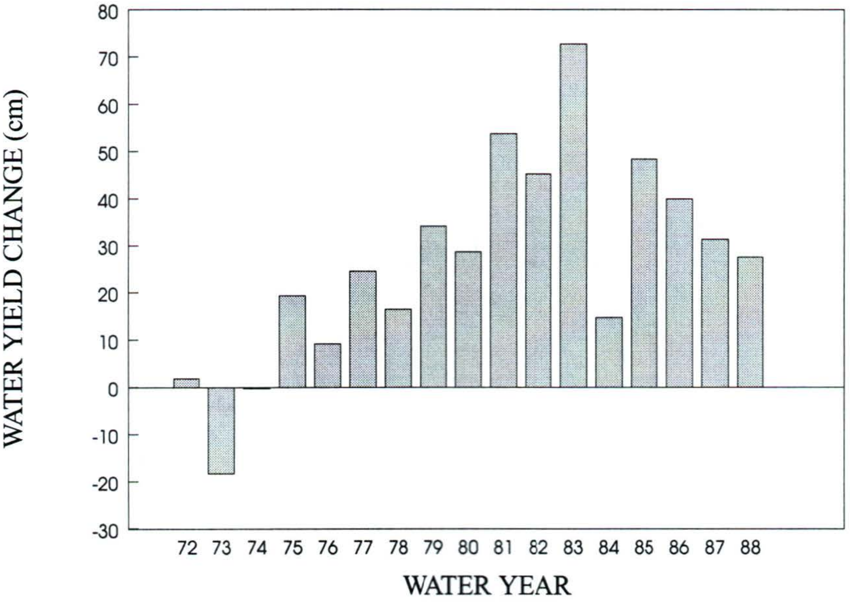

Figure 5.5-2 Changes in annual water yield at treated watershed H compared to control watershed C, 1972-1988

Table 5.5-2 Streamflow changes for annual yields (cm) in H watershed during 1978-1988 post-harvest period

| YEAR | ANNUAL INCREASE (cm) | ANNUAL INCREASE (%) |
|---|---|---|
| 1978 | 16.6 | 9.5 |
| 1979 | 34.2 | 18 |
| 1980 | 28.7 | 13 |
| 1981 | 53.8 | 25 |
| 1982 | 45.2 | 18 |
| 1983 | 72.7 | 34 |
| 1984 | 14.8 | 9.8 |
| 1985 | 48.4 | 25 |
| 1986 | 40.0 | 20 |
| 1987 | 31.4 | 19 |
| 1988 | 27.9 | 17 |
|  | MEAN INCREASE (cm) | MEAN INCREASE (%) |
| 1978-83 | 41.9 | 20 |
| 1984-88 | 32.4 | 18 |
| 1978-88 | 37.6 | 19 |

The remaining 10% of the forest cover in H watershed was harvested in water year 1984. This year was characterised by the lowest post-harvest water yield increase (14.8 cm) and the lowest annual precipitation for the period of interest. Comparison of 1984 H-weir water yield to C-weir data indicates that the H-weir yield is exceptionally low. A leak in H-weir was discovered and patched in August 1986. Based on the observations from 1984, it is possible that the leak started during this period (Hetherington, *personal communication*, 1993).

Annual water yields after 1984 show a decreasing trend, suggesting a return toward pre-harvest levels. The mean annual increase for the period 1984-1988 was 32.4 cm (18%), with yields decreasing 10 cm (24%) from the 1978-1983 period.

Changes in annual water yields at H-weir are more variable when compared to water yields at E weir during the first six years post-harvest (Figure 5.5-3). Increases in water yields occur in all years except 1980 (11.6 cm), 1982 (17.3 cm), and 1984 (1.3 cm) when yields were lower than estimated by the calibration model. Increases ranged from 16.6 cm in 1981 to 43.5 cm in 1983, with a mean annual increase of 12.8 cm (5.3%) between water years 1978-1983.

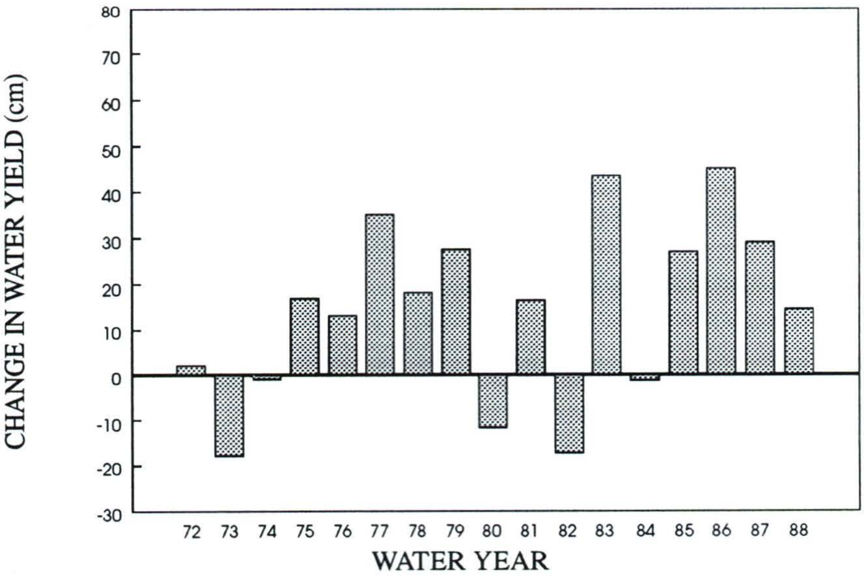

Figure 5.5-3 Relationship between annual water yields for control watershed E and treated watershed H for pre-harvest and post-harvest periods

Water yields at E weir were approximately 90% of precipitation, compared to 72% at H-weir for water years 1980 and 1982. This value is 15% higher than the mean for the period of interest. If yields at E-weir were closer to the mean of 78% of precipitation during these two years, the post-harvest slope would shift, placing all post-harvest points above the pre-harvest calibration (Figure 5.5-4). Water yields at C and J weirs during these two years were 64% and 76% of precipitation, respectively.

For the period 1984-1988, annual water yields at E weir do not exhibit the declining water yields observed at C weir. Annual water yields at E weir increase by 12% during this period with a mean overall increase of 8% for the 1978-1988 period.

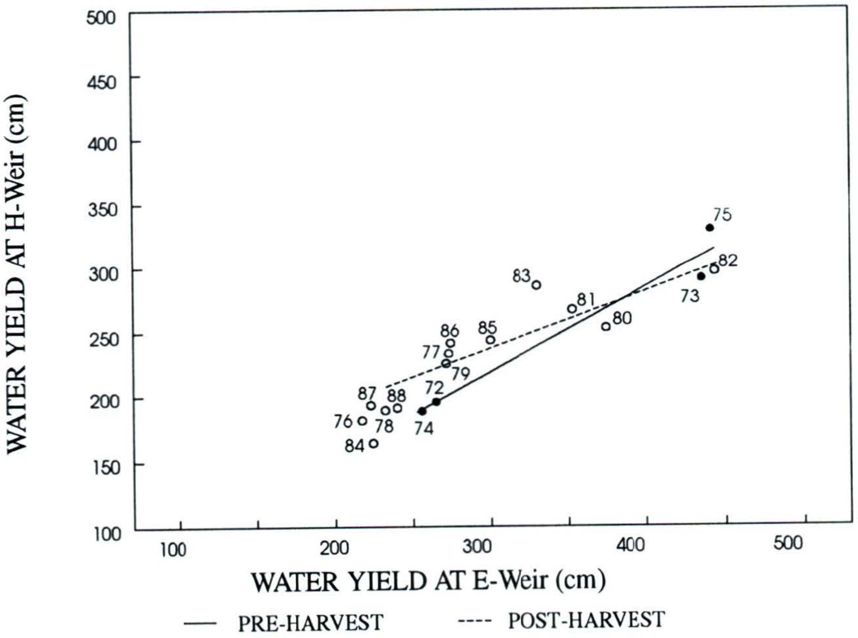

Figure 5.5-4 Relationship between annual water yields for control watershed E and treated watershed H for pre-harvest and post-harvest periods

### J Watershed

Changes in annual water yield were observed at J weir during the 1978-1988 post-harvest period. For all post-harvest years, the annual water yield was higher than the values predicted by the calibration model (Figure 5.5-5). Increases in annual water yield ranged from 27 cm in 1978 to 62.6 cm in 1981 (Figure 5.5-6). During the first six post-harvest years (1978-1983), annual water yields at J-weir increased an average of 29% (50 cm). Although no downward trend is indicated after 1984, water yields remained almost constant over the next 5 years. The average increase in annual water yields between 1984-1988 decreased to 37 cm (27%) (Table 5.5-3). Post-harvest increases in water yield are statistically significant.

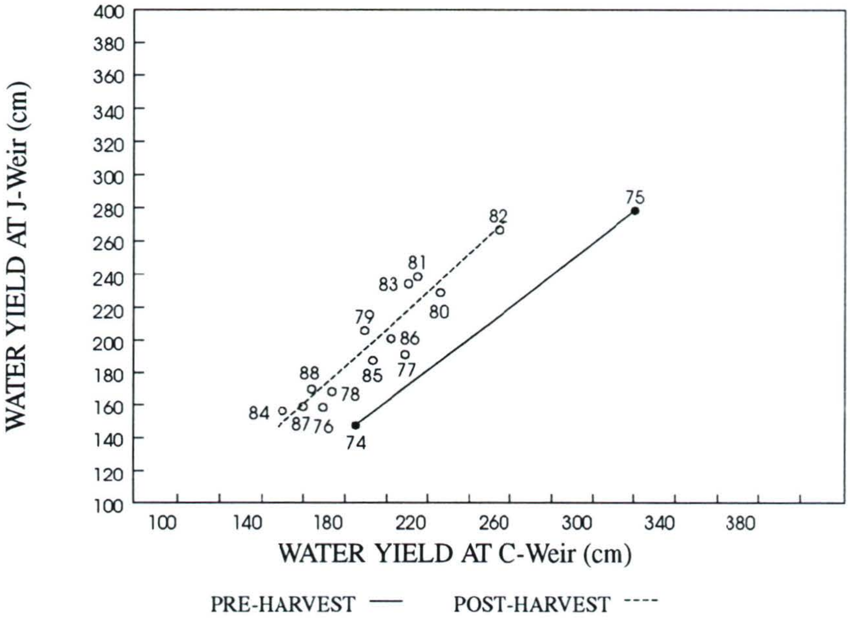

Figure 5.5-5 Relationship between annual water yields for control watershed C and treated watershed J for pre-harvest and post-harvest periods

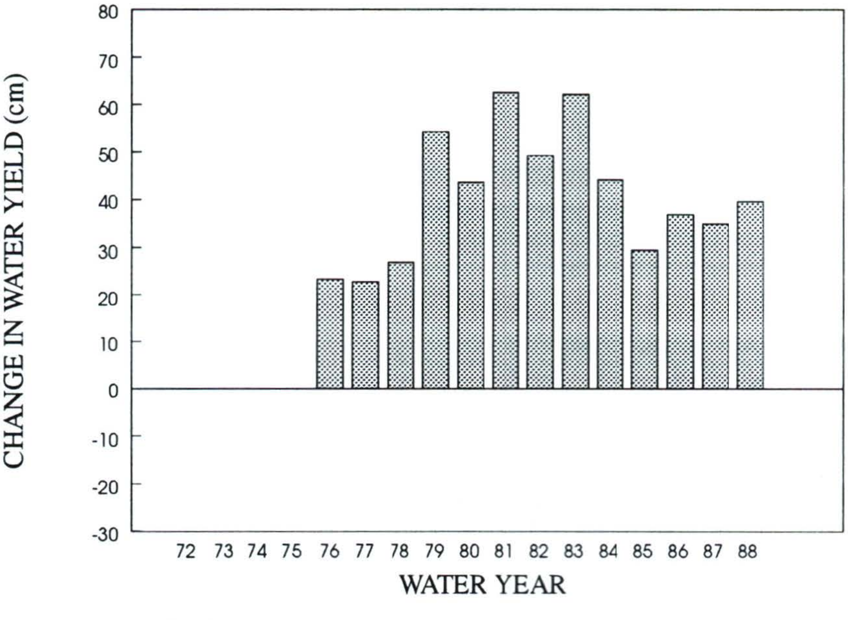

Figure 5.5-6 Changes in annual water yield at treated watershed J compared to control watershed C, 1974-1988

Table 5.5-3 Streamflow changes for annual yields (cm) in J watershed during 1978-1988 post-harvest period

| YEAR | ANNUAL INCREASE (cm) | ANNUAL INCREASE (%) |
|---|---|---|
| 1978 | 27.0 | 20 |
| 1979 | 54.2 | 36 |
| 1980 | 43.6 | 23 |
| 1981 | 62.6 | 35 |
| 1982 | 49.3 | 23 |
| 1983 | 62.1 | 36 |
| 1984 | 43.9 | 40 |
| 1985 | 29.4 | 19 |
| 1986 | 36.9 | 22 |
| 1987 | 27.5 | 28 |
| 1988 | 39.5 | 31 |
|  | MEAN INCREASE (cm) | MEAN INCREASE (%) |
| 1978-1983 | 49.8 | 29 |
| 1984-1988 | 37.0 | 27 |
| 1978-1988 | 44.0 | 28 |

As with H-weir, changes in annual water yields at J-weir were variable when compared to water yields at E weir throughout the post-harvest period (Figure 5.5-7). Increased water yields occurred in all water years except 1982. For the first six post-harvest years, annual water yields increased minimally (1.9%). Largest increases of 9.88 cm (7.9%) occurred between water years 1984-1988 with a mean overall increase of 6.31 cm (4.1%).

### 5.5.2 Seasonal water yield

**H Watershed**

Increases in wet (October-March) season water yields at H weir occurred in the first six post-harvest years when compared to C weir (Figure 5.5-8). Increases ranged from 7.05 cm (5.2%) in 1978 to 56.5 cm (35%) in 1983, with a mean increase of

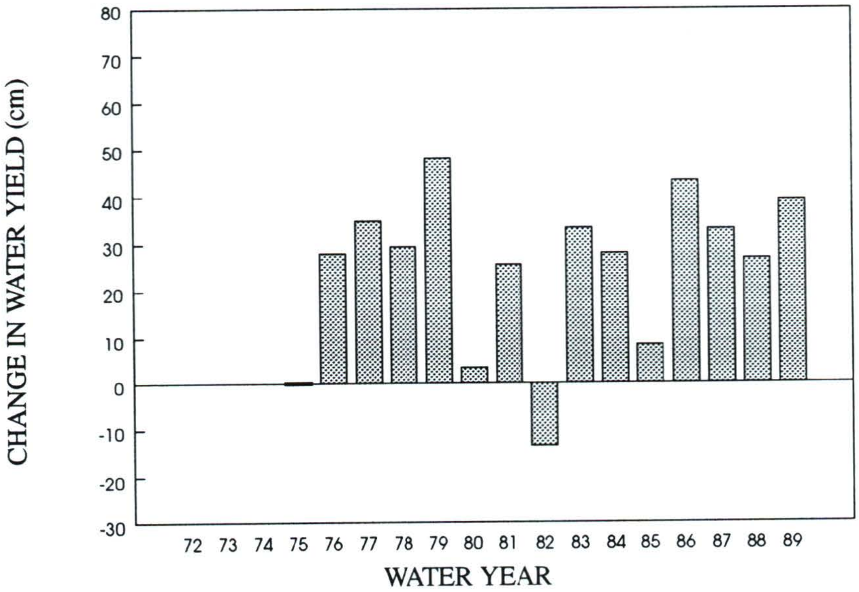

Figure 5.5-7 Changes in annual water yield at treated watershed J compared to control watershed E, 1974-1988

32.3 cm (19%) (Figure 5.5-9). The largest increases occurred six, five and four years post-harvest. The rank of these values closely corresponds to that for annual values. Water yield increases are statistically significant at the 95% confidence limit.

The temporal pattern of wet season water yields at H weir after water year 1983 is similar to the pattern exhibited by annual water yields. A substantial drop in water yield (40 cm) occurred in 1984 when precipitation was 20% below the mean. After 1984, yields decreased, the mean seasonal increase for 1984-1988 dropped to 29.8 cm (22%). Water year 1988 shows a slight increase in water yield which corresponds to increased precipitation during October-March of this year. An overall increase in wet season water yields of 20% was observed between water years 1978-1988 (Table 5.5-4).

During the dry April-September season, increases in water yield at H weir when compared to C weir data occurred in five of the first six post-harvest years. The exception was water year 1982 which was 1.2 cm (3.2%) lower than estimated by the calibration model (Figure 5.5-10). Largest increases were 13.9 cm in both 1981

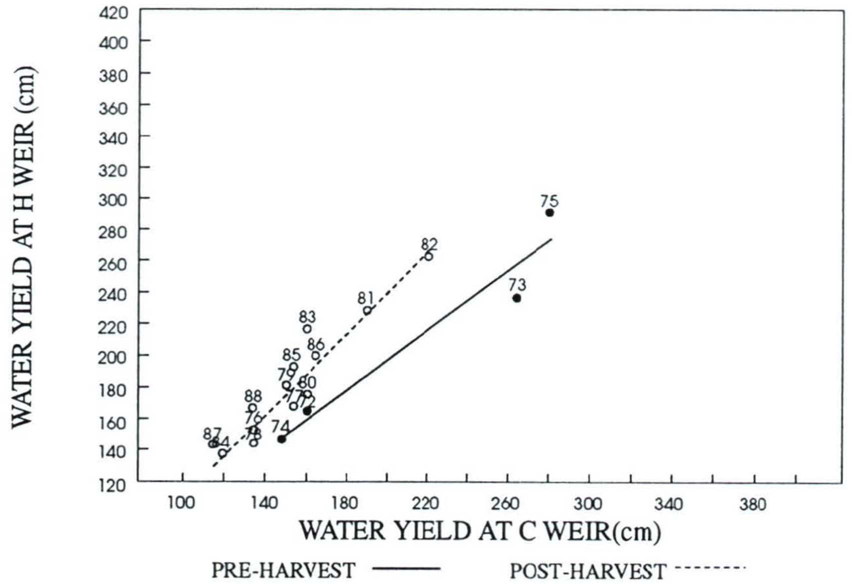

Figure 5.5-8 Relationship between wet (Oct-Mar) season water yields for control watershed C and treated watershed H for pre-harvest and post-harvest periods

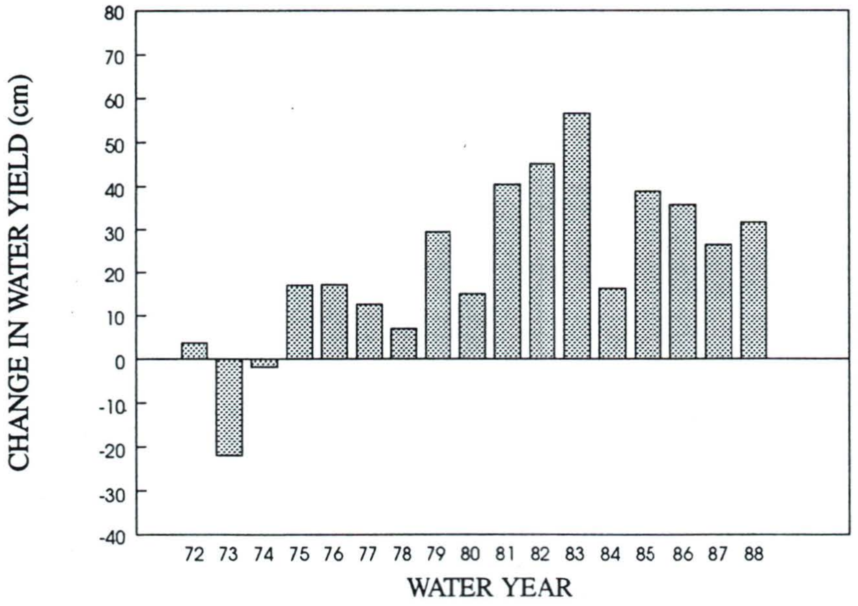

Figure 5.5-9 Changes in seasonal water yields for wet (Oct-Mar) period at treated watershed H compared to control watershed C, 1972-1988

(54%) and 1983 (26%) with a mean increase between 1978-1983 of 8.4 cm (19%). Water yield increased 9.6 cm (25%) in the first year post-harvest (Table 5.5-4).

Dry-season water yields follow a temporal pattern similar to those for both annual and wet-season periods. In 1984, dry-season water yield dropped to pre-harvest levels, increasing again in 1985, followed by a downward trend to 1988. Mean dry-season water yield increase for 1984-1988 was 2.8 cm (7%) with an overall mean dry-season water yield increase between 1978-1988 of 5.8 cm (14%) (Figure 5.5-11).

Fall and winter wet season increases at H-weir during the 1978-1983 post-harvest period were much larger than dry season increases (32 cm vs 8 cm). However, both increases are 19% greater than the estimated pre-harvest yields. In comparison, during the 1984-1988 period when water yields indicate a decreasing trend, wet-season increases were larger than dry season on both absolute (30 cm vs 3 cm) and relative (22% vs 7%) terms. For the 1978-1988 period of interest, overall mean wet-season water yield increases were larger than dry season water yield increases in both absolute (31 cm vs 6 cm) and relative (20% vs 14%) terms.

### J Watershed

Wet-season water yields at J weir increased in all eleven post-harvest years relative to C weir (Figure 5.5-12). The increases ranged from 14.7 cm (12%) in 1978 to 51.3 cm (28%) in 1983 (Figure 5.5-13) with a mean wet-season water yield increase of 37.3 cm (27%). An increase of 51.3 cm was also observed during 1981, but was smaller in relative terms (24%). Wet-season water yields show an increasing trend to

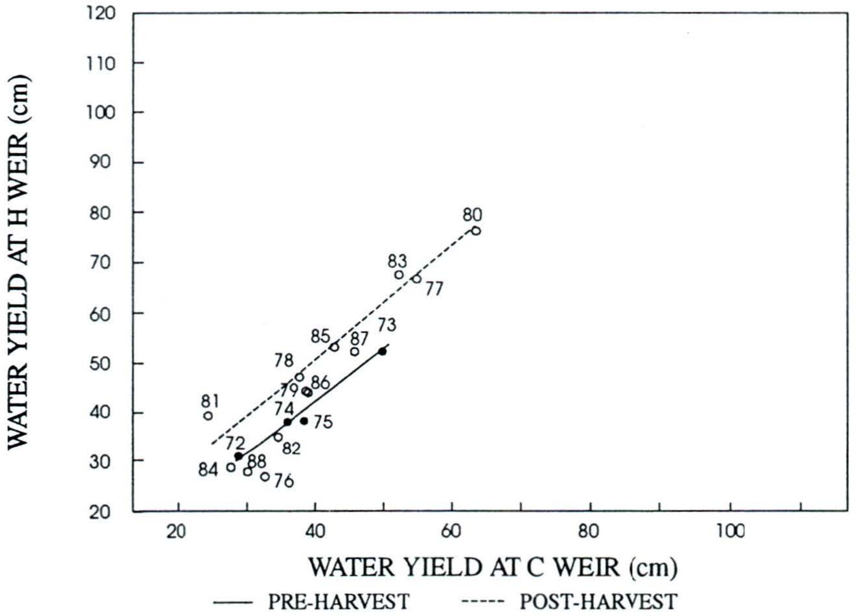

Figure 5.5-10 Relationship between dry (Apr-Sept) season water yields for control watershed C and treated watershed H for pre-harvest and post-harvest periods

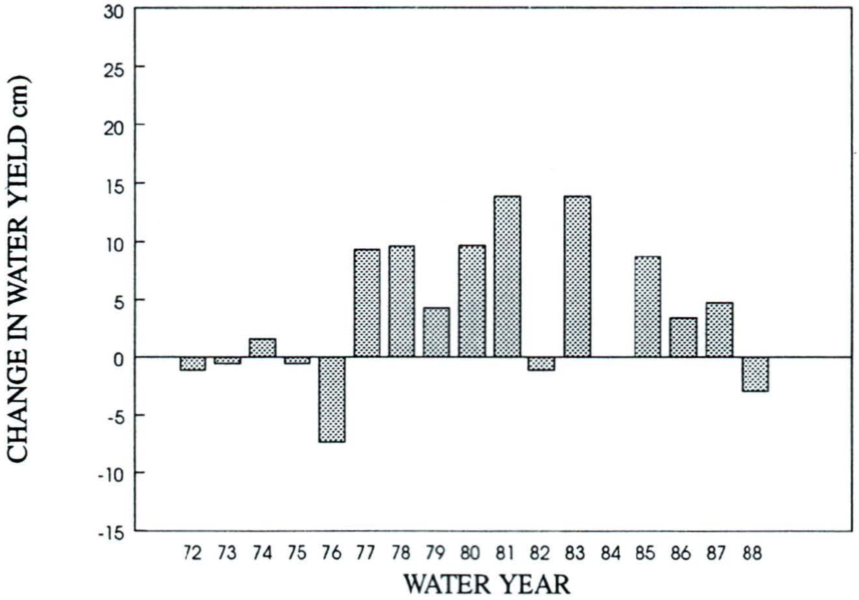

Figure 5.5-11 Changes in seasonal water yields for dry (Apr-Sept) period at treated watershed H compared to control watershed C, 1972-1988

Table 5.5-4 Streamflow changes for seasonal water yields (cm) in H watershed during 1978-1983 post-harvest period

| YEAR | WET (Oct-Mar) | DRY (Apr-Sept) |
|---|---|---|
| 1978 | 7.1 | 9.6 |
| 1979 | 29.5 | 4.3 |
| 1980 | 15.1 | 9.7 |
| 1981 | 40.4 | 14 |
| 1982 | 45.1 | -1.2 |
| 1983 | 56.5 | 14 |
| 1984 | 16.3 | .06 |
| 1985 | 38.7 | 8.7 |
| 1986 | 35.7 | 3.4 |
| 1987 | 26.4 | 4.8 |
| 1988 | 31.6 | -2.9 |
|  | MEAN INCREASE (cm) | MEAN INCREASE (cm) |
| 1978-1983 | 32.3 | 8.4 |
| 1984-1988 | 29.7 | 2.8 |
| 1978-1988 | 31.1 | 5.8 |

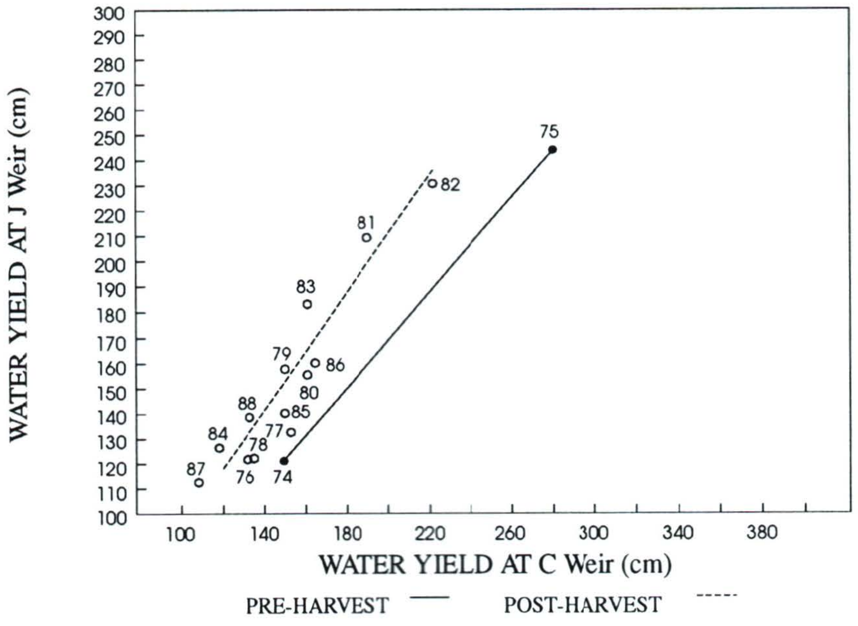

Figure 5.5-12 Relationship between wet (Oct-Mar) season water yields for control watershed C and treated watershed J for pre-harvest and post-harvest periods

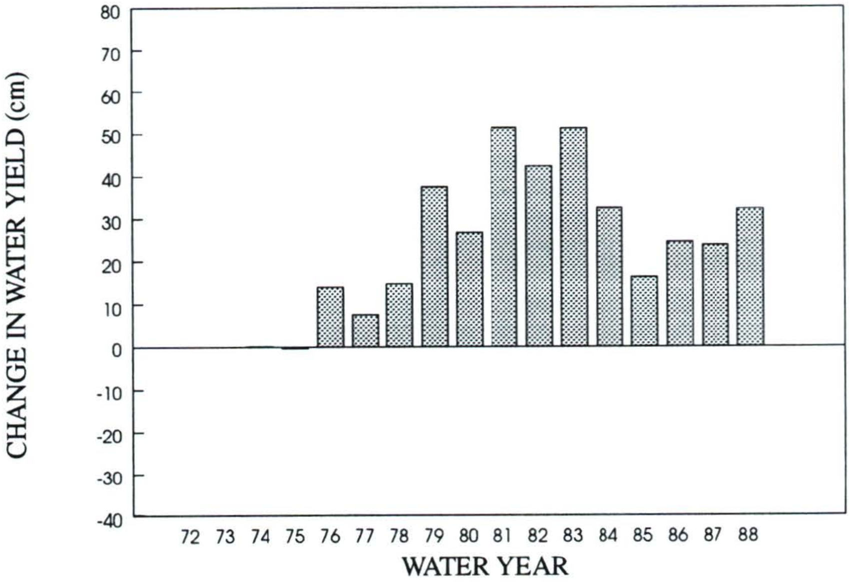

Figure 5.5-13 Changes in seasonal water yields for wet (Oct-Mar) period at treated watershed J compared to control watershed C, 1974-1988

1983, and a decreasing trend to 25.9 cm (24%) between 1984-1988. During water year 1984, a water yield increase of 32.6 cm was observed at J weir, 16 cm higher than observed at H weir the same year. The pattern of higher water yields in 1988 was also observed at J weir and again corresponds to increased precipitation. Mean wet-season water yield increased between 1978-1988
was 32.1 cm (25%) (Table 5.5-5).

Dry season post-harvest water yield changes at J weir compared to C weir were variable (Figure 5.5-14). Although the post-harvest regression equation was strong ($r^2$ = 0.96), pre-harvest water yields for the two years were of similar magnitude, preventing a valid comparison (Figure 5.5-15).

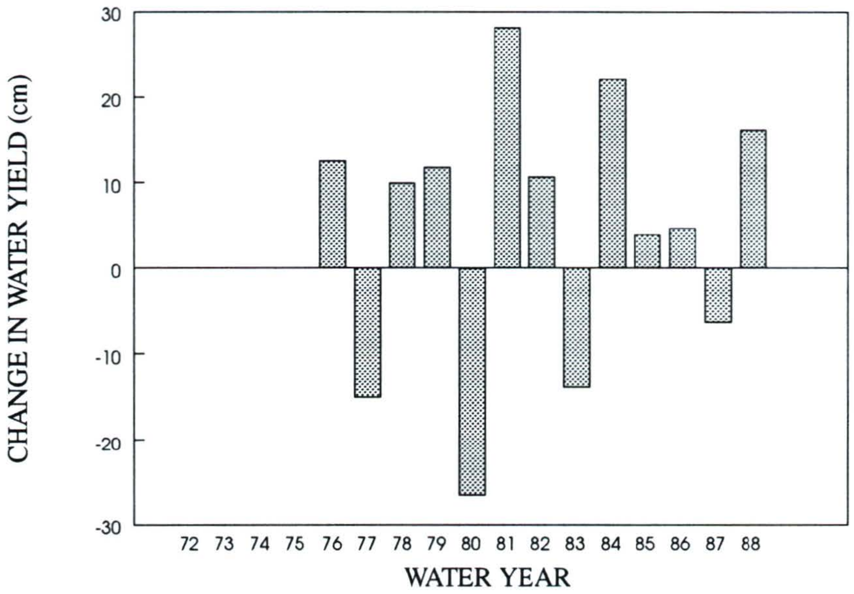

Figure 5.5-14 Changes in seasonal water yields for dry (Apr-Sept) period at treated watershed J compared to control watershed C, 1974-1988

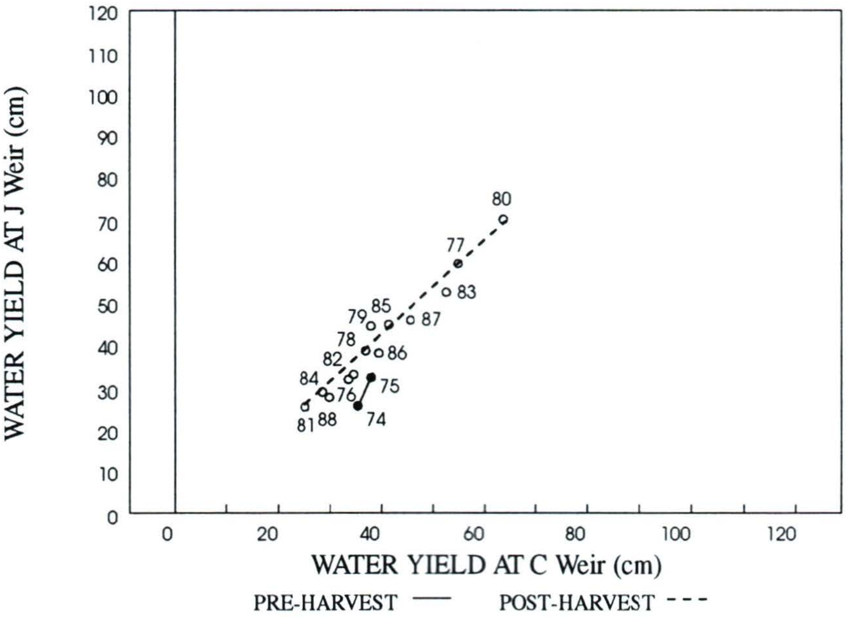

Figure 5.5-15 Relationship between dry (Apr-Sept) season water yields for control watershed C and treated watershed J for pre-harvest and post-harvest periods

Table 5.5-5 Streamflow changes for seasonal yields (cm) in J watershed during 1978-1988 post-harvest period

| YEAR | WET (Oct-Mar) | DRY (Apr-Sept) |
|---|---|---|
| 1978 | 14.7 | 10.0 |
| 1979 | 37.6 | 11.7 |
| 1980 | 26.7 | -26.5 |
| 1981 | 51.3 | 28.2 |
| 1982 | 42.3 | 10.6 |
| 1983 | 51.3 | -13.9 |
| 1984 | 32.6 | 22.2 |
| 1985 | 16.2 | 4.0 |
| 1986 | 24.5 | 4.6 |
| 1987 | 23.8 | -6.4 |
| 1988 | 32.3 | 16.1 |
| 1978-1983 | 37.3 | 3.4 |
| 1984-1988 | 25.9 | 8.1 |
| 1978-1988 | 32.1 | 5.5 |

### 5.5.3 Monthly water yields

#### H Watershed

For the first six post-harvest years in H watershed, mean monthly water yields showed increases ranging from 0.25 cm in March to 11.5 cm in December (Figure 5.5-16). Larger increases were observed for individual winter months (mean=5.8 cm), than for individual summer months (mean=1.73 cm). The largest increases in monthly water yields tended to occur four to six years post-harvest during the winter months and one to three years post-harvest during the summer months, with the exception of April and May.

Minimal temporal variation between monthly water yield increases was observed for October, December, January, May and September in the first six years after

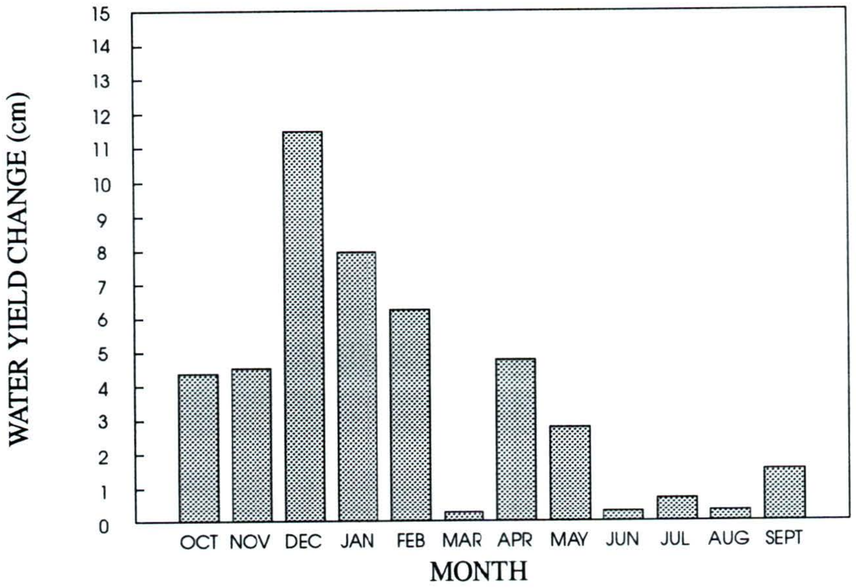

Figure 5.5-16 Mean monthly water yield changes at H watershed during 1978-1983 post-harvest period

harvesting. Relative water-yield changes in remaining months were wide ranging and variable. Post-harvest monthly water yields for November, April and August all exhibited poor correlations between control watershed C and treated watershed H and relative to the pre-harvest regression calibration. Post-harvest regression relationships for these months were not significant ($r^2 = 0.13 - 0.68$). However, each of these months showed a single individual year yield value that was much higher than the monthly mean. As a result, mean monthly water-yield increases appear high.

The distinct increasing and decreasing trends depicted by annual and seasonal yields are not repeated for the monthly periods. There appears to be no consistent temporal pattern exhibited in either of winter wet or summer dry months. The only change shown most clearly is the shift of increased post-harvest water yields for months described as having minimal temporal variations (October, December, January, March, and September). These months illustrate a direct and parallel shift in slope from pre-harvest calibration to the post-harvest period.

### J watershed

Monthly water-yield increases in J watershed were variable. For the period 1978-1988, mean monthly increases ranged from 2.2 cm (15%) in October to 11.0 cm (83%) in March. During the first six post-harvest years, mean increases were highest in March (13.0 cm). The largest increases in mean monthly water yield occurred for individual winter months (mean=5.6 cm). Mean monthly water yields for individual dry season months (April, May, and August), were observed to be below pre-harvest levels.

The temporal distribution of monthly water yields was also highly variable and no temporal pattern was established throughout the post-harvest period for any month. Only November, March and September had consistent water yield increases over the period of interest. The mean increase between 1978-1983 was 10.9 cm, 13 cm, and 1.7 cm, respectively. These increases were lower during the 1984-1988 period at 7.6 cm, 8.7 cm, and 0.39 cm respectively. In relative terms, water-yield increases were large at 46%, 101%, and 26% for these months. In the remaining months, water-yield increases were highly variable and January, April, May and August, no mean monthly water yield increases were observed.

## 5.6 Climatic Variables

The major hydrologic processes influencing water yields have been identified as precipitation, interception and evapotranspiration. The amount and rate at which these occur are dependent on other climatic factors such as air temperature and solar radiation. Observations of mean daily air temperature and solar radiation were analysed and are reported for annual, seasonal and monthly periods to assist in explaining water yield changes.

### 5.6.1 Air temperature

Mean annual air temperatures in the Carnation Creek watershed ranged from 4.4 °C to 14 °C averaging 8.0 °C between 1972-1988. Dry season temperatures averaged

10 °C ranging from 6.8 °C to 19 °C, while winter temperatures ranged from 1.0 °C to 10.5 °C, averaging 4.9 °C (Table 5.6-1). Minimum values generally occur in February and maximums in August. The annual distribution of temperature corresponds to solar radiation input and day length. Temperatures begin rising in spring as the days begin to lengthen and peak in late summer with solar radiation maximums and long-wave radiation emissions from the ground surface (Figure 5.6-1).

Mean pre-harvest air temperatures were lowest during the period of interest at both H and J watersheds at 7.0 °C and 7.5 °C (Table 5.6-1). Temperatures were highest during the first six year post-harvest period (1978-1983) at 8.4 °C and 8.8 °C. At both watersheds, the warmest year during the period of interest was water year 1982. Temperatures dropped slightly between 1984 and 1988 but remained higher than the pre-harvest period with mean annual values of 7.5 °C and 8.4 °C.

Annual temperatures at H and J watersheds were driven by seasonal highs and lows. The pre-harvest wet season temperatures were coooler with the mean seasonal low occurring in water year 1974, at Station C (3.3 °C), and 1988, at Station E (2.5 °C) (Table 5.6-2). Alternatively, dry season temperatures were highest during the 1978-1983 post-harvest period with the mean maximum dry season temperature occurring in 1982 (12.4 °C and 12.9 °C). Seasonal air temperatures for both Station C and E followed the annual distribution by dropping slightly between 1984-1988.

### 5.6.2 Solar radiation

Annual solar radiation inputs average 230 langleys, ranging from 167 to 292 langleys. Seasonal means are highest in summer (Apr-Sept) averaging 353 langleys and ranging from 244 to 485 langleys. They are lowest in winter (Oct-Mar) averaging 108 langleys and ranging from 76 to 138 langleys (Figure 5.6-1). Maximums throughout the year have been observed to occur in July and minimums in December. Annual solar radiation remains relatively constant throughout most of the period of interest,

Table 5.6-1 Mean annual air temperature (°C) at Station C (J watershed) and Station E (H watershed), 1972-1988

| YEAR | STATION C | STATION E |
|---|---|---|
| 1972 | 7.8 | 7.0 |
| 1973 | 7.7 | 7.2 |
| 1974 | 7.0 | 6.8 |
| 1975 | 7.3 | 7.1 |
| 1976 | 8.1 | 7.6 |
| 1977 | 8.2 | 8.0 |
| 1978 | 8.1 | 7.6 |
| 1979 | 8.9 | 7.9 |
| 1980 | 9.8 | 9.4 |
| 1981 | 8.4 | 8.0 |
| 1982 | 9.4 | 9.4 |
| 1983 | 8.4 | 8.2 |
| 1984 | 8.0 | 7.4 |
| 1985 | 8.9 | 7.6 |
| 1986 | 8.8 | 8.2 |
| 1987 | 8.5 | 7.3 |
| 1988 | 8.0 | 7.1 |
| 1972-1975 | 7.5 | 7.0 |
| 1978-1983 | 8.8 | 8.4 |
| 1984-1988 | 8.4 | 7.5 |
| 1978-1988 | 8.6 | 8.0 |

ranging between 220-270 langleys. However, between 1978-1981, values less than 200 langleys occurred, while a spike of 292 langleys was measured in 1987 (Figure 5.6-2).

Pre-harvest annual solar radiation at Station A averaged 243 langleys, slightly below the annual high period between 1984-1988 which averaged 251 langleys (Table 5.6-3). The first six year post-harvest period between 1978-1983 had the lowest solar radiation (206 langleys).

Table 5.6-2 Mean seasonal air temperature (°C) at Station C (J watershed) and Station E (H watershed), 1972-1988

| YEAR | STATION C | | STATION E | |
|---|---|---|---|---|
| | WET | DRY | WET | DRY |
| 1972 | 4.7 | 10.9 | 3.4 | 10.6 |
| 1973 | 3.7 | 11.7 | 3.4 | 11.0 |
| 1974 | 3.6 | 10.4 | 3.3 | 10.3 |
| 1975 | 3.6 | 10.9 | 3.6 | 10.6 |
| 1976 | 4.9 | 11.4 | 4.6 | 10.6 |
| 1977 | 4.6 | 11.7 | 4.3 | 11.6 |
| 1978 | 4.1 | 12.2 | 3.3 | 12.0 |
| 1979 | 5.4 | 12.3 | 4.8 | 11.1 |
| 1980 | 7.2 | 12.3 | 6.5 | 12.3 |
| 1981 | 4.9 | 11.8 | 4.5 | 11.6 |
| 1982 | 6.3 | 12.4 | 5.9 | 12.9 |
| 1983 | 5.3 | 11.5 | 5.2 | 11.3 |
| 1984 | 4.0 | 12.0 | 3.6 | 11.3 |
| 1985 | 4.9 | 12.9 | 3.4 | 11.3 |
| 1986 | 6.1 | 11.5 | 5.3 | 11.1 |
| 1987 | 5.6 | 11.4 | 4.8 | 9.9 |
| 1988 | 4.0 | 11.9 | 2.5 | 11.7 |
| 1972-1975 | 3.9 | 11.0 | 3.4 | 10.6 |
| 1978-1983 | 5.5 | 12.1 | 5.0 | 11.8 |
| 1984-1988 | 4.9 | 11.9 | 4.1 | 11.0 |
| 1978-1988 | 5.3 | 12.0 | 4.6 | 11.5 |

The annual amounts were once again influenced by seasonal effects. Dry season solar radiation was highest between 1984-1988 at 391 langleys. The lowest amount occurred in the pre-harvest period at 295 langleys. Wet season solar radiation was highest in the pre-harvest period (117 langleys) and lowest during the 1978-1983 period (99 langleys).

Table 5.6-3 Mean annual and seasonal solar radiation (langleys) at Station A, 1972-1988

| YEAR | ANNUAL | WET | DRY |
|---|---|---|---|
| 1972 | 247 | 128 | 366 |
| 1973 | 241 | 97 | 385 |
| 1974 | 265 | 138 | 392 |
| 1975 | 219 | 104 | 335 |
| 1976 | 231 | 97 | 365 |
| 1977 | 270 | 130 | 409 |
| 1978 | 201 | 126 | 275 |
| 1979 | 177 | 80 | 275 |
| 1980 | 167 | 89 | 244 |
| 1981 | 190 | 76 | 303 |
| 1982 | 256 | 99 | 413 |
| 1983 | 245 | 123 | 367 |
| 1984 | 254 | 120 | 388 |
| 1985 | 224 | 104 | 345 |
| 1986 | 228 | 98 | 359 |
| 1987 | 292 | 100 | 484 |
| 1988 | 256 | 131 | 381 |
| 1972-1975 | 243 | 117 | 295 |
| 1978-1983 | 206 | 99 | 313 |
| 1984-1988 | 251 | 111 | 391 |
| 1978-1988 | 226 | 104 | 348 |

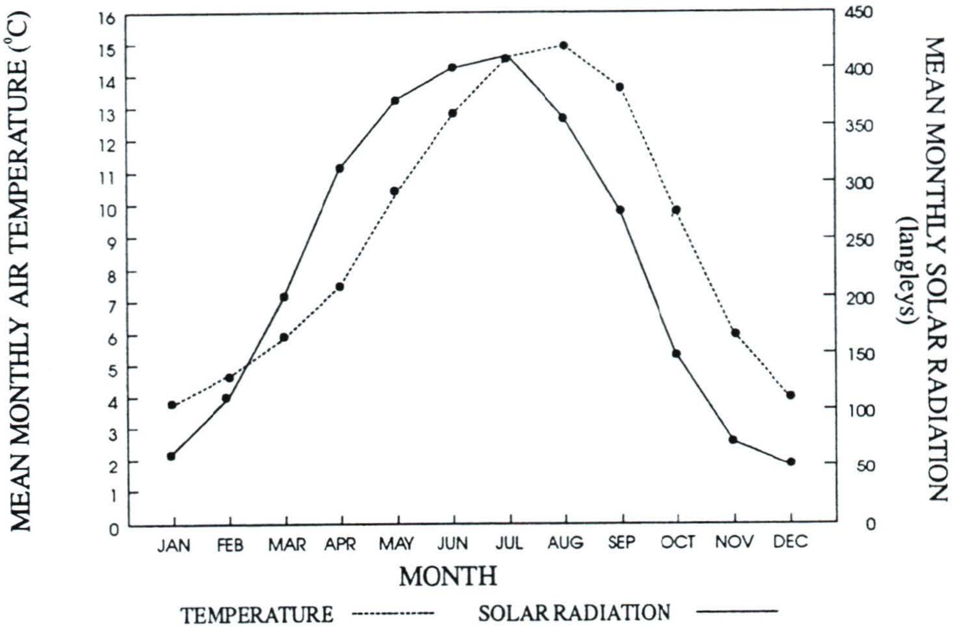

Figure 5.6-1 Mean monthly air temperature and solar radiation in the Carnation Creek watershown as shown by Station A, 1972-1988

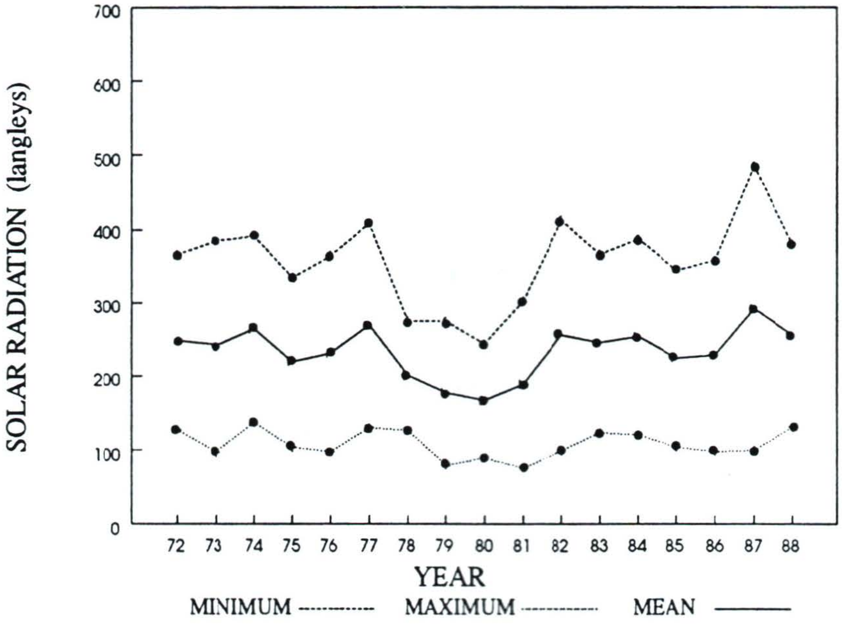

Figure 5.6-2 Minimum, maximum and mean solar radiation for Station A, 1972-1988

# CHAPTER 6

# DISCUSSION

## 6.1 Introduction

The purpose of this chapter is to evaluate and interpret the post-harvest changes in annual water yields at H and J weirs. The discussion begins with a review of the research hypotheses, followed by an examination of post-harvest water yield changes in the treated watersheds. Changes in water yields are explained in terms of forest hydrologic processes and the effects of timber harvesting on those processes. Annual evapotranspiration losses are estimates calculated by subtracting water yield from precipitation as described in Chapter 4. For the purpose of discussion, evapotranspiration estimates will be referred to as observations in the text. As an indepth understanding of the complexities of a west-coast forest hydrologic system would require a more detailed data collection program than was carried out, the interpretation and explanation of annual water yield results in Carnation Creek is acknowledged to be dependent on the available data.

## 6.2 Water Yields

Timber harvesting removes two important physical characteristics of the forest: the ability to intercept precipitation; and, the ability to convert liquid water to vapour at pre-harvest rates. The main hypothesis of this research project states that increases in annual water yield can be attributed to reduced evapotranspiration and interception losses which result in more water being available for streamflow.

This hypothesis was further defined in terms of when these increases might occur throughout the year, timing of increases relative to the harvesting schedule, and the influence of forest hydrological processes on annual water yields. It was hypothesized that increases in annual yield would be greatest during the winter wet season. During this period, soils quickly become saturated and do not require as much moisture to recharge as after the summer dry season, which would allow more available water to enter the stream channel. Increases were also expected to be largest immediately after harvesting and to decrease over time as the regrowth of vegetation occurred.

### 6.2.1 Pre-harvest conditions

Post-harvest changes in annual water yield can be evaluated properly only with an understanding of pre-harvest conditions in the watershed. The calibration period of four years is the shortest of all studies in the Pacific Northwest region, with the exception of one (Mahacek-King and Shelton, 1987), and is acknowledged to be a limitation of the study. A short calibration period may be characterised by uniform climate; therefore, a longer calibration period would increase the chance of including a greater range of data through climate variability (Wilm, 1949). However, despite the short calibration period, substantial climatic variation was observed in all sub-basins. Precipitation maximums occurred during water years 1973 and 1975 and have not been repeated. Precipitation lows occurred during 1972 and 1974 and although not minimum values, were below the mean. The influence of these precipitation patterns was reflected in the corresponding annual water yields which followed this low, high, low, high pattern. The benefit of this variability was in creating a range of values, albeit biased toward the higher end of the scale, against which post-harvest changes could be compared. Had the calibration period been characterised by four low or four high precipitation years, the resulting post-harvest changes would have been markedly difficult to assess.

Climate data available for the Carnation Creek watershed indicate that the pre-harvest period was slightly cooler than the post-harvest period. Mean annual and seasonal air temperatures were lowest and dry season solar radiation was also lowest during this period. The dry season water years 1972 and 1974 correspond to high solar radiation values on both an annual and seasonal basis (Table 5.6-3). Precipitation maximums correspond to low wet season solar radiation values, during 1973 and 1975, when the majority of annual precipitation falls.

A strong pre-harvest relationship exists between precipitation and water yield in both control watersheds C and E, and treated watersheds H and J, as shown by the example given in Figure 5.2-8. The temporal pre-harvest relationship between all four sub-basins is strong, although both precipitation and water yield in E watershed is higher and significantly different than in C, H, and J watersheds.

The premise of the paired basin method is that basins should be similar in size, shape, geology, exposure and elevation (Hewlett, 1971). Control watershed E is different geomorphologically from control watershed C and treated watersheds H and J in size, exposure and elevation, but it was similar in shape and geology. The west-facing aspect and steep, high elevation slopes of watershed E make it directly subject to prevailing storm systems and local orographic effect. C, H, and J watersheds are much smaller in size, have differing aspects (C: north; H and J: south), and are lower in elevation. The impact of these geomorphological differences is reflected in the higher amounts of precipitation received in E watershed and the larger percentage of precipitation which becomes streamflow. As a result, the following discussion focuses on making comparisons with C watershed.

### 6.2.2 Annual water yields

#### H watershed

Annual water yields in H watershed increased by almost 20% between 1978-1983, 18% between 1984-1988, and 19% overall between 1978-1988 after 90% of the watershed was harvested between 1975-1976. The water yield increases were statistically significant at the 95% confidence level allowing rejection of the null hypothesis that post-harvest water yields are not different than pre-harvest water yields. The most significant influence on increased post-harvest water yields would be the removal of timber from the sub-basin and the resulting increase in available water due to reduced evapotranspiration and interception.

A closer look at the distribution of annual water yield increases throughout the period of interest reveals some unexpected results. Annual water yield increases in H watershed were lowest during the first year after harvesting, rising each subsequent year with the highest increase occurring in the sixth post-harvest year. It was expected that increases would be largest immediately after harvesting when evapotranspiration and interception losses would be greatest, with water yields decreasing over time as vegetation regrowth occurred. These results reflect the influence and distribution of post-harvest annual precipitation. In the first year after harvesting, water year 1978, annual precipitation was the lowest for the period of interest (Figure 5.2-3), being 27% below average. The corresponding annual water yield increase during this year was also the lowest at 16.6 cm (9.5%) or 60% below the mean annual increase. This contrasts to water year 1983, six years after harvesting occurred, when annual precipitation was 16% above the mean and the annual water yield increase for that year was 74% above average.

Increases in annual water yields during the first six years after harvesting were matched by corresponding decreases in evapotranspiration for the same water years as the increases occurred. The exception to this was the first year post-harvest (1978) when the observed annual evapotranspiration was higher (by 2.4 cm) rather than lower (Figure 5.4-4). For the evapotranspiration decrease to correspond with the increase in annual water yield during this year, the observed evapotranspiration should have been about 36 cm rather than the actual amount of 55 cm.

The observed evapotranspiration was calculated on a simple water balance method which assumes that the difference between water yield and precipitation is water lost to the atmosphere. The evapotranspiration calculations are, therefore dependent on the original data. For evapotranspiration to be higher than the predicted amount, it can be reasonably assumed that water yield for the same period would be lower than expected.

For evaporation to occur, liquid water is in contact with an unsaturated atmosphere (Lee, 1980). In a forested or harvested stand, this situation happens when precipitation has either been intercepted by vegetation or the exposed soil is wet. After harvesting, remaining slash and ground vegetation will also intercept precipitation, which may subsequently evaporate.

The climatic and physical condition of H watershed likely contributed to the higher than expected amount of evapotranspiration. Midway through water year 1978 (April, 1979), after the winter wet period, 35% of H watershed was slashburned. The burning would result in more precipitation reaching the ground surface, although remaining slash accumulations would still intercept precipitation. Precipitation during the winter wet period (October-March) was 33% below the mean and monthly precipitation values for the same winter period, were 34-79% below average. This suggests that the precipitation which fell during water year 1978 was characterised by rainfall separated by much longer dry periods than normal or by lower rainfall intensities. It is possible that an above average amount of the intercepted precipitation evaporated before it was able to enter the soil and subsequently, the stream channel. During this period also, solar radiation was 18% above normal, ranging from 17-50% above the mean on a monthly basis. This means that more radiant energy was available for evaporation processes. Air temperatures at Station E, immediately adjacent to H watershed, are close to the mean for this period. Therefore, it is possible that more evapotranspiration than predicted occurred as evaporation from the wetted surfaces. Subsequently, this would also result in reduced streamflows.

Between water years 1979-1983, increases in annual water yields in H watershed corresponded with reductions in evapotranspiration, with minor exceptions in 1979 and in 1982. Evapotranspiration estimates made on an annual basis assume that the storage influence is negligible over time. However, this assumption may not hold for every year and storage of soil water may be a factor in those years when reductions in evapotranspiration do not exactly correspond to increases in water yield.

The initial assessment of water yield increases in H watershed focused on the first six year period after 90% of the forest cover was removed. The remaining 10% was harvested in the spring of 1985. Bosch and Hewlett (1982) report that changes in water yield are not detectable when less than 20% of forest cover has been harvested. However, they also reported that in areas covered by coniferous forest, a 4 cm increase will occur for every 10% change in forest cover. A number of factors were in place that prompted the decision to include water year 1984 in the analysis despite this additional disturbance. These factors relate primarily to the below average annual precipitation in 1984, and the initial revegetation in the watershed after harvesting. This combination of climatic and revegetation conditions could potentially offset water yield increases that would result from the additional timber harvesting. Other considerations included the fact that access to the harvested area was from outside the watershed and harvesting was conducted between January and March in a concentrated area. This increased the total clearcut area to 100% in the watershed.

Water year 1984 was characterised by a sharp decline in streamflow in H watershed. This decline marks the end of the pattern of increasing water yields. Over this year, an estimated 15 cm increase in annual water yield occurred, a decrease from 72 cm the previous year and 61% below the mean annual increase. Corresponding evapotranspiration losses for this year were also low (22 cm). The combination of low precipitation and increased surface area on regrowing vegetation for the interception of rainfall would tend to decrease the amount of water available for water yield. The amount of precipitation received in H watershed during this year was the lowest for the period of interest (234 cm or 27% below average). Recovering vegetation had become well-established in the harvested areas, with planted conifers having reached heights of 2 m by the fifth year after harvesting. Understory vegetation, such as salmonberry and sword fern, had reached 90% and 70% coverage respectively (Hartman and Scrivener, 1990). Both trees and understory vegetation would provide increased interception and evapotranspiration surfaces. An additional factor was a leak in H weir, noticed in 1986, which could have been initiated as early as 1984. Water yields were possibly abnormally low for this year as a result of the leak (Hetherington, *personal communication*, 1993).

After water year 1984, streamflow increases in H watershed returned to higher levels, observed in the period between 1978-1983, after which the yields appear to decline at a relatively steady rate to 1988 (Figure 5.5-2). This observation suggests that water yields could be returning to pre-harvest levels. The mean annual increase between 1984-1988 was 32.4 cm, down 9.5 cm from the initial six year post-harvesting period. Excluding 1984, the increase is 36.9 cm or 5.0 cm lower. This indicates the possibility that water yields were beginning to recover. During this period also, mean annual precipitation dropped 52 cm from the 1978-1983 period. As water yield and precipitation are closely associated, the lower amounts of water yield increases during the 1984-1988 period may also be related to the lower amounts of annual precipitation which fell during this period.

It was expected that as water yields decreased, evapotranspiration amounts would increase. Computed annual evapotranspiration amounts at H watershed for the period 1984-1988 was 37.1 cm or 4.6 cm higher than the 1978-1983 post-harvest period (Figure 5.4-4). Again, excluding 1984, evapotranspiration for 1985-1988 is 40.8 cm or 8.3 cm higher. Although these values roughly correspond to the mean water yield change of 32.4 cm or 9.5 cm lower when compared to the 1978-1983 time period, excluding water year 1978 from the analysis results in computed evapotranspiration being 2.3 cm lower (Figure 5.5-2). Either way the results indicate that water yields appear to be recovering more quickly than evapotranspiration amounts, but also that less water is being made available for streamflow.

The difference between recovering water yields and evapotranspiration may possibly be due to the combination of recovering vegetation and soil water storage. As the regrowth of vegetation occurs, evapotranspiration is ongoing but at a lower rate than during the pre-harvest period. Higher rates of evapotranspiration will occur in mature old-growth forests because of the more extensive root systems and greater rooting depths. Deeper rooted plants can tap water in the subsoil and continue to transpire after the water content of the topsoil is depleted (Dunne and Leopold, 1978). Tree height is also important as the upper canopy is subject to higher wind velocities and increased surface roughness where greater turbulence causes an increase in evaporation away from leaf surfaces.

Taking into account the decreasing water yields and the lower rate of water consumption by vegetation, the difference between the two rates could be in part explained by soil water storage. However, it is also important to recognize that evapotranspiration is computed as the difference between precipitation and runoff. As this method only provides an estimate of evapotranspiration and assumes the storage component to be negligible on an annual basis, it is difficult to assess whether or not this difference is a true product of the data or concealed by the method.

### J watershed

Mean annual water yield in J watershed increased 28% during the 1978-1988 post-harvest period. As with water yield increases at H watershed, the results were statistically significant at the 95% confidence limit. The null hypothesis, which states that post-harvest water yields are not significantly different than pre-harvest water yields, was rejected.

The distribution of annual water yield increases in J watershed followed a similar temporal pattern as illustrated by H watershed. During the first six post-harvesting years, increases were lowest the first year and continued to rise until maximum increases were reached in water years 1981 and 1983 (Figure 5.5-6). Again, it was expected that first year increases in water yields would be the largest when the removal of timber would cause evapotranspiration and interception losses to be highest. Precipitation amounts over this period are likely affecting the temporal distribution of water yields. Water year 1978, the first year after harvesting, was marked by the lowest precipitation for the period of interest (26% below the mean). Corresponding water yields for that year were the lowest for the period of interest at 27 cm (20%) or 39% below the mean annual increase. This compares to a water yield increase, six years after harvesting, of 62 cm (36%) or 41% above the mean annual increase. During this year, 1983, precipitation was 15% above the mean and 19% above the post-harvest mean.

In each post-harvest water year, annual water yield increases were matched by corresponding decreases in evapotranspiration. During the same 1978-1983 period, a mean water yield increase of 50 cm compared to a mean evapotranspiration reduction of 52 cm. Evapotranspiration amounts during water year 1984 (one year after harvesting), decreased in J watershed as opposed to the apparent increase in H watershed. It was hypothesized that more evapotranspiration than predicted may have occurred in H watershed as a result of combined low rainfall, extended dry periods and high solar radiation. The difference in the evapotranspiration amounts for that year may be attributed to the proximity of the sub-basins in the watershed to the ocean. Because J watershed is situated closer to the ocean, atmospheric humidity may be higher and the watershed may receive more moist air than H watershed, which is also sheltered somewhat by a ridge.

The post-harvest period between 1984-1988 shows water yields have decreased, although the pattern is not as clearly defined as at H watershed. Water yields increased an average of 35.4 cm, 5.8 cm lower than the 1978-1983 post-harvest period. This observation corresponds to declining water yields for the same period in H watershed, suggesting that the water yields are beginning to return to pre-harvest levels. Water yields at J weir in 1984 did not exhibit the sharp drop as at H weir. The more gradual decline of water yields at J weir supports the suggestion of a leak at H-weir beginning in 1984.

The influence of precipitation on water yields during this period is strong as shown by Figure 5.2-11, where the temporal distribution of both precipitation and water yields follow the same pattern. Precipitation remained consistent during water years 1985 and 1986 with amounts of 275 cm and 283 cm. Annual precipitation then declined to 252 cm and 236 cm during 1987 and 1988. These values represent the least amount of variability of precipitation throughout the period of interest and this is emulated by the resultant annual water yields (Figure 5.5-6). It is possible that the decline in water yields from water years 1978-1983 to 1984-1988 indicate the beginning of recovering streamflows. As a distinct trend in declining water yields is not evident during this period, it is however, difficult to state that water yields at J watershed are returning to pre-harvest levels.

Computed annual evapotranspiration amounts in J watershed between 1984-1988 are 16.6 cm (32%) lower than the initial post-harvest amounts. Mean annual evapotranspiration losses of 35 cm corresponded to water yield increases of 35 cm in J watershed for the 1984-1988 period. Annual evapotranspiration amounts not only correspond to water yields but follow the same temporal distribution as water yields. As with water yields, Figure 5.4-5 shows the reduced amount of evapotranspiration but it is difficult to determine whether or not this is the beginning of a trend.

The decrease in computed annual evapotranspiration in J watershed for the 1984-1988 period compares to a relative increase (4.6 cm) in H watershed for the same time period. It was expected that changes in evapotranspiration would correspond to changes in annual water yield where as water yield recovered, evapotranspiration would follow. This does not apply in H watershed although much of this can be attributed to water year 1978 where the observed evapotranspiration was higher than predicted. If water year 1978 is excluded from the analysis, then the computed evapotranspiration amount of 39.4 cm more closely corresponds to the annual water yield change of 41.9 cm. Computed evapotranspiration for the 1984-1988 period then results in a relative decrease as in J watershed.

### Climate variables

The hypothesis stated increases in annual water yields would be largest immediately after harvesting when evapotranspiration and interception losses would be greatest, with yields decreasing over time as vegetation regrowth occurred. In both H and J watersheds, water yields have been observed to have increased after harvesting and appear to be beginning recovery towards the end of the period of interest. Additional climate data was available to supplement the discussion on annual water yields in terms of these two important forest hydrology processes.

Computed potential evapotranspiration (PET) calculated as the sum of computed interception and transpiration totaled 135.3 cm on an annual basis. The interception and transpiration values computed were 43% and 54% of annual PET. These percentages can be applied to an average pre- and post-harvest year to estimate how much water may have been lost to these processes on an annual basis. If the annual evapotranspiration was 98 cm, then 42 cm and 53 cm could be attributed to interception and transpiration, respectively. For a post-harvest year where evapotranspiration was 54 cm, then interception and transpiration values would decrease to 23 cm and 29 cm respectively.

The above data are estimates only based on computed PET values which assume unlimited moisture availability. It is important to remember that evapotranspiration rates at the end of the period of interest would not have recovered to levels experienced by the pre-harvest coniferous forest. Conifers are reported to have the highest evapotranspiration rates on an annual basis, with deciduous species and brush/grass cover having lower rates (McNaughton and Jarvis, 1983). Regrowth of vegetation after harvesting began with salal, salmonberry and alder species. Although these vegetation types were well-established by this period (Hartman and Scrivener, 1990), evapotranspiration rates would not have recovered to pre-harvest levels.

Interception data collected between water years 1982 and 1988, suggest an average annual interception value of 32%. This data set represents both vertical rain interception and the horizontal interception of low cloud and fog. Where rain collected in the open was less than 'precipitation' under the canopy, this data was extracted and attributed to fog drip and found to equal 11.5%. The mean net annual interception was then determined to be the amount of rain collected in the open less the rain under the canopy which equalled 20.5%.

The interception of fog water by trees has been presented in other studies as influencing the change in annual water yields (Harr, 1982; Ingwersen, 1985: Mahacek-King, 1987). At Carnation Creek, this process was suggested as a possible explanation for apparent decreases in water yield on the mainstem weir and then subsequently discounted (Hetherington, 1982;1987). At H and J weirs, annual water yield increases after harvesting were 37.6 cm and 44.0 cm over the period of interest. If the seven year average of 11.5% is applied to the computed mean annual interception value of 71.6 cm for the period of interest, then 8.2 cm could be attributed to fog precipitation under the canopy.

### 6.2.3 Seasonal water yields

The distribution of annual water yields is important with respect to the varying influence of hydrologic processes. Although annual water yields are driven by precipitation inputs to the forest system, it is the seasonal variation in precipitation which controls the distribution of water yields throughout the year. Water yield increases are expected to be higher in the winter period than in the dry season because of the differing role forest hydrological processes play. Winter is characterised by high precipitation, cloudier conditions, low solar radiation, low daily temperatures and short day lengths. All of the above conditions act to limit transpiration and subsequently, less water made available by precipitation is used by the trees. Conversely, the summer growing season is characterised by low precipitation, clear skies, high solar radiation, high daily temperatures and long day lengths. These conditions act to maximize transpiration whereby more water is taken up for use by the trees leaving a smaller percentage for runoff. The analysis and following discussion of changes in seasonal water yields are used to explain the reasons for annual water yield changes.

### H Watershed

#### Wet (October-March) season

Wet season water yields in H watershed increased 19% between 1978-1983, 22% between 1984-1988 and 20% overall between 1978-1988. Water yield increases were statistically significant at the 95% confidence limit. The null hypothesis, which stated that post-harvest wet season water yields would not be significantly different from pre-harvest water yields, was rejected.

The distribution of wet season water yields closely follows that of annual water yields in H watershed with increases lowest (7.1 cm) during the first year after harvesting and peaking six years later (56.5 cm). These results demonstrate the influence of wet season precipitation on corresponding water yields. Wet season water yield increases in 1978 were 78% below the mean increase for the period between 1978-1983 when corresponding wet season precipitation was the lowest for the period of interest at 33% below the mean. This value compares to water year 1983 when seasonal water yield increases were 43% above average and seasonal precipitation was 8% above average.

Between 1984-1988, the range in water yield increases is smaller (16.3-38.7 cm) and follows the temporal distribution illustrated by annual water yields (Figure 5.5-2). Water yield increases drop 40.2 cm to 16.3 cm in water year 1984, rising 22.4 cm the following year, and then appear to begin a slight downward trend to the end of the period of interest. The exception to this is water year 1988 which shows a small increase of 5.2 cm from 1987. The overall increase in seasonal water yields during this period is 17% lower than the first six years after harvesting which corresponds to precipitation which is 14% lower when compared to the same time period.

These results indicate the influence of precipitation on seasonal water yields. In H watershed, approximately 74% of the annual precipitation falls between October and March. The wet season water yields correspond to this percentage on an absolute basis with 79% of the mean annual runoff occurring during this season. During the post-harvesting period water yields range from 70%-88% of the annual runoff between 1978-1983 and 73%-85% between 1984-1988.

In terms of relative water yield changes, relative being the difference between observed and predicted water yield, the influence of precipitation is not as evident while other hydrological processes are. In the first six years after harvesting, the change in wet season water yields as a percentage of annual runoff ranges from 45% in water year 1978 to 99.5% in 1982 with a mean of 77%. It was expected that wet season water yields would be greater than in summer. This is primarily due to a combination of lower transpiration rates in winter and soils which become saturated from winter rains. Therefore, less moisture is required to recharge the soils leaving more water available for streamflow. This hypothesis holds for the post-harvest period where the amount of seasonal runoff, proportional to the seasonal precipitation, is 83% compared to 74% in the pre-harvest period. The exceptions to this are water years 1978 and 1984 where the change in wet season water yields were below and above average, respectively (45% and 110%).

During water year 1978, the change in seasonal water yields as a percentage of annual runoff was lower in the wet (Oct-Mar) season than in the dry (Apr-Sept) season (43% vs 58%). This can be explained primarily by the variation in seasonal precipitation for this year which was the second lowest for the period of interest at 159.5 cm or 65% of the annual amount (9% below average). The reason why wet season precipitation can be isolated as the primary cause of below average wet season water yield increases can be attributed to other processes. First, in 1978, the percentage of wet season runoff to annual runoff is 75%. Second, dry season precipitation and water yield are also within 5% of the mean values. In comparison, wet season precipitation and runoff are 32% and 29% below average, respectively.

The hydrological process expected to have the greatest influence on water yield increases during the wet season is the reduction in interception characteristics resulting from timber harvesting. Although evapotranspiration estimates were not calculated on a seasonal basis due to the storage component, potential evapotranspiration (PET) calculations can provide a relative measure. The PET calculations were divided into two components, interception and transpiration. Interception values computed for the wet season are approximately 66% of the annual amount, with the wet season PET value being 42% of the annual PET amount.

Rough estimates of water lost to interception can be determined by applying these percentages to an average pre-harvest and post-harvest year. For an average pre-harvest year where evapotranspiration was 98 cm, the wet season value would equal 41 cm (42%) of which 27 cm (66%) would be accounted for by interception. In comparison, for an average post-harvest year where evapotranspiration is 54 cm, the wet season evapotranspiration would equal 23 cm (43%), of which 15 cm (28%) is lost to interception. Perhaps more importantly, however, an additional loss has already been incurred as a result of timber harvesting and a rough determination of how much water was lost to interception could be made by applying this procedure.

During the winter of 1978, reductions in interception and transpiration are noted by wet season runoff which is 90% of precipitation or 16% above the pre-harvest average. So although the increase in water yield can be attributed to reduced evapotranspiration, it is likely that the small increase can be attributed to the below average wet season precipitation, given that the other hydrological processes are all average with the exception of wet season precipitation. Carrying this thought one step further, if the dry season increase for water year 1978 can be assumed to be average at 20% of the annual change and if the precipitation had been higher, then it's possible to speculate that the wet season water yield increase could have been as much as 45 cm rather than the 7.1 cm observed. This would compare to the mean increase of 32.3 cm between 1978-1983.

In 1984, the computed increase in wet season water yields (16.3 cm) at H watershed is 110% of the computed annual water yield increase (14.8 cm). This discrepancy may be attributed to the leak in the weir which likely started that year. If the leak began that year, it would not be accounted for in the regression equation. What the regression analysis does take into account, however, is the reduced water yield, which is a function of low precipitation. Both runoff and precipitation are below the mean at 18% and 24%, respectively. The predicted water yield for this year is 120.7 cm, down 40 cm from the previous year. The actual observed water yield for 1984 is 137.0 cm or 80 cm lower than the previous year.

In an effort to get a sense of how the observed water yields related to the regression analysis and, subsequently, to estimate how much water may have been lost to the leak in H weir, the difference between successive observed water yields for each water year and the difference between successive predicted values for each water year were compared on an absolute basis and found to range 25 cm. The one exception to this comparison is water year 1984 which has ranges 40 cm and 21 cm taken as the differences between 1983-1984 and 1984-1985. The mean of these differences (30 cm) was then taken as an estimate of the amount of runoff lost as a result of the leak and resulted in an estimated water yield increase of 46.3 cm. The resultant difference in precipitation and runoff (P-Q) is considered as water lost to evapotranspiration and storage. It was found to be below the mean for the 1984-1988 period (43% to 57%). Using the average wet season P-Q value of 57%, a second estimate for the observed water yield was determined to be 163 cm or a 43 cm increase for that year, which is still well within what could have been expected based on the declining trend shown in Figure 5.5-9. Therefore, it is possible that approximately 27 cm of runoff could have been lost as a result of a leak.

### Dry (April-September) season

Dry season water yields in H watershed increased 19% between 1978-1983, 7% between 1984-1988 and 14% overall between 1978-1988. Water yield increases were statistically significant at the 95% confidence limit which allowed rejection of the null hypothesis of no difference between pre-harvest and post-harvest water yields.

The distribution of dry season water yields is highly variable and bears no relation to the annual distribution (Figure 5.5-11). The variability is likely due to the smaller proportion of annual precipitation and subsequent runoff in the watershed. On an absolute basis, dry season water yields are on average 20% of the annual runoff and approximately 58% of the dry season precipitation occurs as runoff.

It was expected that increases in dry season runoff would be smaller on an absolute basis than the increases which occurred during the wet season. Dry season water yield increases occur in all post-harvest years ranging from 0.06 cm in 1984 to 13.91 cm in 1981. The exceptions to this include water years 1982 and 1988, where water yields are at pre-harvest levels and show no relative increase. The average increase during the first six years after harvesting, was 8.4 cm and between 1984-1988, the average increase dropped to 2.8 cm.

During both 1982 and 1988, the observed water yield was below the predicted water yield. Although the 1988 value represents conditions 10 years after harvesting and, therefore, includes 10 years of regeneration, both of these water yield values are well below the average. In both cases, seasonal runoff for these years are the lowest and second lowest as a percentage of annual runoff at 12% and 15%, respectively. Dry season precipitation for 1982 is average, although the 1988 value is 36% below the mean and the lowest for the period of interest. The reason for these low water yields is likely attributed to a combination of the low precipitation (1988) and above average air temperatures (1982) (Table 5.6-3).

In concert with this is water year 1984 and the 1984-1988 post-harvest period. The seasonal runoff for 1984 is also below average and the relative increase is neutral. As discussed earlier, this is possibly the result of a leak in the weir. If the 1984 wet season estimate of 163 cm is taken to be proportional to the annual runoff at 80%, then the dry season proportion would be 20%. This would result in an estimated observed 1984 dry season water yield of 41 cm and a subsequent estimated increase of 12 cm.

Water yield increases occurring in the dry season are attributed primarily to reductions in transpiration. Returning to the PET calculations, transpiration values during the dry season are an average of 83% of the annual amount. In comparison, the dry season PET value is an average 58% of the annual amount. If the assumption is made that these percentages can be applied to evapotranspiration values in H watershed for an average pre-harvest and post-harvest year, a determination of water lost to transpiration can be estimated. Returning to the example of an average pre-harvest year where evapotranspiration is 98 cm, and using the percentages above, 57 cm (58%) of water is lost to transpiration and of this, 47 cm (83%) is consumed during the dry season. Conversely, during an average post-harvest year where 54 cm of water is evapotranspired, 31 cm would be lost to transpiration of which 26 cm is lost during the dry season. However, these are rough estimates and intended only to serve to illustrate the hydrological processes and help explain where throughout the year water losses occurred.

## J Watershed

### Wet (October-March) season

The wet season water yield in J watershed increased 27% between 1978-1983, 24% between 1984-1988 and 25% overall between 1978-1988. These values were statistically significant at the 95% confidence limit. This allowed rejection of the null hypothesis stating no significant difference between pre-harvest and post-harvest water yields.

As with the results at H watershed, the increases in seasonal water yields at J watershed followed a temporal pattern similar to the annual distribution. Comparatively with H watershed, the increases in water yield are lowest (14.7 cm) during the first year after harvesting and are highest (51.3 cm) six years later. These results, not surprisingly, reflect the influence of wet season precipitation on the annual distribution. Precipitation in J watershed during this season averages 75% of the annual amount, ranging from 66%-84%. Water yields, on an absolute basis, reflect this as being an average 78% of the annual runoff.

In water year 1978, wet season water yield increases are 61% below the mean for the 1978-1983 period with corresponding seasonal precipitation at 35% below average for the same period. Precipitation is also the lowest for the entire study period. Conversely, in 1983, water yields are 28% above the mean and precipitation is 9% above average.

During the period 1984-1988, wet season water yields are slightly lower with a mean increase of 25.9 cm and continue to follow the annual distribution (Figure 5.5-6). Water yields appear to be declining during this period, but a look at precipitation for the same period shows it to be 12% below the 1978-1983 period. This is likely having an influence on the lower water yields which are 31% lower than the 1978-1983 period.

On a relative basis, wet season water yield increases contribute a larger percentage of the annual increase. Seasonal increases in J watershed average 80% of the annual change in the first six years after harvesting, declining to 69% between 1984-1988. In the first year after harvesting, 88% of the precipitation which fell in J watershed was converted to runoff. This compares to a mean pre-harvest percentage of 68%. Although no seasonal evapotranspiration estimates are available, computed PET data support speculations of how much water could have been lost to interception in J watershed which is comparable to that in H watershed.

Declining water yields between 1984-1988, although partially attributable to lower precipitation, could likely be changing in conjunction with returning vegetation. Hartman and Scrivener (1990) report conifers at 3.5 m in height 10 years after harvesting which would have created an increased surface area for interception to occur.

### 6.2.4 Monthly water yields

The key process attributed to increases in annual water yield was reduced evapotranspiration losses. On the seasonal basis, it was found that interception was the dominant process during the wet (October-March) season and transpiration dominated during the dry (April-September) season. As the seasonal variation in runoff helps to explain increases in annual water yields, the distribution of monthly water yields provides a more indepth look at the increases in seasonal and annual runoff.

#### H watershed

Water yields increased for all months in H watershed overall between 1978-1988. In the first six years after harvesting, water yield increases averaged 5.8 cm for the winter months October to March and 1.7 cm for the summer months April to September. This average increased to 6.5 cm and dropped to 0.79 cm, respectively, between 1984-1988. These increases were statistically significant at the 95% confidence limit for the months of October, December-February, and May.

Although the temporal pattern of wet season water yield increases mirrored the annual distribution, a closer look at the monthly distribution suggests this is a cumulative effect as no temporal pattern is evident in water yield increases for the months October to March. The monthly distribution continues to be highly variable throughout the drier months of April to September which was expected as the seasonal increases were also variable.

The most consistent water yield increases occurred in the months of October, December, January, May and August. The largest increases of 11.7 cm and 8.6 cm occurred in December and January, respectively. December increases were largest on both absolute and relative terms (36%). The late fall increases correspond to seasonal reductions in interception and winter transpiration as well as high precipitation. Close to 30% of annual precipitation occurs in the months of December and January alone and can be as high as 44%.

May and August represent different periods in the dry season. May is in the late spring when soil moisture content is high and monthly precipitation is less than half of most wet season months. August represents late summer conditions when monthly precipitation is at a minimum, transpiration is high and soil moisture content is lower. Although these two months occur when differing hydrological processes dominate in the same season, the consistency may be attributed to precipitation. In both months, the amount of precipitation is relatively consistent with the exception of May 1983. During this year, the maximum monthly precipitation occurred (32 cm) and water yields responded to this with an increase 2.3 times higher than the average. The increases in August are small on an absolute basis (0.31 cm), but large in relative terms (49%). These increases are important because they occur during the time of year when demand for water is highest.

Water yield increases in the remaining months are variable. Monthly precipitation for the post-harvest period is also highly variable ranging from <1 cm to 25 cm, using July as an example. Variable conditions in winter months are likely the result of fluctuating precipitation. Variable conditions in the drier months are likely related to a combination of factors. The dry season corresponds to the growing season when vegetation moisture requirements are highest. It is during this period that climatic factors have their strongest impact. Precipitation is low, transpiration is high, interception and corresponding evaporation are also relatively high during this period. Recovering vegetation will also intercept precipitation, reducing the amount of precipitation reaching the ground surface. These conditions create the potential for a high proportion of precipitation inputs to the watershed to return to the atmosphere. Soil moisture storage is also a factor and some of the precipitation reaching and entering the ground surface will first be used to recharge the soil.

### J watershed

Monthly water yield in J watershed vary from those noted in H watershed, as not all months exhibited increases. Water yield increases ranged from 2.9% in February to 173% in March between 1978-1983. Months where no increases were observed include January, April, May and August. Between 1984-1988, water yield increases were slightly larger on a relative basis ranging from 5.8% in July to 157% in May. On an absolute basis, the mean increase for months in the wet season decreased from 5.3 cm between 1978-1983 to 3.1 cm between 1984-1988. Mean increases in the dry season months were not observed for either time period. All months, except October and March, were not statistically significant.

Following the example set by monthly water yield increases in H watershed, the temporal distribution is variable and does not reflect the trend illustrated by wet season and annual increases. This applies to months in both wet and dry seasons. The most consistent increases occurred in October, November, March and September with the largest increases of 13 cm and 10.9 cm in March and November, respectively.

The number of months with consistent results is fewer than in H watershed although the time of year is similar (late fall, late summer). Accordingly, high amounts of precipitation are replenishing the soil-moisture deficit. November has the highest monthly precipitation with an average of 41 cm for the period of interest and corresponds to the high increase in runoff. The highest post-harvest precipitation occurred in 1983 for the month of November and represents almost 20% of the annual total, for both J and H watersheds. Water yield increases during this year reflect the precipitation inputs and are high enough to be seen through seasonal and annual increases.

The reason for fewer consistent monthly water yield increases is likely related to the calibration period where only two years of data were available. This limits the potential for a greater range in values from which the regression analysis could be conducted. This was very evident in the dry season where the streamflows in the pre-harvest period were similar in magnitude and could not provide a meaningful analysis.

### 6.2.5 Comparisons with other studies

The results of water yield increases in H and J watershed compare well with other studies in the Pacific Northwest region. The majority of research has been conducted in Oregon and four study areas include Fox Creek, Coyote Creek, the H.J. Andrews Experimental Forest and the Alsea Watershed Study (Figure 2.3-2). All of the above watersheds, with the exception of Fox Creek, are rain-dominated and timber harvesting has removed 100% of the forest cover. The precipitation regime at Fox Creek is a mixture of rain and snow, and the timber harvesting method used was patch cut. Therefore, it will be excluded from the comparison.

Annual water yields at H and J sub-drainages in the Carnation Creek watershed increased 41.9 cm (20%) and 49.8 cm (29%) in the first six years after harvesting 90% and 100% of the respective watersheds. Seasonal increases during the winter months (October-March) were observed to be 32.3 cm and 37.3 cm at H and J watersheds. Dry season (April-September) water yield increases were 8.4 cm and 3.4 cm, respectively.

Annual water yield increases at Coyote Creek averaged 70%. The first year increase was 36 cm (29%) with a five year average increase of 29 cm (43%) (Harr, 1979). In the Alsea study, annual increases averaged 21% or 40 cm over a four year post-harvest period after 82% of the watershed was clearcut. In H.J. Andrews watershed 1, a 46 cm increase was observed. Increases were not observed to be statistically significant until 41% of this watershed was cut. Water yield increases in H and J watersheds compare at 42 cm and 44 cm, respectively.

Harr (1979) summarizes the water yield increases in these watersheds and attributes the changes to reductions in evapotranspiration. At Coyote Creek, soil compaction resulted from tractor windrowing of logging slash. The soil compaction lead to increasing overland flow which is described as being one of the reasons for increased annual water yields.

Seasonal increases are more difficult to compare with results from the Carnation Creek watershed because the seasonal division is different. Four hydrological seasons were used in the analysis for the Oregon watersheds compared to the two used in this study.

Water yield increases were attributed to a combination of saturated soils and reduced interception in the fall and winter months (October-March). Spring and summer increases (April-September) were explained by transpiration losses. Winter increases in the three studies were generally larger in absolute terms and smaller in relative where the opposite was found during the summer and early fall seasons. In the Carnation Creek watersheds, the early fall period was included in the wet season therefore the potential for a similar result to occur may have been masked by grouping the data together. Monthly water yield increases were not analysed as part of these studies and therefore no comparison can be made.

# CHAPTER 7
# SUMMARY AND CONCLUSION

## 7.1 Introduction

Results of the analysis of water yield changes from clearcut timber harvesting in Carnation Creek are summarized in this chapter. The relative importance of forest hydrology processes on influencing water yield changes on an annual, seasonal and monthly basis is discussed. Closing remarks on issues raised throughout the study conclude the research.

## 7.2 Summary of Water Yield Changes

Annual water yields increased 19% and 28% in H and J watersheds, respectively, during water years 1978-1988. Sesonal water yields were divided into wet (October-March) and dry (April-September) periods. Wet season water yields increased 20% and 25% at H and J watersheds, respectively, during the same period. This compares to dry season increases of 14% at H watershed only. Poor correlations precluded analysis of dry season water yields at J watershed. Monthly increases on an absolute basis were highest in December and lowest in August for H watershed. Monthly water yield increses in J watershed were highest in March and lowest in April. relative increases for monthly water yields were skewed by wide ranging and variable results.

More water is available for water yields as a result of reduced evapotranspiration and interception losses through the removal of the forest cover. Increased water yields were expected to be largest during the first year post-harvest when evapotranspiration and interception losses would be at a maximum. However, increases were smallest during the first year post-harvest increasing to maximum levels six years post-harvest.

The temporal distribution of water yield increases in both treated sub-basins, over time, were related to climate variability. The water yield patterns over the first six post-harvest years matched precipitation patterns over the same period. Similarly, evapotranspiration losses corresponded to the annual water yield increases during the first six post-harvest years. Decreasing water yields after water year 1983 observed in both H and J watersheds are attributed to regrowth of vegetation.

Increases in evapotranspiration did not correspond to decreases in water yield during the 1984-1988 post-harvest period. Recovering vegetation has different physical characteristics from the pre-harvest vegetation. The establishment of alder, salal and salmonberry, as well as young conifers, after harvesting would transpire at rates lower than the pre-harvest levels. The lower evapotranspiration rates from regrowing vegetation types would possibly explain the slow recovery of evapotranspiration.

Seasonal water yield increases were higher during the winter wet season than the summer dry season on both absolute and relative terms. Differences in forest processes from seasonal influences direct changes in hydrologic response. The high percentage of precipitation occurring between October-March (75-80%), combines with lower evapotranspiration and moist soils to allow more water to be available for runoff.

Dry season water yield increases are relatively more influenced by interception and evapotranspiration. Interception amounts are higher in summer than in winter as a result of lower, lighter rainfall separated by dry periods. Transpiration amounts are also higher. Timber harvesting reduces these characteristics resulting in more water being available to enter into the stream channel.

## 7.3 Future Research

The Carnation Creek Experimental Watershed Project has provided an opportunity to quantify the hydrologic response of a west-coast stream to timber harvesting using the paired basin method. The project is ongoing to 1996 which presents an additional eight years of precipitation and streamflow available beyond the study period of this thesis. Eight years is a considerable amount of time in an environment where high rainfall aids in the recovery of vegetation. A shift in water yield increases was noted after the first six years after harvesting, suggesting that water yields were returning to pre-harvest levels. Harr (1976) has suggested a period of 20-30 years in western Oregon before water yields fully recover. The additional eight years of data would extend the post-harvest period to 19 years. The value and knowledge gained from this period would contribute greatly to an understanding of the recovery rates of vegetation and the impact on recovering hydrologic response in this region.

This research project has shown increased annual water yields for a west-coast stream on Vancouver Island spanning an 11 year post-harvest period. What are the implications, if any, of these increases? The forests of British Columbia hold a wealth of resources and many different uses ranging from forestry, logging, fishing, hunting, camping and many other recreational activities. On an annual basis, a 20% increase in water yield measured over a year, may not have any major implications. However, what needs to be remembered is that the observed changes were the result of intensive logging practices that would not be accepted by today's standards.

What is also important, is when the water yield increases occur. As discussed in the previous chapters, the larger percentage of rainfall occurs during the winter wet season which also produces the higher flows. It is these higher winter rains and subsequent flows which produce and cause other events to occur, such as bank erosion, channel scour and instability, debris flows and torrents. And it is within this time frame that other questions can be raised. Within the annual, seasonal and monthly data base, when are the storm events occurring? What percentage of storm flow is a part of the annual flows? We also know that storms are not unique to winter and that heavy rainfall events on Vancouver Island and coastal British Columbia have occurred in the summer months. Superficially, a 20% increase in annual water yield may not appear significant. However, a more indepth look at individual storm flows may reveal not only when, but with what associated precipitation event, stream disturbance occurred.

This research has contributed to a greater understanding of forest processes on the hydrologic response from timber harvesting on the west coast of Vancouver Island. Climatic variability and the distribution of precipitation throughout the year are unquestionably strong influences on water yield response. Forest hydrology is receiving more attention in the province of British Columbia with the advent of the Forest Practices Code and it is the understanding of forest hydrology processes at the basin scale which will aid in providing useful information for watershed and forest management strategies.

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