ANNOTATED BIBLIOGRAPHY OF HYDROLOGY RESEARCH

IN THE

GREATER VANCOUVER MUNICIPAL WATERSHEDS

by

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ANNOTATED BIBLIOGRAPHY OF PUBLICATIONS, THESES, AND REPORTS ON HYDROLOGY RESEARCH IN THE GREATER VANCOUVER WATER DISTRICT

INTRODUCTION

This bibliography brings together a summary of the publications, theses, and reports of hydrology research in the Greater Vancouver Water District (GVWD) since the program's inception in 1969. In that year, forest hydrology research was established as a cooperative program by the GVWD and the Faculty of Forestry of The University of British Columbia largely through the efforts of the late W.W. Jeffrey, professor of forest hydrology at that time. Funding was provided mainly by the GVWD, Federal agencies, and the Faculty of Forestry. The objectives of the program were (Goodell 1972):

1. To add to the existing knowledge of the hydrologic phenomena of undisturbed watersheds of the coastal mountains of British Columbia.

2. To evaluate the hydrologic effects of forestry practices.

3. To determine how forestry practices can and should be modified to minimize influences detrimental to the water resource and, where possible, to maximize influences that are beneficial.

Of the 59 papers included in this bibliography, 34 were for course or degree requirements at UBC (8 Ph.D. theses, 6 masters theses, 15 bachelors theses, 5 course reports), with most of the seven journal articles and seven conference papers being based on these theses. The overview of research in the GVWD compiled by Lewis (1985) was helpful, particularly for the several papers for which the originals could not be located for this report.

An ongoing program has been carried out to satisfy objectives 2 and 3. Superimposed on this have been short-

term projects (mainly thesis research) directed toward the first objective.

Research was carried out at various locations in the three large watersheds (Capilano, Seymour, and Coquitlam) managed by the GVWD for the water supply of the Greater Vancouver area. These three watersheds comprise 61,000 ha of which 34,000 ha within the coastal biogeoclimatic zone are classified as productive forest. Within this latter zone is Jamieson Creek basin, in the Seymour watershed, where much of the research was carried out.

Jamieson Creek watershed was selected as the "treatment" watershed (in which logging would be carried out) in a paired watershed experiment. Streamflow quantity, timing, and chemical quality in Jamieson Creek were compared to those same variables in Elbow Creek, the "control" watershed (which would remain unlogged), for the pre-treatment period to establish statistically significant regressions. These regressions were then used to predict Jamieson Creek post-treatment streamflow quantity, timing, and chemical quality based on Elbow Creek data in the post-treatment period. It could then be determined if differences between predicted and actual values on Jamieson Creek resulted from the treatment. The pre-treatment period was 1970-1978, and because the treatment (logging 19.2% of Jamieson Creek watershed), took six years, the period following 1978 was divided into a treatment period (1978-1984) and a post-treatment period (1984-1990). Predicted and actual values on Jamieson Creek were compared for both the treatment and the post-treatment periods.

ANNOTATED BIBLIOGRAPHY

Acres Int. Ltd. 1993. GVWD watershed ecological inventory pilot study (Jamieson-Orchid-Elbow drainage). Final Report. Acres International Ltd., Vancouver, B.C.

The purpose of this pilot study was to develop an inventory method based on biogeoclimatic ecological classification principles (a system of classifying ecosystems at a regional climatic and local geophysical level); to test the method at a pilot scale level; and to provide directions for adapting the method to the full-scale inventories to be undertaken on all three GVWD watersheds (Capilano, Seymour,

and Coquitlam). The primary objective of the pilot-scale inventory was to develop a tool that could be used to predict and analyze potential impacts of both natural and human induced events on water quality.

A four-step approach was taken:

1. Collection of information on vegetation, hydrology, terrain, fish and wildlife from published and unpublished sources with a short field program of direct measurement.

2. Integration of terrain and vegetation data to develop ecological and biogeoclimatic classification maps.

3. Combining information from these maps to produce hazard and risk maps.

4. The outcome was critiqued and suggestions made as to how to adapt the pilot study to full scale inventories of the three watersheds.

Maps are included in the report showing sediment sources, surface fuel loadings, terrain stability, fire hazard, wildlife habitat, and other information.

Allison, A.P., R. Arnold, V. Begrand, M.D. Godfrey, D. Holmes, G.Johnson, C.P. MacDonnell, R.J. Pearson, J.G. White, and M.K. Woo. 1969(?). A watershed analysis of the Seymour watershed. (Probably a class exercise for a Forest Hydrology course.) Fac. For., UBC., Vancouver, B.C.

This report consists of 12 sections, each by a different author, on the following topics relative to the Seymour watershed:

-climate
-geology
-soils
-land use
-land ownership
-forest land condition
-developments
-other uses
-general hydrology
-forest hydrology
-water uses and needs
-problems and recommendations

The following needs were recognized:

-better data-collection networks for forecasting long-term hydrologic events and planning major projects,

-research on the compatibility of recreational use of the watershed and a sufficient supply of good quality water, and

-better road access to facilitate management and fire protection.

Beaudry, P.G. 1983. Use of hydrologic simulation models for applications in silviculture. Report for FRST 504. Fac. For., UBC., Vancouver, B.C. 76 pp.

The author's objective was to review models that might be useful in evaluating the hydrologic effects of silvicultural treatments, and to become familiar with the construction and terminology of hydrologic models. The SLUICES model, designed for Jamieson Creek watershed and calibrated with data from this watershed (Chanasyk 1980), received particular attention. The requirements for this model are satisfied by Jamieson Creek, viz., first order stream, steep forested terrain, interflow the predominant hydrologic process (Chamberlin 1972) channeling snowmelt and rain to the stream channel.

The SLUICES model was assessed by setting several forest management objectives for the Jamieson Creek watershed and simulating streamflow to achieve these objectives. The simulations were done to aid in locating cut blocks and in determining their size and distribution, to locate potential landslide areas, and to consider water stress and flood problems related to regeneration and road and culvert placement.

The sluices model was shown to be potentially useful in managing small headwater basins. It can simulate soil water regimes over extended time periods, although input data requirements and computing costs would probably make the model impractical for larger watersheds. The model lacks evapotranspiration and snowmelt routines, and cannot handle changes to soil properties associated with logging and roads.

Beaudry, P.G. 1984. Effects of forest harvesting on snowmelt during rainfall in coastal British Columbia. M.F. thesis. Fac. For., UBC, Vancouver, B.C. 183 pp.

Although the potential for increasing floods and debris torrents by rain-on-snow events has been recognized, the effects of forest harvesting on this phenomenon is not well understood. The objectives of this study were:

1. To compare water balances of a melting snowpack in a forested and in a clearcut site during rain-on-snow events.

2. To describe the physical processes involved during rain-on-snow and how these processes are affected by removal of the forest canopy.

3. To verify the usefulness of the Unites States Army Corps of Engineers (USACE) snowmelt equations for predicting the effects of forest harvesting on snowmelt rates during rain-on-snow in the transient snow zone.

The energy balance of a snowcover and the theory of snowmelt are reviewed, techniques and instrumentation required to compute the energy budget (particularly the aerodynamic technique)are discussed, and the USACE snowmelt equations are considered (particularly their applicability to rain-on-snow situations).

The experimental setup consisted of one study plot in a recent cutover and one in an adjacent western hemlock old-growth forest, both in the Jamieson Creek watershed. Each plot had a 22-m^2 plastic sheet lysimeter with a tipping-bucket device for recording snow melt and runoff rates. Direct measurement of snowpack water equivalent was carried out using snow survey techniques. Wind speed, relative humidity, and air temperature were measured at 0.6 and 1.5 m above the snowpack to evaluate latent and sensible heat fluxes. Snowpack and ground heat exchanges were measured with a profile of five thermistors, and radiation was measured with net all-wave radiometers.

Three winters' (1981-82, 1982-83, and 1983-84) data were collected with several storms of the last two years being analysed in detail. The study indicated that snowmelt runoff rates were greater from the forest than from the clearcut when the storm began as snow and then changed to rain. The snow in the canopy melted at a faster rate than that in the clearcut because of greater energy inputs at canopy level. Such storms occur frequently in the transient snow zone. For rainstorms when there was no snow in the canopy, snowmelt rates were greater from the clearcut. During rain-on-snow,

snowmelt runoff peaked several hours later from the clearcut than from the forest, suggesting the possibility of harvesting to desynchronize snowmelt runoff from forest and from clearcut. Snowmelt values computed with the USACE equations were in general agreement with the snow survey and lysimeter data at the harvested site, were in less close agreement in the forest when the rain began with no snow in the canopy, and were much less than measured values in the forest when the rain began with a heavy snowload in the canopy.

Beaudry, P.G. and D. L. Golding. 1983. Snowmelt during rain-on-snow in coastal British Columbia. Proc. West. Snow Conf., Vancouver, Washington. pp. 55-66.

Preliminary results of M.F. thesis research noted above (Beaudry 1984).

Beaudry, P.G. and D.L. Golding. 1985. Snowmelt and runoff during rain-on-snow in forest and adjacent clearcut. Proc. Snow Property Meas. Workshop, Tech. Memo. 140, Natl. Res. Counc. Canada. pp. 285-311.

Paper based on M.F. thesis noted above (Beaudry 1984).

Briere, D. 1978. The stratification of forested landscapes for intensive management: development and application. Ph.D. Thesis, Fac. For., UBC., Vancouver, B.C. 213 pp. + appendices.

The objective of this study was to develop a classification system, using landscape units based on environmental factors, to integrate land and aquatic systems information into the intensive forest management process. Secondary objectives were:

-that the system be based on remote sensing methods,

-that landform classification be integrated with watersheds using stream order,

-that mapable landscape units be developed that can be grouped into management units incorporating climate, geology, landforms, hydrology, vegetation, and organisms.

The classification system, termed the Aqua-Terra Classification System (ATCS), presents a single base map that integrates environmental factors and provides a framework for interpretation based on the biological characteristics of the land and aquatic systems. The integration of the land and water systems was accomplished by dividing the area into watersheds based on stream order, then subdividing these watersheds into management units using biophysical attributes. The management unit was further divided into landscape units based on biogeoclimatic subzones.

It was shown that:

1. The ATCS drainage basin-ordering system was more useful for local analysis than that attributed to Strahler.

2. Landscape units were characterized by unique combinations of elevation range, slope gradient, soil, forest stand characteristics and vegetation.

Buss, C. 1993. The effect of partial clearcutting on the concentrations of selected ions in the streamwater of Jamieson Creek. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 95 pp.

With six years of pre-treatment data, six years of data during the treatment, and seven years of post-treatment data, the author used multiple linear regressions to assess the impact of clearcutting 20% of Jamieson Creek watershed on the concentrations of H, Na, K, Ca, Mg, SO^4, Cl, NO^3, and SiO^3 in streamwater and bulk fallout (combined precipitation and dry deposition).

The data used were part of that collected as part of the hydrology research program carried out by the Faculty of Forestry from 1970 till the early 1990s. Streamflow was measured at the weirs at both Jamieson and Elbow Creeks and water quality samples were collected in 50-ml polypropylene vials immediately upstream of the stilling ponds. Data for precipitation amount and bulk fallout were used for two of the precipitation stations on Jamieson watershed, 14A at 425 m elevation and 25B at 760 m, and for the precipitation gauge at the Elbow Creek weir. Bulk fallout samples were collected generally only from April to October. Sample analysis was done at the UBC Forest Hydrology lab using an atomic absorption spectrophotometer to determine cation

(sodium, potassium, calcium, and magnesium) concentrations and the Technicon Autoanalyzer II for ion (sulfate, nitrate, and chloride) and dissolved silica concentrations.

This study showed that mean monthly ion concentration followed the same pattern from year to year in both Jamieson and Elbow Creeks. There was one consistent difference between the two streams for both pre- and post-treatment periods: the ion concentrations in Jamieson Creek had greater variation over the course of the year than in Elbow Creek. Peak concentrations occurred during the discharge minima in August for both creeks. All of the chemical species had significant relationships (based on simple linear regression) with stream discharge on both creeks except chloride and nitrate. These two appeared to depend more on atmospheric inputs than on stream discharge.

Seasonal trends in ion concentrations in precipitation were much less consistent than the seasonal trends in streamwater, and there was less similarity between the trends in the two watersheds.

All of the stream chemistry parameters on both watersheds changed from pre-treatment to treatment to post-treatment period. Mean monthly nitrate concentrations increased through the three periods; sodium and calcium declined over the course of the study; potassium, magnesium, and chloride peaked in the treatment period and were lowest in the pre-treatment period; silica was highest in the pre-treatment period and lowest in the treatment period; and sulfate was generally greater in the post-treatment period than in the pre-treatment period. The periodic changes in concentration of precipitation followed the same trends as in streamwater and were positively correlated with streamwater concentrations, with the exception of silica where changes in concentration appeared to be unrelated to streamwater concentration changes.

Acidity of both streamwater and precipitation in both watersheds increased over the period of record (1978-1991). Streamwater acidity changed from a mean pH of 6.13 in the treatment period to 5.97 in the post-treatment period. Over the same period, pH of precipitation declined from 4.97 to 4.61.

The best-fit equations for stream chemistry parameters were similar to the following example:

$$L_{10}[Na]_{JS} = -0.399 + 1.92(L_{10}[Na]_{ES}) + 0.045(L_{10}[Na]_{JP}) + 0.160(L_{10}EP) - 0.243(L_{10}[Na]_{EP})$$

[SEE:0.0079, R2:0.998]

where L_{10} is base 10 logarithm
EP is Elbow bulk fallout (cm)
SEE is standard error of the estimate (mg/l to $\log_{10}$)
R^2 is coefficient of multiple determination
$[Na]_{JS}$ is the concentration of Na in Jamieson streamwater (mg/l)
$[Na]_{ES}$ is the concentration of Na in Elbow streamwater (mg/l)
$[Na]_{JP}$ is the concentration of Na in Jamieson precipitation (mg/l)
$[Na]_{EP}$ is the concentration of Na in Elbow precipitation (mg/l)

The modeling results indicated that clearcutting on Jamieson Creek watershed caused a change in the concentrations of sodium, magnesium, and nitrate. Sodium and nitrate concentrations decreased during the treatment period and sodium and magnesium concentrations increased in the post-treatment period. However, concentrations of all ions were within the limits set for drinking water in Canada during all three periods (pre-treatment, treatment, and post-treatment) of the study. Acidity was the only parameter that ranged outside the guidelines of 6.5-8.5, both before and after the treatment.

Chamberlin, T.W. 1972. Interflow in the mountainous forest soils of coastal British Columbia. *In* Slaymaker, H.O. and H.J. McPherson (eds). Mountain Geomorphology, Tantalus Res. Ltd., Vancouver, B.C. pp. 121-127.

The objective of this project was to study the movement of water from infiltration at the surface organic layers, and percolation to relatively impermeable layers that commonly occur at shallow depth, resulting in concentrated lateral, or "interflow". The study was carried out in the Seymour River drainage in a mature western hemlock-red cedar stand at 700 m elevation on a 30^0 slope. The soil, over quartz-diorite bedrock, averaged 1 m in depth and had 10-30 cm thick organic layers. Rapid response tensiometers were installed at 10, 30, 70, and 100 cm depth to measure three-dimensional water potential. Water was added by an irrigation system (plus one rainfall event).

Conclusions were:

1. The organic horizon easily transmits high intensity inputs (1.7 cm/h), with no overland flow observed.

2. At the equilibrium "wet" state, the saturated basal zones had a Darcy conductivity of 35 cm/h, conductivities in the unsaturated B horizon were 0.3-1.7 cm/h, but the total profile transmitted water at rates up to 200 cm/h.

3. Open drainage must exist between organic layers and basal zones. Initial B horizon wetting is thus from both top and bottom.

4. Interflow is predominantly saturated flow over shallow bedrock aided by transmission through intervening soil.

Chanasyk, D.S. 1980. A land use hydrologic response model. Ph.D. thesis. Fac. Eng., Univ. Alberta, Edmonton, Alberta. 260 pp.

Development of the distributed hydrologic model SLUICES (soils and land uses affecting interflow and creating effects on streamflow) is described. This model recognizes the possibility of a saturated layer within the soil due to a flow-impeding subsurface layer. It considers the water holding and transmissive properties of the soil thus allowing simulation of the saturated layer and the formation of a lateral flow component.

The model considers the spatial variation of watershed parameters by using a grid system dividing the watershed into small homogeneous elements. Each element has its own set of watershed parameters making the model adaptable to any watershed. Modeling the soil profile as a reservoir is done by using saturation, wilting point, and field capacity as descriptors of the various soil types. Conductive properties of the soil are characterized by a conductivity coefficient and soil depth.

The SLUICES model was validated by comparing simulated output produced by the model to actual outputs of Jamieson Creek watershed for specified inputs. Jamieson Creek was chosen for the validation because interflow is the predominant process (Chamberlin 1972) on this watershed and

it is a first order, steep, forested watershed, the type of watershed for which this model was developed.

Results of the validation indicate that the model does better for storms with wet antecedent conditions than for those with dry antecedent conditions. A small error in initializing moisture content would affect the simulated discharge much more for dry than for wet antecedent conditions.

Cheng, J.D. 1972. Evaluating soil-water drainage of a humid mountain forest site in southwestern British Columbia by two field techniques. M.Sc. thesis. Fac. For., UBC., Vancouver, B.C. 66 pp.

This study was conducted on Jamieson Creek experimental watershed during the summer of 1971. The objectives were:

1. To calculate and measure soil water drainage completely *in situ* by two simple, inexpensive field techniques.

2. To investigate soil water drainage and its relation to rainfall and streamflow in the humid mountainous forest areas of Southwestern British Columbia.

The methods used were (1) a tension lysimeter, and (2) a calculation based on Darcy's equation.

The tension lysimeter system incorporated a simple capability for manually regulating suction to the lysimeter plate corresponding to tensions in the surrounding soil and also a lysimeter plate that ensured contact between it and the natural soil. Application of various suctions to the lysimeter plate was accomplished by controlling the height of a continuous water column hung from the lysimeter plate. Application of Darcy's equation to soil water drainage evaluation was based on *in situ* measurements of hydraulic gradient with a tensiometer-manometer system and *in situ* determination of hydraulic conductivity using data from another tensiometer-manometer system and a neutron soil moisture probe. Soil water drainage rates derived from tension lysimeter data and from the method of Darcy's equation were compared for both drying and wetting periods. Cumulative soil water drainage amounts for the drying period obtained by the two methods were compared with those determined by a water balance equation.

The following conclusions were drawn:

1. The tension lysimeter can quantify soil water drainage adequately if attention is given to hydraulic contact between undisturbed soil and the lysimeter plate and that suctions applied to the plate are adjusted to that of the surrounding soil.

2. With adequate determination of hydraulic conductivity and hydraulic gradient of soil, *in situ* soil water drainage can be calculated using Darcy's equation.

3. There was good agreement between soil water drainage rates determined with the tension lysimeter and with Darcy's equation.

4. The two methods gave reasonable estimates of soil water drainage during the drying periods in the study but are limited in dealing with the wetting stage.

5. In the humid coastal region of southwestern British Columbia, soil water drainage is a major component of the water balance for the root zone of forest soils.

Cheng, J.D., R.P. Willington, B.C. Goodell. 1973. Evaluating soil water drainage by two field techniques. J. Chinese Soil and Water Conser. 4(1):26-57.

Paper based on M.Sc. thesis listed above (Cheng 1972).

Cheng, J.D., T.A. Black, and R.P. Willington. 1975. The generation of stormflow from small forested watersheds in Coast Mountains of Southwestern British Columbia. Proc. Can. Hydrol. Symp.-75, Winnipeg, Manitoba. Nat. Res. Counc. of Can., NRCC No.15195. pp. 542-551.

Paper based on Ph.D. thesis listed below (Cheng 1976).

Cheng, J.D. 1976. Study of the stormflow hydrology of small watersheds in the Coast Mountains of Southwestern British Columbia. Ph.D. thesis. Fac. For., UBC, Vancouver, B.C.

The objectives of this study were:

1. To provide background information on the paired watersheds, Jamieson and Elbow Creek.

2. To describe the mechanisms of the land phase of stormflow generation.

3. To evaluate the channel phase of Jamieson Creek stormflow and compare storm hydrographs from the two watersheds.

The analysis showed that overland flow of the classic Horton type rarely if ever occurs on coastal watersheds with hydrologic environments similar to the study area. Instead, rain water takes alternative subsurface pathways through the soil to the stream channel. Two types of subsurface pathways of stormflow were identified: (1) the matrix of the forest floor and mineral soil beneath, and (2) channels within or passing through the forest floor and mineral soil. In these two watersheds most of the soil channels were developed from dead or decaying roots. After passing through these two types of pathways, subsurface stormflows feed the expanding stream channel system laterally while rainfall is feeding the system from above. The subsurface stormflows are mainly in the form of saturated return flow from the ground and seepage flow through saturated stream banks. It was shown that the magnitude and rate of stormflow from the watersheds is closely related to the rate at which the stream channel expands in response to a storm.

It was concluded that the principal factors controlling stormflow concentration are:

1. Depth and hydrologic properties of the soil, particularly the nature and extent of soil channels and antecedent soil moisture.

2. Amount and intensity of rainfall.

3. Surface and subsurface topographic features on both the macro- and micro-scale.

Jamieson Creek had sharper peaks, higher peak-flow ratios and steeper recession limbs than did Elbow Creek, suggesting that topographic differences and the possibility of leakage around the Elbow Creek weir exist.

deVries, J. and T.L. Chow. 1973. Hydrologic behavior of a forested mountain soil in coastal British Columbia. Water Res. Res. 14(5):935-942.

The water-potential field of a West Coast forested mountain soil was measured during the wetting and drainage phases of simulated rainfall events. The field was measured as a continuous function of time with an array of 13 tensiometers in combination with pressure transducers and a data collection system. Measurements were made with the forest floor intact, partly disturbed, and totally removed.

It was concluded that during a simulated rainfall event, water flow through the profile was partitioned between root channels and the soil matrix traversed by the channels. Proportion of flow conducted by the channels was at its maximum during the non-steady phase of the event, decreasing to a minimum as steady state was approached. During rainfall, water infiltrates the forest floor moving laterally as free water on reaching the less permeable H and Ae horizons until it reaches a root channel opening (usually at the top of the H horizon). It then moves downward in response to a gravity potential gradient. Water moves much more slowly through the H and Ae horizons and out into the soil from the root channels in response to a matric potential gradient. Early in the storm, the root channel contribution to drainage is much greater than the drainage contribution from the soil matrix. This difference gradually reduces as the matrix wets up from the H horizon down and from the root channels outward. When rainfall ceases, the preferential drainage pathways (i.e., the root channels) soon cease to carry water.

Surface disturbance on these coarse-textured, open, forested mountain soils tended to close off root channel openings, resulting in a reduction in the size of peak flows. Little overland flow occurred at simulated rainfall intensities of 2.6 cm/hr or less, even on disturbed sites.

EESI. 1991. Greater Vancouver watershed management evaluation and policy review. Final Summary Report prepared for the Greater Vancouver Water District by Economic and Engineering Services, Inc. 79 pp. + appendices.

This report deals with the review of the current policies and operations in the GVWD's three municipal watersheds. There were two components to the review:

1. Evaluate the existing Watershed Management Program in light of its current mandates and administration.

2. Identify impediments to better management and recommend changes to improve the Watershed Management Program.

The review was carried out by a GVWD-appointed panel comprised of specialists in municipal watershed management, water quality, forest soils, silviculture, forest hydrology, wildlife, and fisheries.

The panel found that the current Watershed Management Program meets the terms put forth in the Amending Indenture and by past GVWD Boards. (The Amending Indenture is the legal agreement drawn up in 1967 between the GVWD and the B.C. Ministry of Lands, Forests, and Water Resources as the basis for the forest management program in the GVWD.) Forest practices, including road building and timber harvest, are generally conducted in an environmentally sensitive manner with no significant impact on water quality.

However, the panel concluded that the program should not be encumbered by the secondary objective of sustained-yield forestry which was part of the Amending Indenture. Also, the management philosophy of the program should be updated to incorporate advances in forest watershed management and social values.

The key recommendations were:

1. The Amending Indenture should be revised to remove the requirements for "...growing continually successive crops of forest products to be harvested in approximately equal annual or periodic cuts..." and other sustained-yield forestry considerations.

2. Changes in internal funding are needed so that the Watershed Management Program is not solely dependent on timber-harvest revenues for its operation.

3. A detailed ecological inventory is needed to provide the data base necessary to develop comprehensive long term management plans for all forest resources and the protection of water quality.

4. A low-level, pro-active forest watershed management program be developed based on watershed management

criteria, particularly with regard to fire, insects, and long term forest stability. Timber harvesting and road building components should be specifically targeted towards high risk and impact areas such as fuel management.

5. A periodic review process of watershed management should be established, to be conducted every five years.

Eller, W.B. 1976. Road drainage structure maintenance (Hydraulic Design Series Volume 2). B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 50 pp. + appendices.

The objective of the study was to develop a documented road drainage-structure maintenance program for forest roads. The conclusions were:

1. Road maintenance costs can be substantially reduced using a system of drainage-structure inventory, appraisal, and treatment of identified problems.

2. A documented maintenance system allows better evaluation and selection of maintenance equipment, and provides for contracting-out maintenance activities.

3. Using the proposed system on the Seymour watershed road system could have reduced road failures caused by the fall 1976 storms by as much as 60%.

Golding, D.L. 1983. Hydrogen separation by oxygen isotope analysis. Report to the Greater Vancouver Water Bd.

This report describes a limited trial of the use of oxygen isotopes for hydrograph separation (i.e., the separating of streamflow into base flow and quick flow). Weekly samples of precipitation and streamflow during 1981 was used in this pilot study.

Conclusions:

1. The groundwater contribution is a large proportion of streamflow in Jamieson Creek as indicated by the low variation in O^{18} values in streamwater samples.

2. Such a high base flow component even during major storms indicates that little overland flow reaches streams during such events.

Golding, D.L. 1987. Changes in streamflow peaks following timber harvest of a coastal British Columbia watershed. Proc. Int. Symp. For. Hydrol. and Watershed Mgnt., Vancouver, B.C. IAHS-AISH Publ. No.167:509-517.

Changes in streamflow peaks following cutting of 19.2% of Jamieson Creek watershed were determined using the paired-basin approach with Elbow Creek the control basin. Streamflow data for the pre-treatment period (1972-1978) and post-treatment period (1984-1986) were used in the analysis. The cutting took place over the 6-year period 1978-1984.

Winter storm peaks, which usually result from rain on melting snowpacks, showed a treatment-induced increase of a maximum of 13.5%. There was no indication that the increases were limited to a particular storm-size class. Summer storms showed no treatment-induced increase. Peak winter flows were highly correlated with snowmelt rates.

Golding, D.L. 1988. Jamieson Creek experimental watershed in the Greater Vancouver municipal catchments. Proc. Can. Hydrol. Symp. No.17, Can. Res. Basins: Successes, Failures and Future. Banff, Alberta. Natl. Res. Coun. of Can. pp. 229-236.

This paper discusses the objectives of the forest hydrology research program on the GVWD from the perspective of the strengths and weaknesses of research basins as an experimental method. Brief reviews are given of masters' and Ph.D. thesis research carried out on the GVWD.

Goodell, B.C. 1972. Water quantity and flow regime: influences of land use, especially forestry. *In* Slaymaker, H.O. and H.J. McPherson (eds). Mountain Geomorphology, Tantalus Res. Ltd., Vancouver, B.C. pp. 197-206.

The author discusses the influence of land use on water quantity and flow regime, and briefly describes the forest hydrology research program conducted in the Greater Vancouver municipal catchments. It is noted that the poorly

defined boundaries of the Elbow Creek watershed will prevent determination of a water balance for that watershed. This illustrates the limitations on hydrologic research imposed by the immature and glaciated character of the mountains of coastal British Columbia. Another limitation is that the excessively steep gradients of most of the smaller streams render them unsuited to accurate gauging by conventional methods. The choice of Elbow Creek as a control watershed for the Jamieson Creek treatment watershed was based on:

1. A channel reach suitable for accurate streamflow gauging.

2. Forest cover.

3. Accessibility.

4. Proximity to Jamieson Creek.

5. Non-existence of another stream having characteristics similar to Jamieson Creek.

Gosselin, C.R. 1985. Effects of storm size on peak stormflow changes following logging of a small coastal watershed in southwestern British Columbia. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 75 pp.

The objective of the study was to determine:

1. If the 1978-1984 harvest and road building that cleared 19.2% of the Jamieson watershed affected streamflow peaks from summer-storms (i.e., rainfall only, excluding rain-on-snow and snowmelt).

2. If the effect on streamflow peaks differs for different storm-size classes.

It was shown that logging did not change summer-storm peak streamflow when all storms were combined. However, when peak flows were separated by size it was found that peaks from the smallest rainfall class (5-30 mm) decreased significantly in the post-treatment period , whereas there was no change for peak flows in the intermediate (31-60 mm) and large (>60 mm) peakflow classes.

A possible explanation for the difference in streamflow response between storm-size classes is given as follows. If logging closes soil channel (macro-channel) openings at the

surface then water must move through the soil matrix before entering macro-channels. For any but the smallest storm sizes, water can enter macro-channels from the saturated soil surrounding the macro-channels even if the macro-channel openings have been disrupted at the surface. Small rain storms do not produce enough water to saturate even the surface soil, so that the much slower unsaturated flow through the soil matrix is the dominant flow mechanism.

Gray, G.C. 1974. Analysis of the existing water supply areas within the Greater Vancouver Regional District. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C.

The intent of this thesis was to bring together information on the Capilano, Seymour, and Coquitlam watersheds regarding history, physiography, climate, parent material and soil, forest cover, land use, hydrology, and water-related problems. It includes the history of the Greater Vancouver water supply system from its beginning as the Vancouver Waterworks Company of 1886 to the present Greater Vancouver Water District created in 1924.

The following conclusions were drawn from the study:

1. The primary purpose of the GVWD is supplying good quality water.

2. Timber production at the 1974 levels is compatible with water supply, but recreational use is controversial.

3. The catchments have the potential for supplying over three million people.

4. Improved inventory is needed of climate, soils, vegetation, and wildlife

5. The research program should be increased and coordinated with other studies.

Green, J.H. 1976. Piping in basal till in Southwestern British Columbia. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 30 pp. + appendices.

The purpose of the study was to evaluate the extent and significance of piping in basal till and to develop management strategies to cope with the effect on forest

roads. The report was mainly descriptive but did analyse six days of flow data obtained at one soil pipe in the Seymour watershed. Piping was documented at several locations.

Conclusions were:

1. Early detection of piping is the key to controlling road maintenance costs.

2. The monitored pipe showed a slight increase in flow co-incident with rainfall-caused streamflow peaks at Elbow and Jamieson Creeks.

3. Pipes tend to form in pockets of coarser till where one till overlays another, or in fractures in the till.

4. Water commonly enters pipes at till-bedrock contacts.

Gulyas, G. 1995. Terrain stability assessment using logistic regression for the Jamieson-Orchid-Elbow Creeks subdrainage, Seymour River basin, British Columbia. M.Sc. thesis. Fac. For., UBC, Vancouver, B.C. 160 pp.

A terrain stability assessment procedure was developed using case-control sampling and multiple logistic regression analysis, widely used statistical techniques in biomedical research and epidemiology. The procedure developed provides a quantitative tool to assess the risk of landsliding and to define the most important terrain attributes contributing to soil mass movement.

A case-control study of 20x20 m grid cells with average slope greater than 10° was conducted on the Jamieson-Orchid-Elbow Creeks watersheds. All of the 101 landslide cases were compared to 264 control grid cells. Multi-way cross classification tables were constructed to study the relationship between landsliding and selected terrain attributes. A logistic regression analysis was then performed within a Geographic Information System (GIS) environment to develop a landslide risk model. Based on this risk model, a landslide risk matrix was constructed from which landslide risk categories were developed. The spatial distribution of landslide risk, classed as very low, low, moderate, high, and very high was portrayed within 20x20 m grid cells on a landslide risk map.

The procedure provides a method of quantitative landslide risk assessment that should discourage qualitative landslide hazard assessments because of their inherent subjectivity. In this study, risk represents the outcome of a hazard and is expressed as the product of the probability of a hazard, the probability of exposure to the hazard, and the probability of a particular outcome given the exposure.

Other results of the study include:

1. The statistical procedures were shown to be useful in determining the cause-effect relationships between landsliding and various landscape attributes.

2. The factors that play an important role in the development of landslides on the study area are slope, transient snow zone, surficial material type, soil depth, and local catchment area.

3. At greatest risk of rapid, shallow soil mass movements were sites in the transient snow zone (450-900m) with slopes of 55° or greater, on shallow soil of bedrock outcrop surficial material. The importance of the transient snow zone may be explained by the hydrologic characteristics of this zone where rain-on-snow events are common and peak flows are more frequently produced within this elevation band.

4. Sites of 55° or greater have a five times greater chance of experiencing a landslide than sites of 10-25° slope. Degree of slope influences flow rates of water and sediment by controlling the rate of energy expenditure or stream power available to drive the flow.

5. Sites with bedrock outcrop surficial material have a 4.5 times greater chance of landslides than sites with other types of surficial material.

6. Sites with a local catchment area of 1.2 ha or less have a 2.5 times greater risk of landsliding than sites with greater catchment areas. Channel heads seem to coincide with small-scale debris flow scars in topographic hollows. The local catchment area is a good indicator of the location of channel heads.

7. A simple raster-based GIS was shown to be capable of managing and manipulating the spatial quantitative information and of creating colour maps and images.

8. This study used 20-m resolution but it was felt that 40-m resolution would have been sufficient.

Hall, R.G. 1989. Precipitation intensity-duration-frequency curves for Jamieson Creek and Elbow Creek watersheds in the Seymour basin. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 35 pp.

Rainfall intensity-duration-frequency (IDF) curves were developed for three stations in the Seymour basin, using the Gumbel distribution. The stations are Elbow Creek (305 m elevation), and the two stations in the Jamieson Creek watershed, 21-A (640 m elevation) and 25-B (762 m elevation). The data used were the annual series of maximum rainfall events for storm durations of 0.5, 1, 2, 6, 12, 24, and 48 hours for 13 years (1976-1988) at Elbow Creek, 11 years (1978-1988) at 21-A, and 8 years (1981-1988) at 25-B. To compare the IDF values for each station only the 8 common years, 1981-1988, were used.

IDF curves for the seven durations are given in the report for return periods of 2, 5, 10, 20, 50, and 100 years. However, given the short period of record, particularly in the case of station 25-B, the 50 and 100-year return periods are pushing the data.

Short duration storms (less than 6 hr.) showed significant variation between the three stations. For example, the 1-hr storm with 20-year return period has an intensity of 1.41, 1.91, and 1.46 in/hr for Elbow Creek, 21-A, and 25-A respectively. As expected, the lowest elevation station, Elbow Creek, had the lowest rainfall intensity, but the mid-elevation station, 21A, had the highest intensity. The longer duration storms show little variation between stations. For example the 24-hr storm of 20-year return period has an intensity of 0.30, 0.34, 0.36 in/hr for the three sites, increasing in intensity with increasing elevation as expected.

The intensity-duration-frequency table for Station 21-A in the Jamieson Creek watershed is given below (Table 1).

Table 1. Rainfall intensities for Station 21-A, Jamieson Creek watershed (Maximum Likelihood Method)

Return period (yrs)	Storm duration (hours)						
	0.5	1	2	6	12	24	48
2	1.38	0.87	0.54	0.34	0.26	0.20	0.15
5	1.90	1.14	0.70	0.43	0.30	0.24	0.17
10	2.25	1.32	0.81	0.48	0.36	0.27	0.19
20	2.58	1.49	0.92	0.54	0.40	0.29	0.20
50	3.01	1.71	1.05	0.61	0.45	0.33	0.23
100	3.33	1.88	1.15	0.66	0.49	0.35	0.24

Harkema, J.A. 1987. A nutrient (Na, Ca, NO^3) study of Jamieson Creek pre-and post-disturbance. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 85 pp.

This study was conducted when only 13% of the Jamieson Creek watershed had been harvested. Linear regressions using Jamieson concentrations as the dependent variable and Elbow concentrations as the independent showed no significant change in the concentrations of sodium, calcium, and nitrate in Jamieson stream water.

Henderson, G. 1981. Physical and chemical aspects of water repellent soils affected by slashburning at Vancouver, British Columbia. M.Sc. thesis. Fac. For., UBC, Vancouver, B.C. 78 pp.

The persistence and severity of water repellency in soils as affected by slashburning was examined in the municipal watersheds of Vancouver by the water-drop penetration time (WDPT) and contact angle methods. Hydrophobic materials were extracted from soil, separated by column-absorption chromatography, and analysed for functional groups by infrared absorption.

It was shown that soil water repellency, as assessed by WDPT, was increased by slashburning. Soil in slashburns was more frequently repellent than unburned soil in all one- and two-year burns, but after about six years the effect of slashburning became negligible. A greater percentage of soil samples from burned sites were repellent than from unburned sites. The incidence of repellency decreased with depth in

both burned and unburned sites. It was suggested that chemicals released in decaying litter are chiefly responsible for water repellency in soil. There was no evidence of a translocated water repellent layer situated below a wettable soil layer, although this might have been due to inadequate sampling.

Because water repellency is a dynamic property, changing with moisture content and time, a single WDPT as an index of water repellency is misleading. A series of penetration times over a range of soil moisture contents would be more revealing.

The contact angle method of assessing water repellency was not successful, the reason suggested being a combination of practical and theoretical factors.

The study showed, for the soils sampled, that 1 mg of hydrophobic substance could be extracted from only 30 g of soil and that 1 mg could induce repellency in 5 g of formerly wettable sand. The degree of repellency was increased by heating up to 250° C but decreased with greater temperatures until no repellency existed when heated above 325° C.

Extracted hydrophobic materials have hydrophilic and hydrophobic ends with adsorption onto soil particles occurring via the hydrophilic end leaving the hydrophobic end to form the outer surface.

Henderson, G. and D.L. Golding. 1983. The effect of slash-burning on the water repellency of forest soils at Vancouver, British Columbia. Can. J. For. Res. 13(2): 353-355.

Based on M.Sc. thesis noted above (Henderson 1981).

Hetherington, E.D. 1974. Investigation of orographic rainfall in south coastal mountains of British Columbia. Ph.D. thesis. Fac. For., UBC, Vancouver, B.C. 296 pp.

This study was motivated by the belief that available information on weather systems and atmospheric conditions could be used with knowledge of local terrain configuration to improve estimates of short-duration precipitation amounts and distribution over coastal mountainous terrain. The

central goal of the thesis was to elucidate and quantify orographic rainfall production in the context of the physiographic and atmospheric conditions of the area.

The specific objectives of the study were:

1. To measure storm rainfall within a mountainous area with the aim of quantifying rainfall variations and distribution in relation to specific terrain features.

2. To analyse individual storms to determine those synoptic and atmospheric characteristics that are specifically related to the production of orographic rainfall in the study area.

3. To develop an analytical model for evaluating the orographic component of short-period storm intensities based on terrain configuration and storm meteorological characteristics.

4. To assess areal patterns and small scale variations of rainfall within the study area in relation to topography and meteorological variables.

The first three objectives were pursued in the GVWD, the fourth at the UBC Research Forest.

Storms in the study ranged from 10 to 130 mm with all but one showing an orographic effect. There were significant relationships between the amount of orographic rain and the following storm variables:

-the wind speed component normal to the mountain barrier,

-moisture content of the lower atmosphere,

-freezing level, and

-air mass stability.

Classifying storm types in relation to orographic rainfall met with limited success. A physical model for estimating rainfall intensities over windward mountain slopes was adapted and tested on stable and unstable storms. Procedures are given for applying this model. For stable storms, the model can give consistent estimates of rainfall amount and distribution over the mountain slopes. For unstable storms,

model estimates are unreliable due to uncertainty in estimating convective vertical wind velocities. The study demonstrated that topography exerts a dominant influence on rainfall production and distribution in the study area.

Jeffrey, W.W. and B.C. Goodell. 1970. Land management in municipal watersheds. J. Amer. Water Works Assoc. 62(6):380-385.

A brief review of land management, particularly forest management, relative to its effects on water quantity, regime, and quality in municipal watersheds. Included are several paragraphs on the management of the Vancouver and Victoria municipal watersheds.

Jones, R.D.O. 1974. Optimization of the rain gauge network on the Jamieson Creek watershed. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C.

The objective of this thesis was to optimize the Jamieson Creek watershed rain-gauge network, outline a method for determining the areal precipitation pattern, and evaluate the various types of available gauges.

On the basis of the three years of precipitation data, the author recommended discontinuing four (2800-D, 2100-B, 2100-C, and 1400-B) of the 12 gauges because of high correlation of amounts at these gauges with amounts at the remaining eight gauges.

Joyce, G.M. 1976. Analysis of fluvial and glaciofluvial landforms and their associated vegetation of the Seymour watershed of southwestern British Columbia. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 78 pp. + appendices.

The author examined the feasibility of using panchromatic, colour, colour-infrared, and thermal-infrared media to detect three subsurface geomorphologic modifications found within a glaciofluvial deposit:

1. The occurrence of two fine-textured strata.

2. Occurrence of a glaciomarine deposit, thinly veneered with outwash.

3. The relation between river alluvium and surrounding outwash.

The three modifications were detectable by air-photo analysis with none of the media showing superior interpretative qualities. Best results were obtained by combining the results from all four media. However, for general forestry applications, e.g., landform, soil texture, vegetation density, vegetation stress and disease, and species identification, colour-infrared was superior.

Joyce, G.M. 1977. Design of a recording peizometer. Report prepared for a Fac. For. course, UBC, Vancouver, B.C.. (Course number was not indicated.)

This report describes a recording piezometer that is inexpensive and will operate unattended for 3-4 days.

Kalmokoff, J.C. 1993. Correcting the water balance of Elbow Creek watershed. B.Sc. thesis. Fac. For., UBC, Vancouver, B.C. 63 pp.

Elbow Creek serves as the control watershed for the paired watershed study with Jamieson Creek the treatment watershed. The weir on Elbow Creek has consistently measured stream flow on a unit-area basis well below the flow in Jamieson Creek and the levels expected in Coastal British Columbia.

In the back of the watershed a major tributary of Elbow Creek is split by a surface topographical divide, one of the branches rejoining the main stem below the weir. Water is also being lost to the main stem along a road running beside the watershed boundary. Traverse data showed that the location of the weir is upstream of where it is shown on the map, resulting in a reduction in the area of the watershed from 121.4 ha to 82.4 ha.

A regression equation was developed to correct discharge at the weir based on measurements of flow at various locations along the channel and at various discharge levels.

The equation,

$$Q = 0.362 + 1.25X \qquad [R^2: 0.999]$$

where Q is corrected streamflow at the Elbow weir, in cubic feet per second
X is actual streamflow at the Elbow weir, in cubic feet per second

Application of the regression equation to actual mean monthly discharge allowed correction of the basin water balance resulting in an estimate of annual evapotranspiration of 26.7 in. (17.5% of annual precipitation), compared to 22.0 in. (14.6% of annual precipitation) on Jamieson Creek.

Leadbeater, C. 1976. Use of 70 mm photography to measure morphological parameters pertaining to stream inventory. B.S.F. thesis. Fac For., UBC, Vancouver, B.C. 39 pp.

The objective of this study was to develop a method using 70-mm areal photography for reliable stream assessment (stream length and width, debris amounts, streambank materials and adjacent forest cover). The trial used 70 mm photography taken by helicopter and the results were compared to ground survey of Burwell Creek.

It was shown that the results from the 70 mm areal photography were not significantly different from the ground measurements, leading to the conclusion that 70 mm photography can be used for stream inventory and can provide information not easily obtained from ground surveys.

Lewis, T. 1985. Overview of research in the watersheds of the Greater Vancouver Water District. Report funded by the British Columbia Ministry of Forests (Section 88; Ref.No. KV99021). 28 pp. + appendices.

This is an overview of the published and unpublished material on research carried out in the GVWD. It includes not only reports on hydrology research but has sections on forest management, silviculture, and protection; forest biology and ecology; and fisheries, wildlife and recreation. The report also includes conclusions and recommendations for each of these sections.

Luo, J. 1992. Applications of GIS in hydrologic modeling. M.Sc. thesis. Dept. Bio-Res. Eng., UBC, Vancouver, B.C. 115 pp.

A hydrologic model using a Geographic Information System (GIS) was constructed to simulate stormflow hydrographs for Jamieson Creek. The model consists of three components: stormflow generation, translation, and detention. Two major aspects were emphasized in the model:

1. Using GIS to extract, overlay, and delineate land and water-related characteristics required for stormflow modeling.

2. Integrating GIS with hydrologic modeling to simulate both spatial and temporal transformations of rainfall into stormflow.

The model combined the characteristics of both distributed and lumped models and can be used not only for modeling stormflow in a well-gauged watershed but also for giving reasonable simulation of stormflow in ungauged watersheds. There was good agreement between simulated and observed stormflow hydrographs from Jamieson Creek. The model was also applied to the Nitinat watershed on Vancouver Island and it was demonstrated that it is capable of handling the effects of soil complexities, land use, topography, and rainfall intensity on stormflow simulation.

One of the assumptions in the Rational method is that maximum peak flow occurs as soon as storm duration equals time of concentration. The simulation showed that this is rarely true except for small, uncomplicated urban watersheds. For storms of a given return period and intensity on watersheds with large storage capacity, the maximum peak flow increases with longer storm duration. That is, peak flow is greatly attenuated and the time to peak is delayed.

Loukas, A. 1991a. Analysis of the response and the rainfall distribution in a mountainous watershed. M.A.Sc. thesis. Dept. Civil Eng., UBC, Vancouver, B.C. 159 pp.

The objectives of this study were:

1. To identify possible changes in the response of a small, steep, forested watershed (Jamieson Creek) under a

variety of rainfall events, and to examine the rainfall distribution in the watershed.

2. To test the linear response of the watershed, which is the basic assumption in the development of many hydrologic models.

3. To analyse the effects of rainfall representativeness on streamflow simulation and to test the accuracy of the rainfall distribution using predictor equations.

The hydrologic response of the watershed was investigated using a simplified watershed model developed for the study. The model utilizes the linear storage routing technique and treats runoff as fast flow and slow flow. Separation of rainfall input to each of the components of runoff was done using a non-linear exponential equation for P_s, (slow routing),

$$P_s = a * t^{-n} + b$$

where a,n, and b are constants that characterize the watershed and depend on initial conditions,
P_s is rainfall input that goes to slow routing, at time t
t is time,

and for P_f, (fast routing),

$$P_f = P_t - P_s$$

where P_t is rainfall input that goes to fast routing, at time t.

Hourly rainfall averaged from five gauges and hourly streamflow were used as input to the model.

The model performed well and showed that the hydrologic response of the watershed is reasonably linear except for intense summer rainstorms under dry soil conditions. Rainfall distribution showed that a linear increase of precipitation with elevation is not valid for rainfall. The rain depth per event increased up to mid-elevation and then decreased at upper elevations. Furthermore, the hourly intensity decreased with height and the two dominant hillslopes did not receive the same amount of rain. This variation in rainfall is explained in the thesis by

meteorological processes and the physiographic features of the watershed.

The performance of the model was highly affected by the accuracy and representativeness of rainfall data. For example, when weighted averages of several precipitation stations were used, the model performed well. With only single point rainfall the model performance was poorer. As a result, unless rainfall and runoff are known with precision, it is difficult to make an accurate determination of the storage characteristics of the basin, and consequently, it may not be possible to distinguish between the accuracy of different routing models.

Loukas, A. 1991b. Application of WRENSS model to two watersheds in British Columbia. FRST 585 Report, Fac. For., UBC, Vancouver, B.C. 20 pp.

The Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) model was applied to two watersheds, Carnation Creek, on the west coast of Vancouver Island, and Jamieson Creek, in the Seymour watershed of the Greater Vancouver municipal catchments, to estimate the increase in annual flow resulting from harvest and road building. Data requirements for the model are: area of watershed, area of each watershed subdivision, and area harvested in each subdivision, monthly precipitation, leaf area index (LAI) and rooting depth for pre-treatment and post-treatment periods.

The version of the model used on Jamieson Creek watershed was for rain-dominated areas, and the whole watershed was considered as one hydrological unit (i.e., the watershed was not subdivided on the basis of elevation, aspect, slope, or forest cover). The model predicted an increase of only 3 mm in annual water yield for the harvest of 19.2% of the watershed. This result is in line with the observations of the actual increase that showed no detect-able increase in annual flow. One of the data requirements for application of the model is LAI. In the absence of measurements of this variable on Jamieson Creek watershed, values were obtained from the literature for similar forest cover. The model was run simulating different harvest percentages. The increase in water yield was shown to be exponential with increasing harvest area, becoming significant at a 40% cut, with the increase reaching 550 mm for a 100% clearcut of the watershed. Seasonal increases predicted by the model were

greatest in spring, followed by winter, fall, and finally summer.

Loukas, A. and M.C. Quick. 1993a. Hydrologic behaviour of a mountainous watershed. Can. J. Civil Eng. 20(1):1-8.

Paper based on M.A.Sc. thesis noted above (Loukas 1991).

Loukas, A. and M.C. Quick. 1993b. Rain distribution in a mountainous watershed. Nordic Hydrol. 24(4):225-242.

Based on M.A.Sc. thesis noted above (Loukas 1991).

Loukas, A. 1994. Mountain precipitation analysis for the estimation of flood runoff in coastal British Columbia. Ph.D. Thesis. Dept. Civil Eng., UBC, Vancouver, B.C. 320 pp.

Precipitation distribution in coastal British Columbia was described and a technique proposed for the reliable estimation of the frequency of rainfall-generated floods from ungauged watersheds. The study included analysis of long- and short-term precipitation for two medium sized watersheds, the Seymour and Capilano; development of a 24-hour design storm for coastal British Columbia; generalization of the results over the coastal region of British Columbia; examination of the precipitation distribution during flood-producing storms; identification of the applicability of a meteorological model for the estimation of short-term precipitation; development of a physically-based stochastic-deterministic procedure for the estimation of flood runoff from ungauged watersheds of the region.

It was shown that the strong frontal storms that form over the North Pacific Ocean and travel eastward generate most of the precipitation during the winter and fall months, whereas convective rain-showers and weak frontal storms produce the dry summer-period precipitation.

The study analysed the distribution of annual, seasonal, and monthly precipitation, and its distribution with elevation. Annual and wet-period (October-March) precipitation increased with elevation to about 400 m in the Capilano River watershed, and because of the topography to

long-term pattern. The import-ance of this is that in coastal British Columbia only about one-third of precipitation stations are recording gauges capable of measuring short-term precipitation. This preliminary result suggests that long-term precipitation may be used as an indicator of short-term precipitation. Moreover, the distribution pattern of the storm was not affected by the type of precipitation, whether rain, snow, or a combination of the two.

The final goal of the study was to find techniques to accurately estimate the flood runoff from ungauged watersheds of the region. The 24-hour design storm developed with data from the Seymour watershed was shown not to differ significantly from regional data, and can be transposed over the region. The 24-hour annual rainfall of a given return period is a constant percentage of mean annual precipitation. A technique was developed to estimate the flood frequency for ungauged watersheds with limited data. The procedure was applied to eight coastal British Columbia watersheds and compared with other regional techniques. The method was shown to be easy to apply, required limited data, and was efficient and reliable for determining hourly and daily peak flows.

Morton, C. 1975. Tree contribution to soil stability. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 66 pp. + appendices.

The objectives of this study were to use O'Loughlin's (1973) data to evaluate apparent root cohesion; to apply derived root-stress values for conditions of no seepage to obtain representative slope failure curves; and to evaluate the effect of reducing apparent root cohesion on the potential shear failure surface.

The study showed that both susceptibility to failure and apparent root cohesion increased with greater slope angle and that apparent root cohesion decreased with greater depth beneath the surface. That is, the depth to the potential shear-failure plane affected the extent to which roots acted as a strengthening agent (the shallower the soil the more important are the roots to slope stability).

O'Loughlin, C.L. 1972. A preliminary study of landslides in the Coast Mountains of Southwestern British Columbia.

In Slaymaker, H.O. and H.J. McPherson (eds). Mountain Geomorphology, Tantalus Res. Ltd., Vancouver, British Columbia. pp. 101-120.

This paper gives the preliminary results of that part of O'Loughlin's (1974) Ph.D. research dealing with landslides in southwestern British Columbia.

O'Loughlin, C.L. 1973. An investigation of the stability of the steepland forest soils in the Coast Mountains, Southwest British Columbia. Ph.D. thesis. Fac. For., UBC, Vancouver, B.C. 146 pp.

The objective of this study was to determine the extent and seriousness of landsliding on undisturbed forested and clearcut slopes, and to clarify some of the natural and human-caused factors that are detrimental to slope stability in the Coast Range.

The study area was a 640-km^2 triangular block between Howe Sound and Indian Arm north of the city of Vancouver. Within this area, 77 large debris-avalanche type landslides were located by areal photo interpretation and field reconnaissance. Landslides not associated with roads were predominantly confined to long, uniform slopes of over 30^0 underlain by poorly-drained podsolic soils. Slopes underlain by shallow, regosolic soils were relatively resistant to mass wasting.

Road construction, responsible for 14 large slides and more than 100 smaller failures, appeared more likely to cause instability of slopes than other human activities. Large landslides were more frequent on clearcut areas than on undisturbed slopes.

A network of simple piezometers established in steep drainage depressions revealed that the piezometric surface within the soil mantle rose toward the surface during rain and snowmelt periods, causing a marked increase in pore-water pressure. Pressures greater than $800kg/m^2$ were recorded at the base of the soil mantle. Such pressures significantly reduce the effective normal stress acting on potential failure planes, thus decreasing slope stability. Rainfalls exceeding 120mm per day caused complete saturation of most drainage depression soils.

Direct shear tests performed in the field indicated that soil strength was positively related to the bulk weight of roots in the soil. Dense root networks can impart several hundred kg/m^2 to the soil's shear strength. Laboratory tests of tree root strength showed that Douglas fir and cedar roots deteriorate rapidly after the death of the tree. Within three to five years after cutting, small roots may lose over half of their original tensile strength.

O'Loughlin, C.L. 1974. A study of tree root strength deterioration following clearfelling. Can. J. For. Res. 4(1):107-113.

This study was carried out in association with O'Loughlin's Ph.D. research in landslides in the southern British Columbia mountains near Vancouver. The objective of the study was to determine the tensile strength of tree roots sampled from living trees and to identify the rate at which root strength deteriorates after the parent trees are felled. Roots were taken from mature, living Douglas fir and western red cedar and from stumps of the same species on slopes clearfelled from two to 10 years earlier. Tensile strengths were determined in the lab.

Tests on small roots, between 1 and 12 mm in diameter, showed that Douglas fir and cedar roots rapidly lose their tensile strength after death of the parent tree. Within 3-5 years after felling of the parent tree small roots may lose over half of their original tensile strength.

Plamondon, A.P. 1972. Hydrologic properties and water balance of the forest floor of a Canadian west coast watershed. Ph.D. thesis. Fac. For., UBC, Vancouver, B.C. 126 pp.

This study consisted of four parts:

1. A survey of the spatial variability of hydrologic and physical properties of the forest floor at a site in the Seymour River watershed. Depth, bulk density, and water retention capacity were determined for biophysically-different areas of the watershed.

2. Development and testing of methods of estimating evaporation from the forest floor. This was carried out in a Douglas fir plantation on the UBC research forest.

Evaporation calculated by the energy balance and aerodynamic methods was compared with that measured by a small weighing lysimeter.

3. Measurement of the water balance components of the forest floor on a 30^{0} slope in the Seymour watershed during natural wetting and drying periods.

4. Laboratory measurement of the conductivity characteristics of the forest floor.

The conclusions drawn from the study are:

1. The average forest floor depth can be predicted from factors readily obtained from a topographic map, viz., elevation, slope, distance north of a reference point, and radiation index (a function of latitude, slope and aspect). The radiation index itself accounted for 30% of forest-floor depth variation because of its effect on decomposition rate.

2. The energy balance of the forest floor was considerably different for wet and for dry soil conditions.

3. Water holding capacity of the forest floor effected only relatively small peak flows (caused by short duration rainfall). The water holding capacity was too small to be a factor during extreme peak flow events.

4. The most important contribution of the forest floor to watershed hydrology are protection of the mineral soil against raindrop impact and provision of numerous surface depressions that temporarily store water.

Plamondon, A.P., T.A. Black, and B.C. Goodell. 1972. The role of hydrologic properties of the forest floor in watershed hydrology. Proc. Natl. Symp. Watersheds in Transition, Amer. Water Res. Assoc., Urbana, Illinois. pp. 341-348.

Based on Ph.D. thesis noted above (Plamondon 1972).

Rogers, R.E. 1972. Some effects of high-lead logging on a mountain stream in coastal British Columbia. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C.

The objective of this study was to determine changes in stream temperature and suspended sediment concentrations in Lembke Creek following high-lead cross-stream yarding. The old-growth trees were felled across and into the stream, and yarded across and through the stream.

The conclusions of the study were:

1. Clearcutting of the 60-acre block caused no significant change in stream temperature in the first year after logging.

2. Pre-logging sediment concentrations were 0.3-14 ppm. For brief periods during cross-stream yarding, concentrations were as high as 1650 ppm near the point of disturbance.

3. Suspended sediment concentrations decreased rapidly downstream with significant increases persisting for only a few hundred feet.

Rutherford, W.L. 1978. Slope stability and its relationship to landscape units in the Seymour watershed. B.Sc. thesis. Fac. For., UBC, Vancouver, B.C. 41 pp.

The objectives of this study were:

1. To show the relationships between slope instability (i.e., landslides) and the particular site factors of aspect, basin order, and slope hygrotope/position.

2. Using management units as defined in Briere's (1978) Aqua-Terra forest land classification system, to relate landslides to their starting zones and the management units through which they move down slope.

The study was based on the management-unit mapping information by Briere along with airphoto interpretation. No fieldwork was done. The study showed that because slope instability was related to the management units described by Briere, his classification system could be useful in planning logging operations and road construction, and that more slides occur on south aspects, on first-order basins, and on slopes contained in shedding zones.

Schaefer, D.G. 1982. Meteorological conditions associated with slides and floods in the Lower Mainland of British Columbia in late October, 1981. Unpub. Rept. Sci. Serv. Div., Atmos. Environ. Serv., Vancouver, B.C. 45 pp.

This is a summary of the meteorological conditions that preceded the M Creek slide, which occurred in the early hours of October 28, 1981, and the conditions that led to severe local flooding in West and North Vancouver just three days later. The former event was not shown to have been associated with unusually heavy rainfalls for the area and time of year. In contrast, flooding in West and North Vancouver was preceded by much more statistically-extreme rainfalls, ranging from hours to days, but confined to a relatively well defined and limited area to the north of Burrard Inlet. The report contains intensity-duration-frequency curves for numerous stations in the lower mainland and Vancouver Island. It is interesting to note that the UBC gauges in the GVWD showed less rain in the rainfall events of October 30th and 31st than did the lower elevation GVWD gauge at Seymour Falls.

Schaefer, D.G. and S.N. Nikleva. 1973. Mean precipitation and snowfall maps for a mountainous area of potential urban development. Proc. West. Snow Conf. pp. 80-89.

The objective of this study was to provide background information for an assessment of the climatological suitability of the area north of the city of Vancouver for urbanization. A simple model was developed to obtain estimates of mean annual precipitation with elevation. The model took into account the two topographical factors influencing precipitation amounts:

1. The mountain slopes that provide a mechanism for lifting the air and thereby increasing the amount of precipitation.

2. The valleys and channels that open out to the general air flow and provide a funneling effect that results in increased precipitation due to convergence of the air.

Mean annual snowfall was estimated using relationships related to mean annual precipitation and elevation. Maps of mean annual precipitation and snowfall are presented along with curves of precipitation and snowfall by elevation for the mountain slopes and the valley axes.

St.John, R.K. 1969. Water uses and needs in the Greater Vancouver Water District. Forestry 482/483 report, Fac. For., UBC, Vancouver, B.C. 65 pp.

This report assesses the water supply of the Greater Vancouver Water District and the water uses and needs of the lower mainland of British Columbia. It looks at surface and groundwater supply; domestic, irrigation, and industrial use; transport of sewage and heat from industrial cooling; the provision of navigation and hydro-electric power; on-site uses such as flood control and recreation; and water supply for present and future needs.

Thompson, G. and D.L. Golding. 1990. Mass wasting in GVWD watersheds: an inventory of events and an evaluation of the Aqua-Terra Classification System. Report to Greater Vancouver Water District. Fac. For., UBC, Vancouver, B.C. 85 pp.

This study inventoried the number and types of mass wasting events that occurred on the Capilano, Seymour, and Coquitlam watersheds within each of the five classes of the Aqua-Terra Classification System (ATCS) (Briere 1978). The intent was to provide not only an inventory of slides on the watersheds but also a preliminary evaluation of the capability of the ATCS to identify unstable areas.

There were 319 mass movements that satisfied the criteria established for the study, i.e., that the movements occurred from 1964 to 1987 and that they be at least 45 m x 15 m in size, the minimum size detectable on the 1:15,000 scale aerial photographs. Where a mass movement was initi-ated in one ATCS class and moved into a lower class it was entered as a slide in each class.

The number of slides moving through a given ATCS class increased with increasing class number for both Seymour and Coquitlam watersheds (except for class 5 which includes only those slides that moved from a class 5 area into a forested area), as would be expected if the ATCS satisfactorily evaluates terrain stability. However, in Capilano watershed this trend is evident only for classes 1, 2, and 3, with a dropping off in the number of slides in class 4 (Table 2).

Table 2. Number of slides by ATCS class (These are the number of slides that moved through a given ATCS class, not the number that initiated in that class.)

Watershed	ATCS class				
	1	2	3	4	5[1]
Capilano	10	44	84	40	3
Seymour	5	15	37	61	10
Coquitlam	21	19	39	77	6

[1] The number of slides under ATCS class 5 are only those that initiated in class 5 and moved into the forest (i.e., into a class 4 or lower).

Table 3. Number of slides within each watershed

Watershed	Number of slides		
	Total	In cutovers	At roads
Capilano	117	2	5
Seymour	96	7	0
Coquitlam	106	2	3

There is no obvious trend in the number of slides initiating at roads or in cutovers, the total for the three watersheds being 8 and 11 respectively (Table 3).

There are so few slides in most of the ATCS classes in harvested areas (from 0.0 to 5) that discussion of trends on a unit-area basis is tenuous. However, there is an increasing number of slides per unit area from class 1 (0.0 for all watersheds) to class 4 (0.0 on Capilano and Coquitlam, to 37.0 on Seymour), as would be expected (Table 4). In the uncut areas there is a more obvious trend of increasing number of slides with increasing ATCS class (from 0.0 to 1.5 for class 1, to 6.2 to 13.7 for class 4).

Table 4. Number of slides initiated in cut and uncut areas in ATCS classes 1-4[1]. (Slides per 1000 ha in brackets)

ATCS Class	Capilano		Seymour		Coquitlam		Total
	Cut	Uncut	Cut	Uncut	Cut	Uncut	
1	0 (0.0)	3 (1.5)	0 (0.0)	1 (0.5)	0 (0.0)	0 (0.0)	4
2	2 (4.5)	13 (4.4)	2 (4.1)	5 (2.1)	1 (3.1)	9 (3.7)	32
3	5 (26.7)	62 (13.7)	4 (18.9)	18 (6.2)	4 (28.2)	23 (9.4)	116
4	0 (0.0)	36 (14.6)	1 (37.0)	55 (16.3)	0 (0.0)	63 (16.0)	155
Total	7	114	7	79	5	95	307

[1] This table is not in the report. The area of each ATCS class was not available until after the report was completed. The slide data of the report was converted to a unit-area basis and presented in the Final Summary Report of the Watershed Management Evaluation and Policy Review (EESI 1991).

Thurber Eng. Ltd. 1991. Geotechnical assessment of 1990-1991 landslide events in Greater Vancouver Water District watersheds. Report To Greater Vancouver Water Dist. by Thurber Engineering Ltd., Vancouver, B. C., May, 1991. 33 pp. + appendices.

The report evaluates the 35 landslides that occurred in the Capilano, Seymour, and Coquitlam watersheds of the Greater Vancouver Water District during heavy rainstorms in the fall of 1990 (November 9-11, 23, and December 3) and spring of 1991 (April 3-4). The study was conducted by analysis of GVWD information, aerial photographs, helicopter reconnaissance, and field inspection. Most of the landslides were small (1,000 to 2,000 m^3 of debris) or very small (> 1,000 m^3), the two largest, Sisters Creek and Spoon Creek, containing about 15,000 m^3 of debris. The total amount of debris activated by all of the landsides is estimated at about 100,000 m^3. Most of the debris flowed in torrents down steep gullies that often had evidence of previous (ancient) activity. Twenty nine of the slides started in old growth or mature reforested areas and 6 occurred in patch clearcut areas. The report concludes that

each of the clearcut areas was hydrologically stressed before harvest, although evidence of potential instability may not have been visible in the natural forest if a geotechnical inspection had been carried out prior to harvest. Root strength deterioration is not believed to have played a critical role in any of the 6 clearcut slides.

Todd, G. 1984. An analysis of the U.S.E.P.A. hydro-logical model entitled: an approach to water resources evaluation of non-point silvicultural sources, with respect to conditions in a typical southwestern coastal British Columbia watershed. B.S.F. thesis. Fac. For., UBC, Vancouver, B.C. 41 pp.

The WRENSS model was applied to Jamieson Creek watershed using 1971-1982 data to simulate existing streamflow and the changes that would take place with logging. The watershed was subdivided into three hydrologic zones based on the biogeoclimatic classifications. The model predicted that a clearcut area of 48.6% of the watershed would result in an increase of 14.4% in annual streamflow, with net reductions in high flow rates and increases in lower flow rates. Seasonal increases in annual flow were greatest for spring, as in Loukas (1991), but in the reverse order for the other three seasons. The reversal of the order for the latter three seasons may be the result of the subdivision of the watershed into three hydrologic zones, and the use of different LAI and rooting depths than used by Loukas.

Willington, R.P. and D.S. Jamieson. 1971. Slashlogging: an alternative to slasburning? Unpub. Rept. to the Greater Vancouver Water Dist. 33 pp.

This study was carried out in overmature cedar-hemlock of the CWHb zone. Slashlogging requires salvaging large wood waste, breaking up the continuity of fine slash and crushing it so that it lay close to the ground. Slashlogging:

1. Reduced fire hazard sufficiently to satisfy the Forest Service abatement requirements.

2. Resulted in salvage of a significant volume of merchantable wood.

3. Left the site in better hydrologic condition because of:

(a) Better coverage of protective litter.
(b) Less exposure of mineral soil and bedrock.
(c) Probably less chemical leachates to stream.

Zeman, L.J. 1973. Chemistry of tropospheric fallout and streamflow in a small mountainous watershed near Vancouver, British Columbia. Ph.D. thesis. Fac. For., UBC, Vancouver, B.C. 154 pp.

The purpose of this study was to evaluate ionic input in tropospheric fallout and output in discharge water from a small mountainous watershed, emphasizing the processes involved. Jamieson Creek watershed was selected as a topographically well-defined watershed with relatively watertight bedrock and an undisturbed coniferous forest ecosystem. Precipitation and stream discharge were sampled November 1970-October 1971 and were analyzed for 11 ionic constituents.

Ionic input-output budgets show net losses of sodium, potassium, calcium, magnesium, bicarbonate, sulfate, chloride, silica, and phosphate from the watershed in streamflow. Exceptions were nitrate and ammonium loads with net gains in the watershed. Tropospheric fallout provided most of the ionic loads of the following constituents of discharge water: nitrate, ammonium, sulfate, and chloride. The terrestrial sources, however, were the major suppliers of silica, calcium, bicarbonate, magnesium, and potassium. Phosphate and sodium were derived equally from tropospheric and terrestrial sources.