DEVELOPMENT OF HYDROLOGIC HAZARD CURVES FOR ASSESSING HYDROLOGIC RISKS FOR STRATHCONA, LADORE FALLS AND JOHN HART DAMS ON THE CAMPBELL RIVER, BC

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Executive Summary

The Campbell River hydroelectric system (BCHydro) is comprised of the Strathcona, Ladore Falls and John Hart Dams on the Campbell River on Vancouver Island, BC. In 2003, a new study of Probable Maximum Precipitation (PMP) was completed that increased the PMP estimate by 33% and required re-analysis of the Probable Maximum Flood (PMF). Reservoir routing of the updated PMF indicated overtopping of all three projects. Interim measures were taken to reduce the likelihood of dam overtopping from an extreme flood at Strathcona Dam, which is a 53-m high earthfill structure that impounds 900-million m^3 (723,000 acre-feet) at normal pool. A probabilistic flood study was initiated to estimate the likelihood of various flood magnitudes for use in assessing hydrologic risk at the projects for various potential failure modes.

A stochastic flood model was developed for use in developing magnitude-frequency estimates for floods, particularly extreme floods. The stochastic flood model utilized a deterministic flood computational model (UBC Watershed model) and treated the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures were used to allow the climatic and storm-related input parameters to vary in accordance with that observed in nature. Hydrometeorological inputs that were treated as variables included: seasonality of storm occurrence; magnitude of extreme storms, temporal and spatial distribution of storms; temporal temperature pattern during the storm; 1000-mb and freezing level temperatures; hydrologic model antecedent conditions (snowpack, soil moisture, initial streamflow), and initial reservoir storage.

Sixty-thousand computer simulations were conducted to develop magnitude-frequency relationships for the flood characteristics of peak discharge, maximum reservoir release, runoff volume, and maximum reservoir level. The AEP for flood waters reaching the top of the lock blocks on Strathcona Dam (226.30 m) was estimated to be 1:5,500,000 and the annual probability of flood waters reaching the top of the impervious core (224.60 m) was estimated to be 1:34,000. The annual probability of overtopping at Ladore Dam (179.35 m) was estimated to be 1:960,000. The annual probability of overtopping of John Hart Dam (141.73m) was estimated to be 1:1,400,000 and overtopping of the impervious core, slurry wall and sheet piles (140.50m) was estimated to be 1:65,000.

Overview of the Stochastic Approach

The basic concept employed in the stochastic approach is the computer simulation of multi-thousand years of flood annual maxima. This is accomplished by utilizing a deterministic flood computation model (UBC Watershed Model) and treating the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Multi-thousand years of extreme storm and flood annual maxima are generated by computer simulation. The simulation for each year contains a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserves dependencies between the hydrometeorological input parameters. Execution of the UBC Watershed Model, and reservoir routing of the inflow floods provides the computation of a corresponding multi-thousand year series of annual maxima flood characteristics. Characteristics of the simulated floods such as peak discharge, maximum reservoir release, runoff volume, and maximum reservoir level are the flood parameters of interest. An annual maxima series is created for each of these flood parameters and the values are ranked in descending order of magnitude and a non-parametric plotting position formula and probability-plots are used to describe the magnitude-frequency relationships.

Stochastic Event Flood Model

The stochastic flood model employed here is considered an event model even though the UBC Watershed Model is a continuous runoff model. It is termed an event model because each simulation consists of modeling the flood and reservoir response from a specific storm event embedded within the UBC model continuous simulation period. Thus, each simulation produces one maximum for flood peak discharge, maximum reservoir release, runoff volume, and maximum reservoir level at each of the three dams. These maxima are used in assembling annual maxima series representing multi-thousand years of flood events.

Campbell River Watershed Model

Project Description

The Campbell River hydroelectric system is located on central Vancouver Island in the province of British Columbia, Canada (Figure 1). The Campbell River originates in east-central Vancouver Island and discharges into Discovery Passage. The system is comprised of three dams. Upper Campbell Lake and Buttle Lake are impounded behind the 53 m (174 ft) high earthen Strathcona Dam which discharges into Lower Campbell Lake. Lower Campbell Lake is impounded by the 37.5 m (123 ft) high concrete gravity Ladore Dam. Lower Campbell Lake discharges into John Hart Lake, which is the reservoir impounded behind the 34 m (112 ft) high concrete and earthfill John Hart Dam.

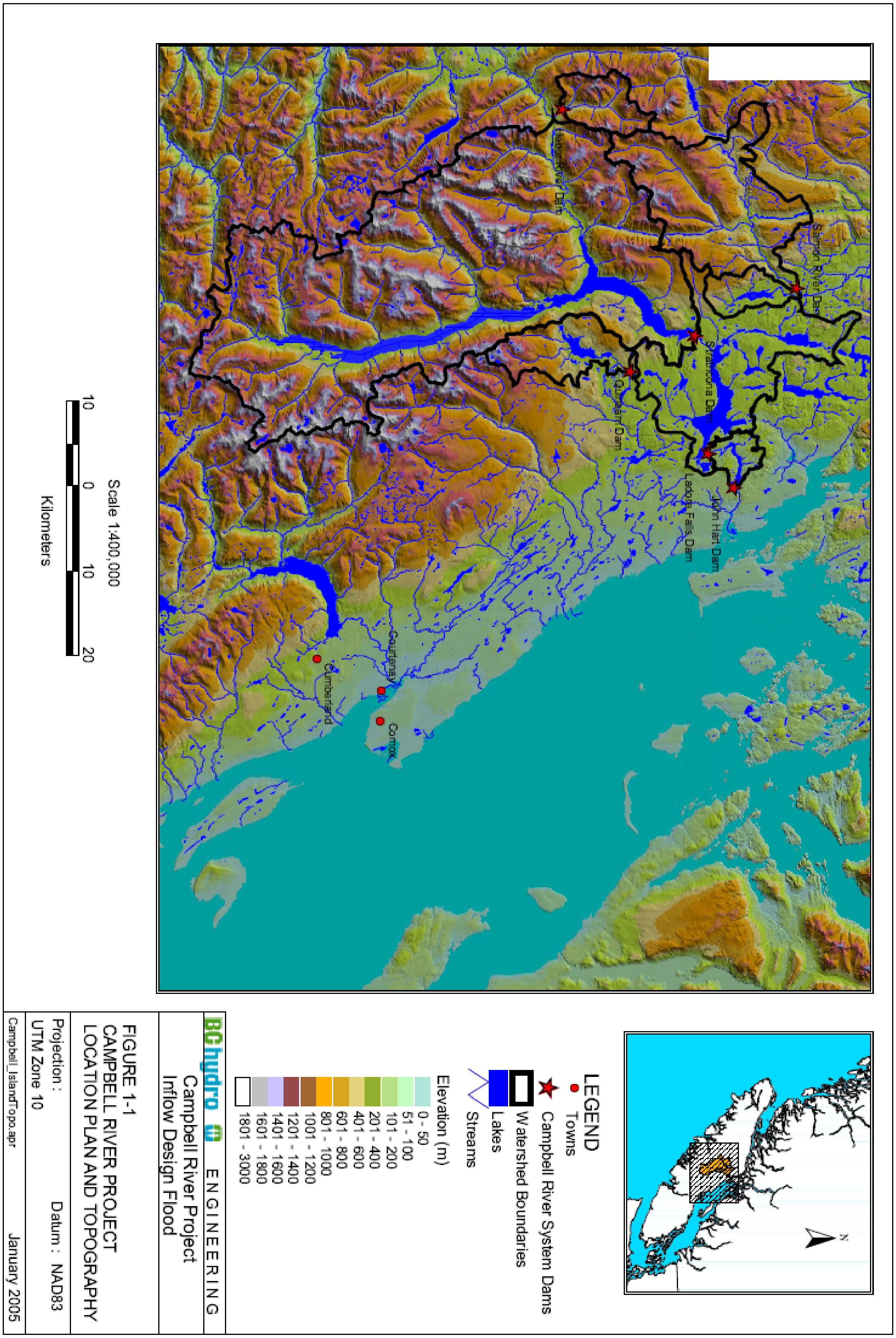

Figure 1. Campbell River Project Location and Topography

UBC Watershed Model

The UBC Watershed Model developed by BC Hydro to analyze the Campbell River System Probable Maximum Flood (PMF)[1] was adapted for use with the stochastic simulation approach for the current analysis. The UBC Watershed Model[2] was designed primarily for the calculation of streamflow from mountainous watersheds where streamflow consists of runoff from snowmelt, rain, and glacier outflow. The watershed is delineated into zones based on elevation with precipitation and temperature time-series defined for each zone. The elevation zone delineation for the Campbell River watershed used in the UBC Watershed model is shown in Figure 2 with areas listed in Table 1a, and 1b for the Strathcona, and Ladore watersheds, respectively.

Table 1a. Contributing Area for Each Elevation Zone in the UBC Watershed Model for Strathcona Dam

Elevation Zone	Area (sq km)
135m - 350m	144.7
351m - 550m	140.2
551m - 750m	138.2
751m - 925m	131.5
926m - 1050m	109.6
1051m - 1200m	140.5
1201m - 1375m	160.7
1376m - 1600m	157.0
>1600m	70.7
Total	**1193.1**

Table 1b. Contributing Area for Each Elevation Zone in the UBC Watershed Model for Ladore Dam

Elevation Zone	Area (sq km)
153m - 200m	52.2
201m - 250m	52.8
251m - 290m	51.0
291m - 250m	51.4
>350m	37.2
Total	**244.6**

The UBC Watershed model was used to simulate inflows to the Upper Campbell Lake (Strathcona Dam) and Lower Campbell Lake (Ladore Dam). The local area tributary to John Hart Lake is small (25.3 sq km) relative to the Strathcona and Ladore watersheds. For this reason, the local inflow to John Hart was determined by scaling the local inflow to Ladore by the ratio of the local tributary areas of John Hart to Ladore, 0.0988.

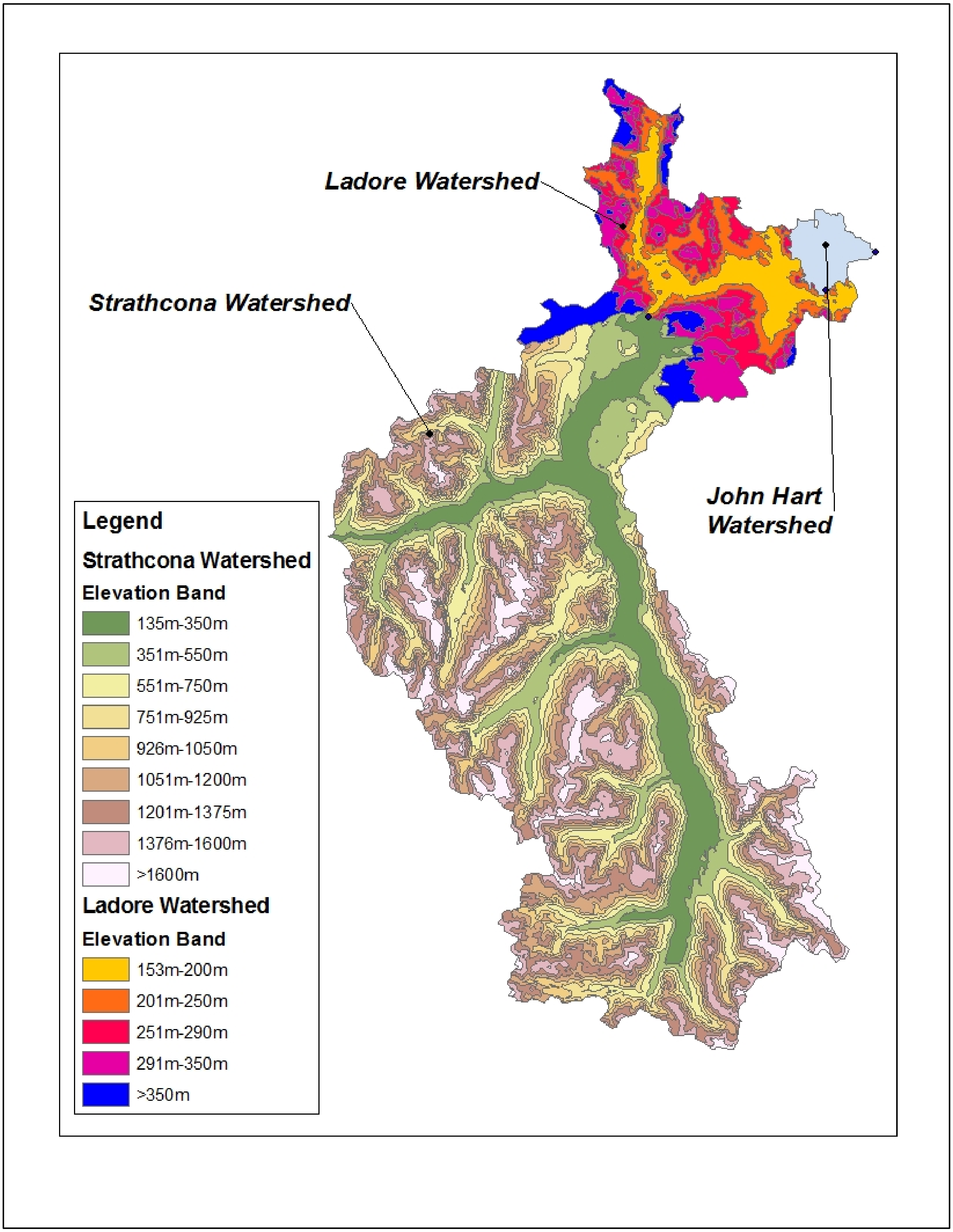

Figure 2. Campbell River Watershed, Showing Elevation Zone Delineation Used in UBC Watershed Model

Hydrologic calculations were performed on a continuous basis and the UBC Watershed Model may be run on either a daily or hourly time step. Antecedent conditions (soil moisture accounting, snowpack, initial streamflow) were determined using a daily time step. An hourly time step was used for flood simulation and reservoir routing.

The UBC Watershed Model has three main analysis modules:

- Meteorological Module – Distributes precipitation time-series and temperatures to all elevation zones in the watershed.

- Soil Moisture Module – The soil moisture module divides the water input (rain and snowmelt) into four components of runoff; fast, medium (interflow), slow (upper groundwater) and very slow (deep groundwater). The impermeable area is the fast responding region of the watershed and is assumed to be adjacent to a well developed stream channel system. These areas change as a function of the soil moisture (variable source area approach).

- Routing Module – The UBC model utilizes a linear reservoir algorithm to route flows. The model does not include a reservoir routing routine and a separate program must be used to simulate reservoir hydraulics using inflow hydrographs produced by the model. For this analysis, a level pool routing routine in SEFM was used to route flows through each of the three reservoirs.

Hydrometeorological Input Parameters to the Stochastic Model

Table 2 lists the hydrometeorological inputs to the stochastic model and the dependencies that exist in the stochastic simulation of a particular input. Analyses of historical data and computer simulations were conducted for end-of-month conditions to allow the seasonal aspects to be properly represented. Each of the hydrometeorological inputs is described in the following sections and the procedures used in stochastic simulation are described in a following section titled *Simulation Procedures*.

Table 2. Listing of Hydrometeorological Inputs to Stochastic Flood Model and Dependencies that Exist in Simulation of the Hydrometeorological Inputs

Hydrometeorological Inputs for Stochastic Model				
Model Input		**Dependencies**	**Probability Model**	**Comments**
1	Storm Seasonality	Independent	Normal Distribution	End-of-month storm occurrences
2	72-Hour Precipitation Magnitude	Independent	4-Parameter Kappa Distribution	Developed from regional precipitation analyses and Isopercental spatial storm analyses
3	Temporal and Spatial Distribution of Storms	Independent	Resampling from Historical Storms Storms are equally-likely	15 Prototype Storms, 3-Day to 6-Day time-series
4	Temperature Temporal Pattern	Temporal patterns are matched one-to-one to Prototype Storms	Resampling from Historical Storms	Pattern Indexed to 1000-mb Temperature and Freezing Level for Day of Maximum 24-Hour Precipitation
5	1000-mb Temperature	Storm Magnitude	Physically-based Stochastic Model	For Day of Maximum 24-Hour Precipitation in storm
6	Air Temperature Lapse-Rate	Independent	Normal Distribution	For Day of Maximum 24-Hour Precipitation in storm
7	Freezing-Level	1000-mb Temperature, Temperature Lapse-Rate and Storm Magnitude	Physically-based Stochastic Model	For Day of Maximum 24-Hour Precipitation in storm
8	UBC Model Antecedent Conditions	Seasonality of Storm	Resampling of Historical Conditions Oct 1983 – Sep 2003	Sampled from the end-of-month antecedent condition files. Sampled year is independent, sampled month corresponds to month sampled from seasonality of storm occurrence.
9	Initial Storage in Reservoirs	Seasonality of Storm and UBC Model Antecedent Conditions	Resampling of Historical Conditions Jan 1998 – Sep 2010	Sampled from recorded reservoir level data. Sampled year has similar antecedent precipitation as year sampled for UBC Model antecedent conditions. Sampled month and day corresponds to 30 day period surrounding sampled end of month for storm occurrence.

Seasonality of Storm Occurrence

The seasonality of storm occurrence was defined by the monthly distribution of the historical occurrences of 72-hour storms with widespread areal coverage that have occurred over Vancouver Island and nearby areas with similar climatic characteristics. This information was used to select the date of occurrence of the storm for a given simulation. The basic concept is that the seasonality characteristics of extraordinary storms used in flood simulations will be the same as the seasonality of the most extreme storms in the historical record.

Storms considered in the analysis were storm events where 72-hour precipitation maxima exceeded a 10-year recurrence interval at 3 or more stations. This was done to assure that only storms with both unusual precipitation amounts and broad areal coverage would be considered. This procedure resulted in identification of 69-storm events in the period from 1896-2009. A probability-plot was developed using numeric storm dates and it was determined that the seasonality data could be well described by a Normal distribution (Figure 3). A frequency histogram (Figure 4) was then constructed based on the fitted Normal distribution to depict the twice-monthly distribution of the dates of extreme storms for input into SEFM.

A review of Figure 3 shows historical extreme storms to have occurred in the period from near October 1st through about March 15th with a mean date of December 21st. Flood simulations were conducted using SEFM for end-of-month conditions. The probability of occurrence of a storm for any given end-of-month can be determined from the incremental bi-monthly probabilities depicted in Figure 4.

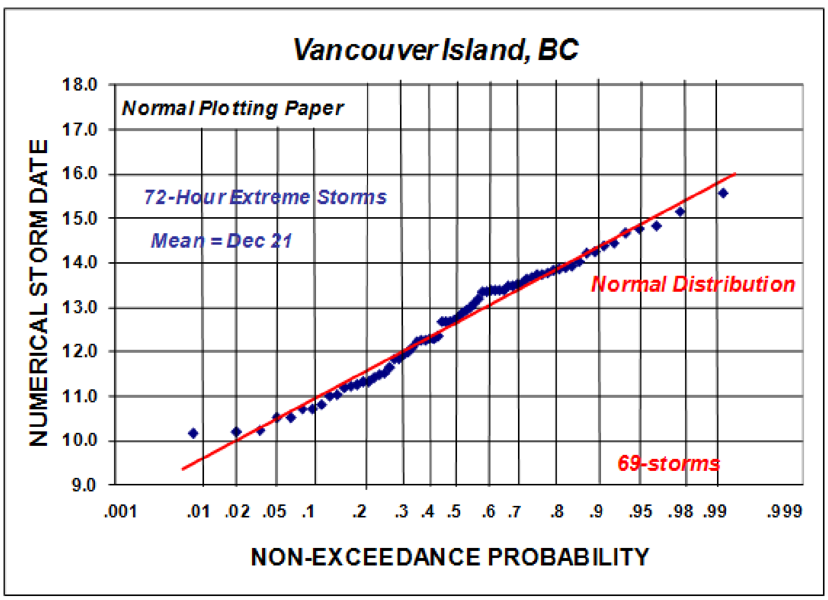

Figure 3. Probability-Plot of Numeric Date of Occurrence of Extreme Storms at the 72-Hour Duration for Vancouver Island

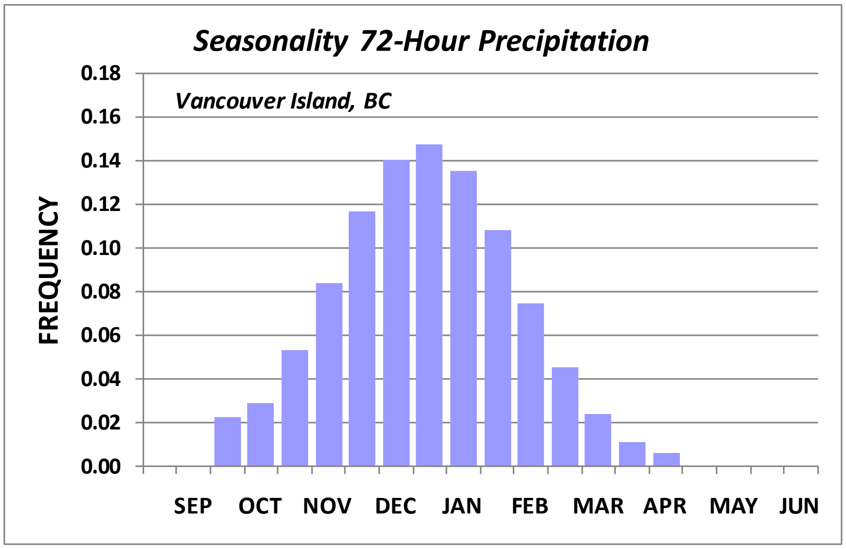

Figure 4. Frequency Histogram of Dates of Occurrence of Historical 72-Hour Extreme Storms for the Campbell River Watershed on Vancouver Island

Table 3. End-of-Month Probabilities for Occurrence of Extreme Storms

End-of-Month Probability for Storm Occurrence						
Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
0.052	0.137	0.258	0.283	0.183	0.069	0.018

Regional Precipitation Frequency Analysis

Regional analysis methods (Hosking and Wallis[3]) have been used extensively in conducting analyses of hydrometeorological data. Regional analyses are preferred because of the ability to obtain robust estimates of probabilistic parameters by utilizing large datasets of the same phenomenon which reduces the effects of sampling variability.

In particular, regional analysis methods were used in analyzing the characteristics of extreme precipitation. Using this approach, storm data were assembled from all locations that were climatologically similar to the Campbell River watershed. This included assembling precipitation annual maxima series data for the 72-hour duration from all stations on Vancouver Island and stations between latitude 47°00′N and 52°00′N from the Pacific Coast eastward to the crest of the Coastal Mountains (BC) and Cascade Mountains (US) (Figure 5). Specifically, annual maxima series datasets were assembled for each station using a calendar year basis that included 72-hour precipitation maxima at automated gages and 3-day precipitation at non-recording gages and the dates of occurrence. Data were obtained from electronic files of Environment Canada, the National Climatic Data Center in the United States and from BCHydro. This totaled 143 stations and 6,609 station-years of record for stations with 25-years or more of record.

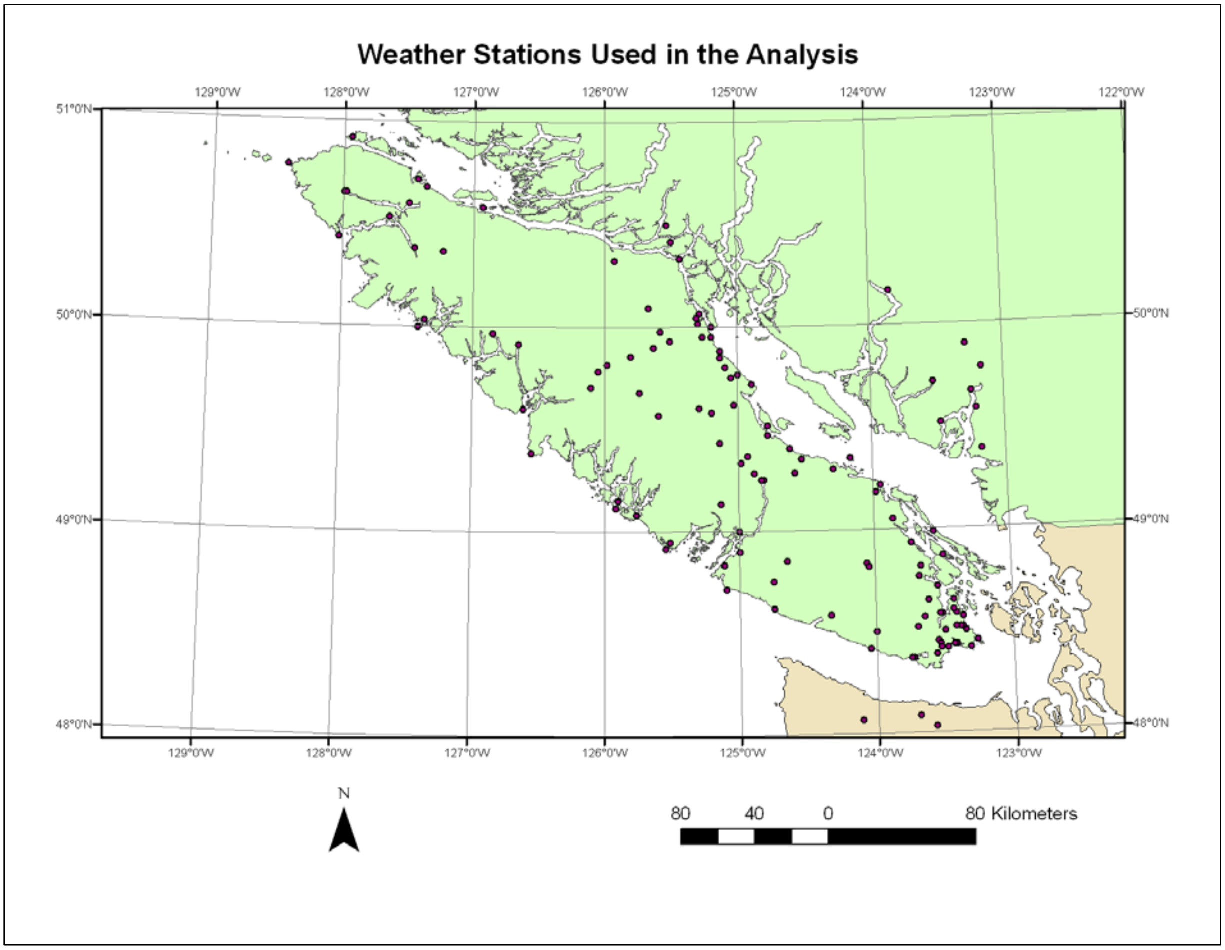

Figure 5. Precipitation Measurement Stations Used in Regional Precipitation-Frequency Analysis

Development of 72-Hour Basin-Average Precipitation-Frequency Relationship for Strathcona Basin

Storms for the Strathcona basin are scaled within SEFM by precipitation magnitudes obtained from the 72-hour basin-average precipitation-frequency relationship for the Strathcona basin (Figure 6). This relationship was developed through regional analyses of point precipitation and spatial analyses of historical storms to determine basin-average precipitation for the Strathcona basin. Regional L-moment ratios[3] and Kappa distribution parameters[3] for the Strathcona basin precipitation-frequency relationship are listed in Tables 4a,b. The basin-average mean value for the Kappa distribution was adjusted downward by 2% during model calibration to improve the match between simulated and observed streamflows (discussed in the section on *Watershed Model Calibration*). The final Kappa distribution parameters used in the SEFM-UBC model for the Strathcona basin are shown in Table 4c.

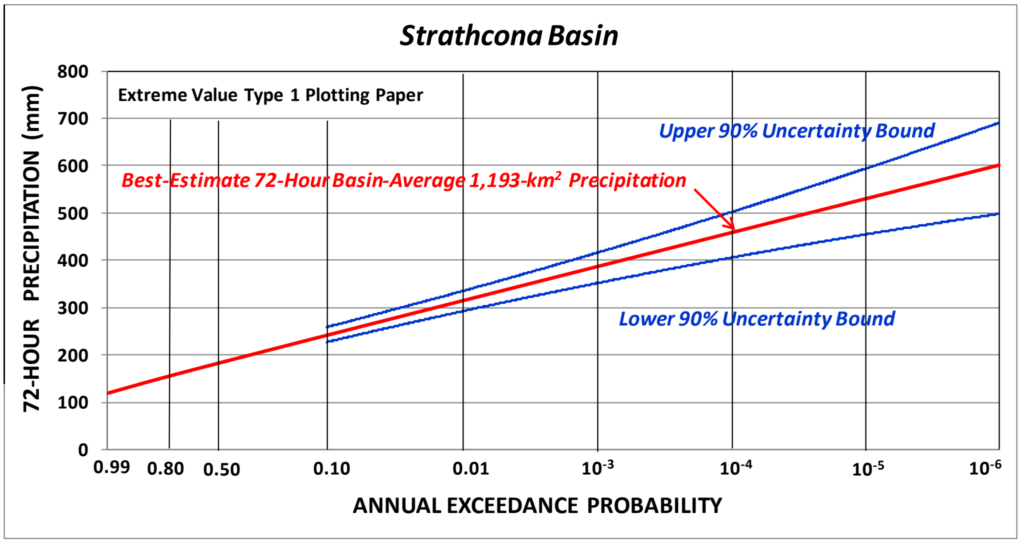

Figure 6. Best-Estimate 72-Hour Basin-Average Precipitation-Frequency Relationship for Strathcona Basin

Table 4a. Estimates of Population L-Moments for Basin-Average 72-Hour 1,193-km^2 Precipitation for the Strathcona Basin

Regional L-Moments			
At-Site Mean	**L-Cv**	**L-Skewness**	**L-Kurtosis**
189.0-mm	0.117	0.158	0.151

Table 4b. Four-Parameter Kappa Distribution Parameters for Basin-Average 72-Hour 1,193-km2 Precipitation for Strathcona Basin

Xi (ξ)	Alpha (α)	Kappa (κ)	h
172.000	31.200	0.001	-0.06

Table 4c. Adopted Four-Parameter Kappa Distribution Parameters Following Hydrologic Model Calibration for Basin-Average 72-Hour 1,193-km^2 Precipitation for Strathcona Basin

Xi (ξ)	Alpha (α)	Kappa (κ)	h
168.560	30.576	0.001	-0.06

Temporal and Spatial Distribution of Storms

Scalable spatial and temporal storm templates are needed for stochastic generation of storms. A spatial storm template contains the spatial distribution of precipitation over the basin and is comprised of the 72-hour precipitation amount for each elevation zone which aggregates to the 72-hour basin-average precipitation for the basin. The temporal storm template consists of a collection of dimensionless precipitation mass curves, one mass curve for each elevation zone in the basin. Nine dimensionless precipitation mass curves are needed for the Strathcona basin and five mass curves are needed for the Ladore basin corresponding to the number of elevation zones in each basin for each storm. Construction of the storm templates in this manner allows for generation of storms to any desired precipitation magnitude and the storm template for a given historical storm is given the name *prototype storm*.

Stochastic storm generation is accomplished by linear scaling of the spatial and temporal storm patterns for a selected prototype storm. Specifically, the spatial and temporal storm templates are scaled by the proportion of the desired 72-hour basin-average precipitation relative to the 72-hour basin-average precipitation observed in a selected prototype storm.

A brief summary of the process for development of temporal and spatial storm templates can be described as follows.

- The historical storm record for the Campbell River watershed for the period from 1980 through 2009 was reviewed and 15 storms were identified for use in stochastic modeling of floods. (BCHydro began comprehensive measurement of hourly precipitation for the Campbell River watershed in the early1980s.)
- The 10-day period encompassing each storm of interest was examined and the starting and ending times for the 72-hour basin-average precipitation maxima was identified.
- The spatial storm template for a given storm was developed using isopercental analyses to compute basin-average 72-hour precipitation for the Strathcona and Ladore basins and to compute areally averaged 72-hour precipitation for each elevation zone.
- The 10-day period of precipitation encompassing the 72-hour precipitation maxima was examined using daily synoptic weather maps, radiosonde data and air temperature temporal patterns. The time span was identified during which there was a continuous influx of atmospheric moisture from the same air mass where precipitation was produced under similar synoptic conditions. This assessment identified the starting and ending times for the precipitation segment that is independent of surrounding precipitation and scalable for stochastic storm generation. Figure 7 depicts the observed 10-day period of basin-average precipitation for the storm of October 14-23, 2003 for the Strathcona basin where the blue-colored portion of the hyetograph was identified as the independent scalable segment of the storm and therefore adopted for use as a prototype storm for stochastic storm generation.

- The temporal storm pattern was developed for each elevation zone in the Strathcona and Ladore basins as a weighted-average of hourly precipitation time-series from precipitation stations operating during a given storm. These were stored as dimensionless precipitation mass-curves where the indexing value was the 72-hour precipitation maxima for each elevation zone obtained from the spatial storm templates. The collection of dimensionless precipitation mass-curves for the various elevation zones is termed the temporal storm template.

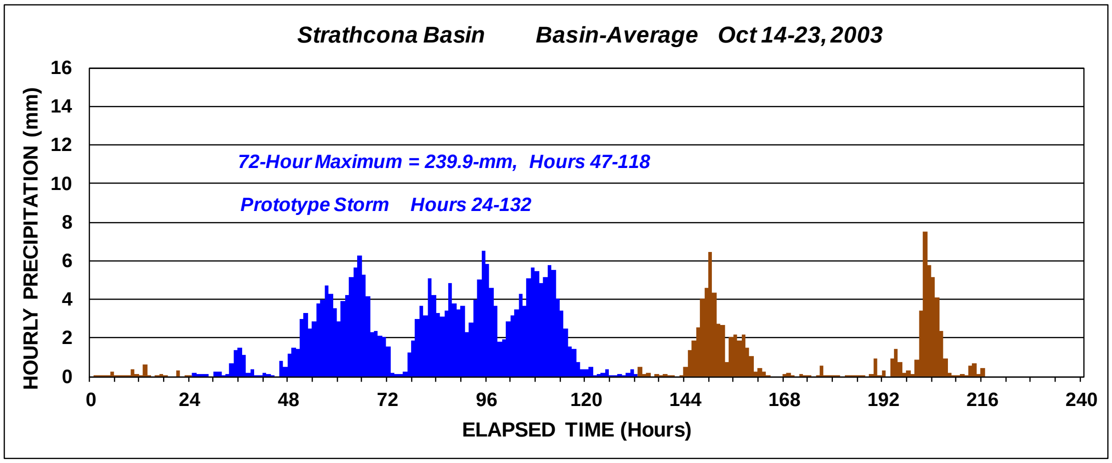

Figure 7. Basin-Average Temporal Pattern for Storm of October 14-23, 2003
Blue-Colored Storm Segment Identified for Use as Prototype Storm for Stochastic Storm Generation

The basin-average temporal pattern for the prototype storm of Oct 2-12, 1984 is shown in Figure 8a. Results from the Isopercental analyses for this storm is shown in Figure 8b and spatial distributions of 72-hour precipitation maxima is shown in Figure 8c. General characteristics of the 15 prototype storms are listed in Tables 5a and 5b for the Strathcona and Ladore basins, respectively.

Table 5a. Values of Computed 24-Hour, 72-Hour and 96-Hour Basin-Average Precipitation for Storms Used to Develop Strathcona Basin Prototype Storms

Computed Basin-Average Precipitation in Historical Storms						
Prototype Number	Storm Date	24-Hour (mm)	72-Hour (mm)	96-Hour (mm)	Ratio 24-Hr/72-Hr	Ratio 96-Hr/72-Hr
1	Mar 5-14, 1983	104.8	130.9	142.6	0.801	1.089
2	Oct 2-12, 1984	117.8	247.5	275.5	0.476	1.113
3	Mar 1-7, 1987	115.2	210.9	215.2	0.546	1.020
4	Nov 5-17, 1990	137.7	247.5	287.3	0.556	1.161
5	Nov 18-27, 1990	182.3	213.1	213.1	0.855	1.000
6	Jan 25-31, 1992	112.8	186.3	210.3	0.605	1.129
7	Nov 25 - Dec 5, 1993	106.9	141.3	149.4	0.757	1.057
8	Nov 2 - 12, 1995	139.1	165.9	176.0	0.838	1.061
9	Nov 11-21, 1995	121.1	191.3	195.6	0.633	1.022
10	Oct 14-23, 2003	101.0	239.9	243.9	0.421	1.017
11	Jan 13-23, 2005	84.5	171.6	187.6	0.492	1.093
12	Dec 30, Jan 10, 2007	109.8	166.3	171.7	0.660	1.032
13	Nov 1-7, 2006	85.0	136.4	160.5	0.623	1.177
14	Nov 12-23, 2006	150.5	197.7	203.7	0.757	1.030
15	Nov 10-20, 2009	130.2	188.6	200.0	0.690	1.060

Table 5b. Values of Computed 24-Hour, 72-Hour and 96-Hour Basin-Average Precipitation for Storms Used to Develop Ladore Basin Prototype Storms

Recorded Basin-Average Precipitation in Historical Storms						
Prototype Storm Number	Storm Date	24-Hour (mm)	72-Hour (mm)	96-Hour (mm)	Ratio 24-Hr/72-Hr	Ratio 96-Hr/72-Hr
1	Mar 5-14, 1983	54.9	66.7	71.0	0.823	1.064
2	Oct 2-12, 1984	55.5	126.9	138.0	0.437	1.087
3	Mar 1-7, 1987	52.3	95.5	99.9	0.548	1.046
4	Nov 5-17, 1990	56.2	110.7	136.0	0.508	1.229
5	Nov 18-27, 1990	110.9	132.7	136.3	0.836	1.027
6	Jan 25-31, 1992	66.5	126.3	136.3	0.527	1.079
7	Nov 25 – Dec 5, 1993	64.1	94.4	106.5	0.679	1.128
8	Nov 2 - 12, 1995	91.3	116.4	118.8	0.784	1.021
9	Nov 11-21, 1995	71.2	114.7	117.5	0.621	1.024
10	Oct 14-23, 2003	51.9	115.8	121.0	0.448	1.045
11	Jan 13-23, 2005	37.5	86.4	97.4	0.434	1.127
12	Dec 30 - Jan 10, 2007	59.1	91.2	92.2	0.648	1.011
13	Nov 1-7, 2006	47.2	68.2	74.0	0.692	1.085
14	Nov 12-23, 2006	83.4	97.7	98.0	0.854	1.003
15	Nov 10-20, 2009	88.1	130.6	134.2	0.675	1.028

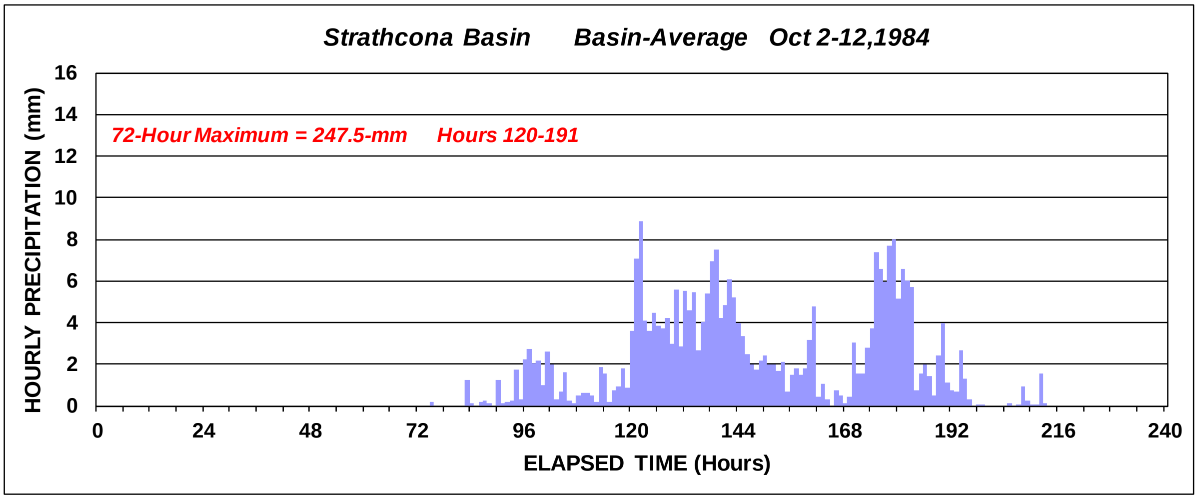

Figure 8a. Basin-Average Temporal Pattern for Storm of October 2-12, 1984

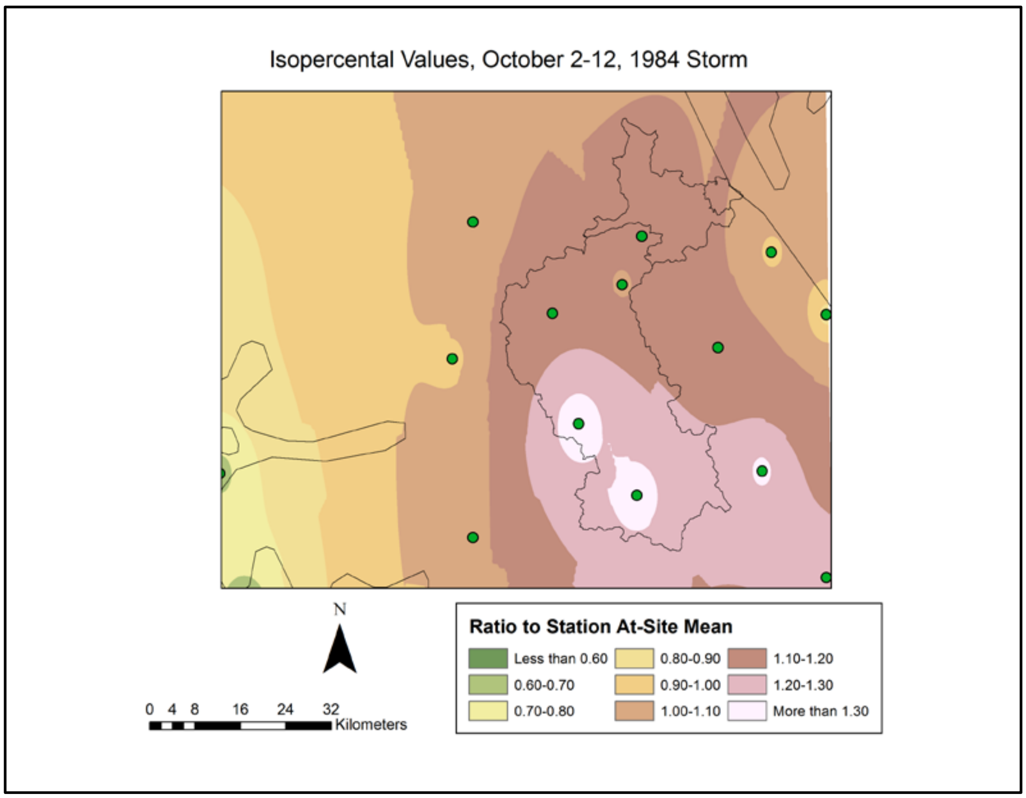

Figure 8b. Results from Isopercental Analyses for Storm of October 2-12, 1984

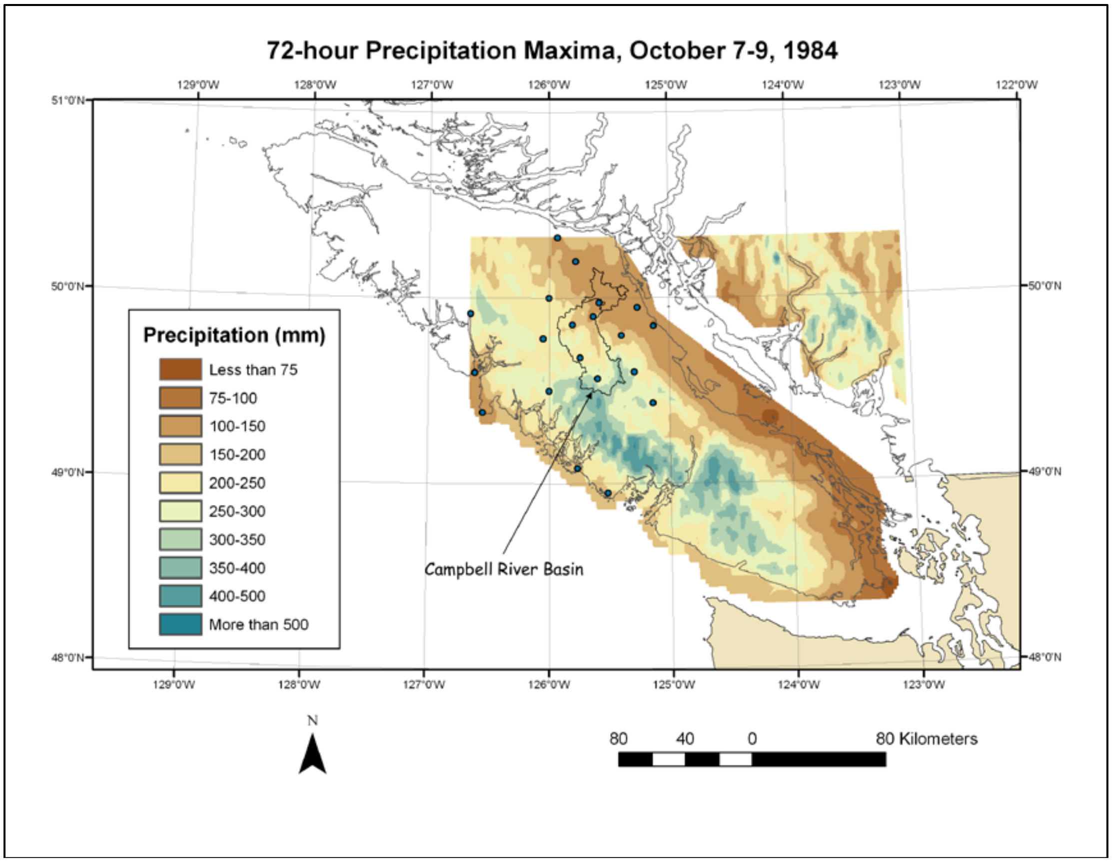

Figure 8c. Spatial Pattern of 72-Hour Precipitation Maximum for Storm of October 2-12, 1984

Temperature Temporal Patterns

Temperature temporal patterns are used in computing snowmelt runoff. Scalable temperature temporal patterns were created by first computing hourly time-series for the 1,000-mb temperature and freezing level. This was accomplished using land-based hourly air temperature data from the Campbell River Airport, BCHydro stations located within and near the Campbell River watershed, and twice-daily radiosonde temperature measurements from Quillayute Washington. An example of 1,000-mb temperature and freezing level hourly time-series are shown in Figure 9a for the storm of Oct 14-23, 2003. Resultant air temperature time-series for selected elevations are shown in Figure 9b along with the basin-average precipitation temporal pattern (Figure 9c) to allow comparison of precipitation and temperature time-series.

The temperature temporal pattern for 1,000-mb air temperature was created by rescaling the hourly ordinates of the observed 1,000-mb temperature time-series by subtracting the 1000-mb index value. The 1,000-mb index value is the highest 6-hour average 1,000-mb temperature observed during the day of maximum 24-hour precipitation, which for the storm of Oct 14-23, 2003 storm was 12.9ºC for the 6-hour period from hours 106-111 (Figure 9a). In a similar manner, the temporal temperature pattern for freezing level was created by rescaling the freezing level hourly time-series by subtracting the index freezing level, which was 3,100-m for the Oct 14-23, 2003 storm. The index freezing level is the average freezing level for the same 6-hour period used to compute the temperature index. The indexed 1000-mb temperature and freezing level temporal templates are shown in Figure 9d.

During operation of SEFM, 1,000-mb temperature and freezing level time-series are created by reversing the process used to create the temperature temporal templates. Stochastic simulations are used to generate a 1,000-mb temperature index value and a freezing level index value for a selected prototype storm. These values are then used to rescale the indexed 1,000-mb temperature and freezing level temporal patterns (Figure 9d) by adding the simulated index values. This yields simulated 1,000-mb temperature and freezing level hourly time-series similar to those shown in Figure 9a. Hourly interpolation between the 1,000-mb temperature time-series and freezing level time-series allows air temperature time-series to be computed for each elevation zone similar to that shown in Figure 9b.

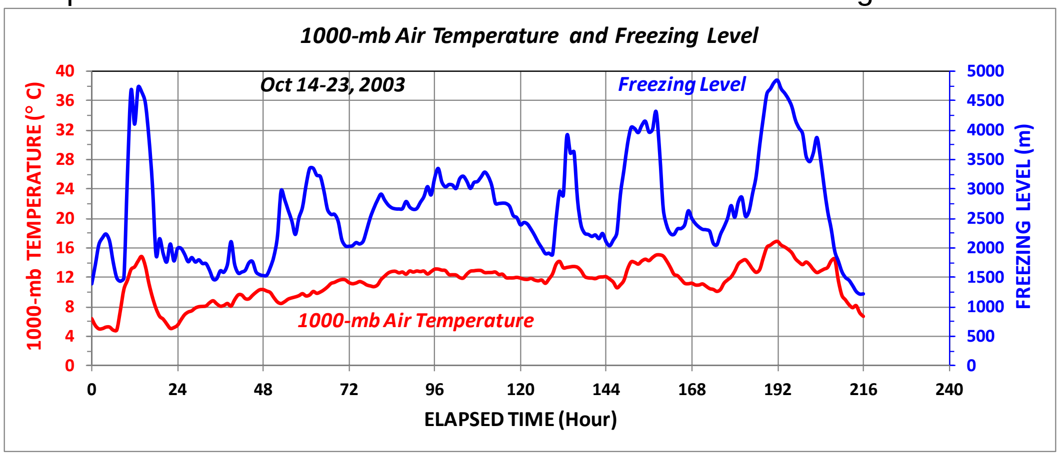

Figure 9a. 1000-mb Temperature and Freezing Level Hourly Time-Series for Storm of Oct 14-23, 2003

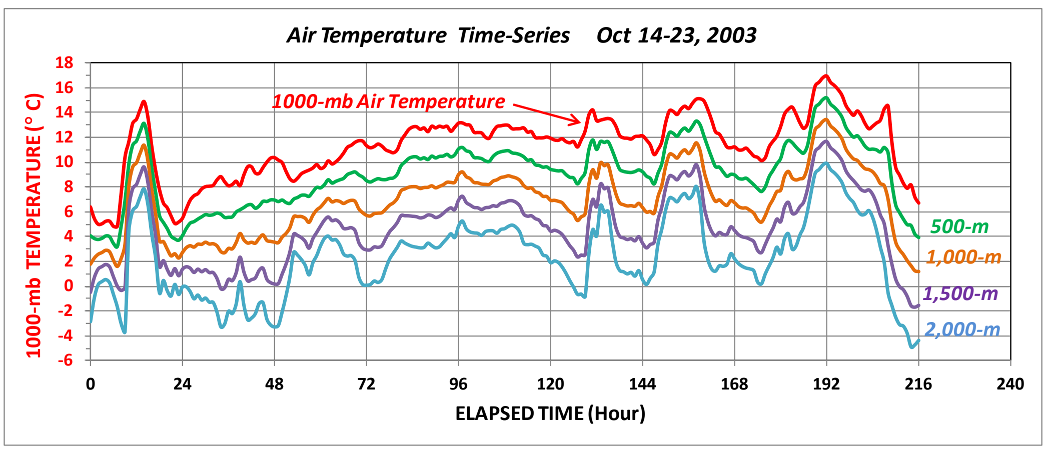

Figure 9b. Computed Temperature Time-Series for Selected Elevations During Oct 14-23, 2003 Storm

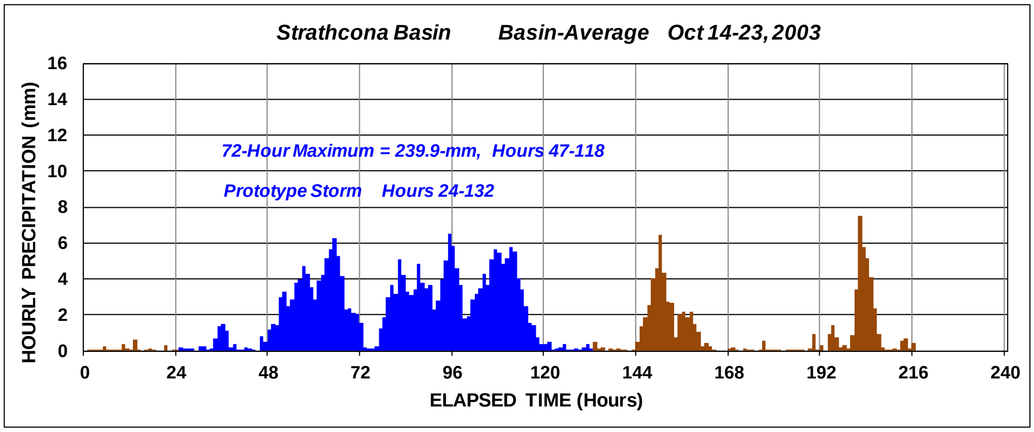

Figure 9c. Precipitation Temporal Pattern for Storm of October 14-23, 2003 (same as Figure 7)

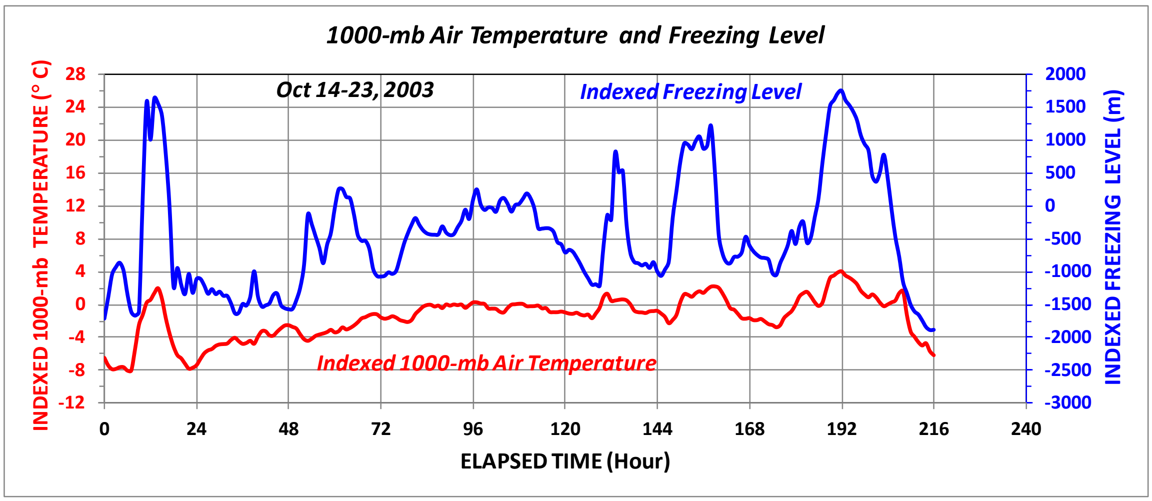

Figure 9d. Indexed 1000-mb Temperature and Freezing Level Temporal Patterns for Storm of Oct 14-23, 2003

1000-mb Temperature Simulation

Temperatures at the 1,000-mb level (near sea-level) during extreme storms were simulated using a physically-based probability model for 1,000-mb dewpoint temperatures derived from monthly maximum dewpoint data[4]. This probability model utilizes end-of-month upper limit dewpoint data obtained from the February 2003 Water Management Consultant's Report of Probable Maximum Precipitation (PMP)[5] and the magnitude of the maximum 24-hour precipitation within the storm relative to 24-hour PMP. The 1,000-mb dewpoint temperatures are drawn from a symmetrical Beta Distribution bounded by lower and upper bounds as depicted in Figure 10. Details on the operation of this stochastic sampling approach are described in the SEFM Users Manual[6].

Simulated 1,000-mb air temperatures on the day of maximum 24-hour precipitation are obtained by adjusting the simulated 1,000-mb dewpoint temperature upward by 2ºC. This accounts for relative humidity being near but somewhat less than 100% as observed in the historical data. The resultant 1,000-mb air temperature is then used for scaling of the 1000-mb temperature temporal pattern (for example, Figure 9d).

The range of possible 1,000-mb dewpoint temperatures for a given maximum 24-hour basin-average precipitation amount within a storm is shown in Figure 10. It is seen in Figure 10 that larger storm amounts are generally associated with higher 1000-mb dewpoints. This occurs because high levels of atmospheric moisture are needed to support large precipitation amounts and high levels of atmospheric moisture require higher air temperatures to sustain those moisture levels. A separate relationship, similar to Figure 10, is used for each end-of-month because 1,000-mb dewpoint climatology changes with season. Higher maximum 1,000-mb dewpoints are possible in the fall months of October and November than in the colder winter months of January and February. Thus, freezing levels tend to be somewhat lower for storms in the colder winter months.

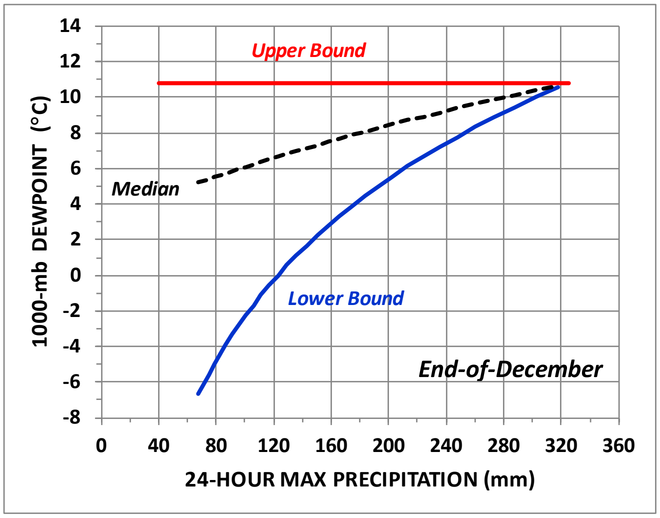

Figure 10. Example Range of 12-Hour Persisting 1,000-mb Dewpoint Temperatures Utilized by Dewpoint Temperature Probability Model, Example for End-of-December

Air Temperature Lapse-Rates

Radiosonde data for Oakland CA and Quillayute WA were analyzed to determine temperature lapse-rates for modeling of freezing levels. Since the rate of change of temperature with elevation was being evaluated, data from the two stations could be combined. Results of the analysis showed that air temperature lapse-rates on the day of maximum 24-hour precipitation for noteworthy storms were well described by the Normal Distribution (Figure 11). The mean value was found to be 5.1ºC/1,000-m which is near the saturated pseudo-adiabatic lapse-rate. Similar results were found if examining the data from Quillayute WA or Oakland CA separately and the data from the two stations were combined to provide a larger sample for computing the distribution parameters.

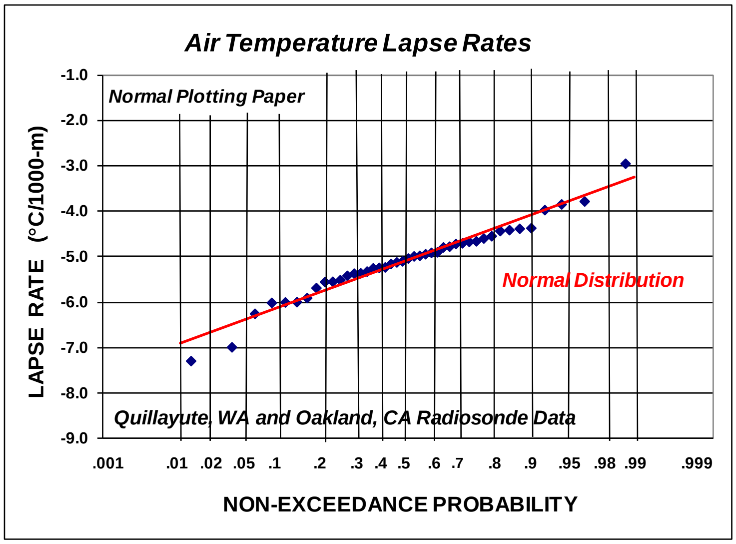

Figure 11. Air Temperature Lapse-Rates for Day of Maximum 24-Hour Precipitation for Storms at Campbell River BC and American River CA

Freezing Level

Freezing level on the day of maximum 24-hour precipitation is used for scaling the freezing level temporal pattern (for example, Figure 9d). Simulations are conducted by stochastically generating a 1,000-mb air temperature as described above, selecting an air-temperature lapse-rate from the Normal Distribution depicted in Figure 11 and computing the resulting freezing level. The computed freezing level is then used to scale the freezing level temporal pattern by adding the value of the computed freezing level to the indexed temporal pattern.

Figure 12 depicts an example of 600 computer simulations of freezing level which shows moderate variability in freezing level with storm magnitude. The behavior of freezing level for extreme storms adds some non-linearity to the flood response in that higher temperatures and larger snowmelt contributions are associated with larger precipitation amounts.

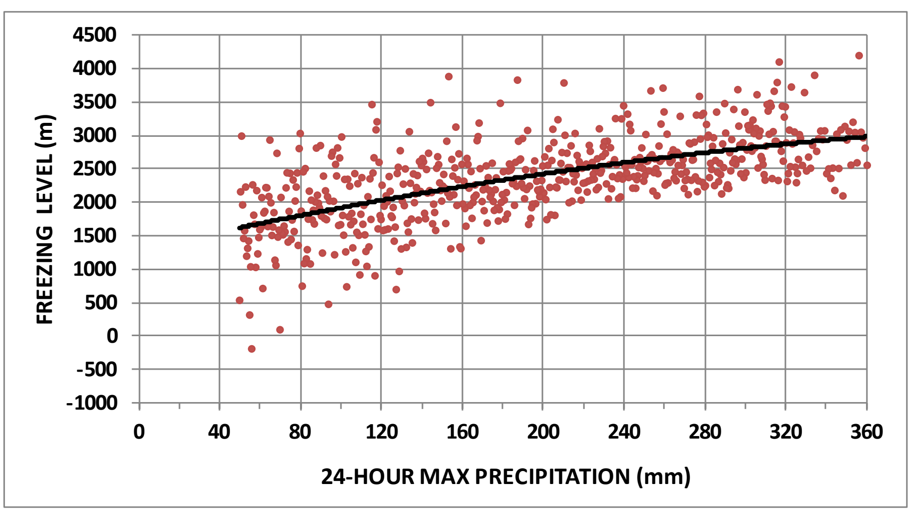

Figure 12. Example of Variability in Simulation of Freezing Level Including Variability Due to 1,000-mb Air Temperature and Air Temperature Lapse-Rate

End-of-Month Flood Simulations

During the early development of SEFM it was recognized that data limitations for many watersheds would limit the ability to simulate floods continuously throughout the storm season. Specifically, data are needed for antecedent precipitation, evapo-transpiration, and snowpack water equivalent to conduct soil moisture accounting for the full range of climatic conditions and elevations in a mountainous watershed over the entire storm season. In addition, seasonal reservoir level data are also needed for routing of reservoir inflows. Given these common constraints, SEFM was set up to conduct flood simulations for end-of-month conditions. Thus, a storm/flood occurring at the end-of-November is considered representative of watershed conditions from mid-November through mid-December.

For the case of the Campbell River watershed and use of the UBC Watershed Model, some antecedent conditions such as initial reservoir level were resampled over the full time period from preceding mid-month to the following mid-month for a selected end-of-month. Antecedent soil moisture and snowpack conditions for end-of-month conditions in the various elevation bands were set through resampling as described in the following section on *UBC Watershed Model Antecedent Condition Sampling*.

UBC Watershed Model Antecedent Condition Sampling

A resampling approach was used to determine the model state variables (initial snowpack, soil moisture conditions, and initial streamflow) at the onset of a stochastically generated storm. The UBC Watershed Model (UBCWM) developed by BC Hydro to analyze the Campbell River System Probable Maximum Flood (PMF)[1] was adapted for use with the stochastic model. Model input for the calibration period (October 1983 through September 2003) was used to simulate daily streamflow. Model state variables were saved at the end of each month during the simulation using a feature in the UBCWM that saves all relevant model variables and antecedent conditions allowing for the model to restart at that time without rerunning the previous period. This provided a total of 21-years of antecedent conditions on a monthly basis for resampling.

UBCWM state variables were randomly selected from one of the 21-years for the month of storm occurrence. Each year was equally-likely to be chosen using the resampling approach. Antecedent precipitation for the year selected, defined as the cumulative precipitation from October 1 until the onset of the storm, was also computed. The antecedent precipitation was used to select initial reservoir levels from a year with similar seasonal moisture conditions (described in the next section).

Reservoir Level at Beginning of Simulation

A resampling approach was used to determine the reservoir elevation at the beginning of the simulation for Strathcona and Ladore Dams. The reservoir level for John Hart Dam varied little throughout the year and was set to a constant value of 139.28 m at the beginning of each simulation, which represents the mean elevation for the period of record. Resampling from the historic record that reflects current seasonal operation rules were used and included data from January 1998 through September 2010.

Because the reservoir resampling period was different from the UBC Watershed Model antecedent condition sampling period (October 1983 through September 2003 for the UBC Watershed Model), it was necessary to ensure that the year selected for reservoir level resampling had similar seasonal moisture and runoff characteristics as the year selected for the UBC Watershed Model antecedent conditions. This was accomplished by selecting the reservoir levels from years with similar antecedent precipitation as the year selected for the UBC model antecedent conditions. Antecedent precipitation was defined as the cumulative precipitation from October 1 until the onset of the stochastically generated storm and was computed using precipitation data from the Wolf River DCP gage. The procedure for sampling the UBC Watershed Model antecedent conditions and initial reservoir level is summarized in the example below.

- The storm date is first selected using the Normal Distribution for storm seasonality (Figure 4). For example, if January 13th is selected, this corresponds to simulation for the end-of-December (encompassing December 16 to January 15).
- The state variables for the UBC Watershed Model were then selected for the end of month prior to the storm date for a year randomly selected from the October 1983 through September 2003 period. In this example, December 31, 1993.
- The antecedent precipitation from October 1, 1993 through December 31, 1993 for the Wolf Creek DCP gage was then computed as 973 mm.
- The initial reservoir level would be selected for January 13th from one of three years with antecedent precipitation closest to the 973 mm value. For this example, the final date would be selected from three years selected at random (equally-likely) as shown in Table 6. For this example, candidate date 1 was selected (January 13, 2004) and the initial reservoir elevation at the start of routing computations was set to 216.69m.

Table 6. Candidate Dates for Selection of Initial Reservoir Elevation

Antecedent Precipitation (mm)	Antecedent Precipitation Date	Final Candidate Dates for Initial Reservoir Level	Initial Reservoir Level for Candidate Date (Strathcona Dam)
967.0	12/31/2004	January 13, 2004	216.69 m
974.3	12/31/2002	January 13, 2002	220.17 m
1050.7	12/31/1999	January 13, 1999	219.26 m

To ensure that the sampled initial reservoir level was not elevated due to an ongoing flood in the historic record, an upper limit was established for both the Strathcona and Ladore reservoirs. The upper limit corresponds to the elevation where the spillway gates are opened during a flood (220.0 m for Strathcona and 177.7 for Ladore). If the sampled reservoir elevation exceeded this value, then the initial reservoir elevation was set to the limit value. A minimum limit was also set for Ladore reservoir, which had several unrepresentative periods in the historic record where the reservoir was drawn down for maintenance or other operational reasons. Graphs summarizing the reservoir level data for the resampling period are shown in Figures 13a, 13b and 13c.

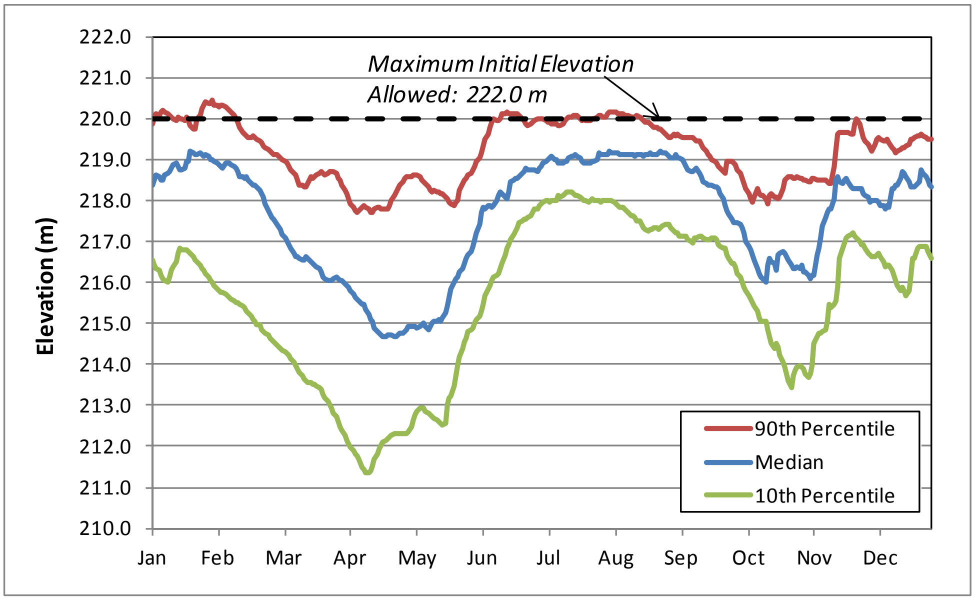

Figure 13a. Strathcona Dam Initial Reservoir Elevation Data Summary January 1998 through September 2010, Used for Selecting Initial Reservoir Elevation

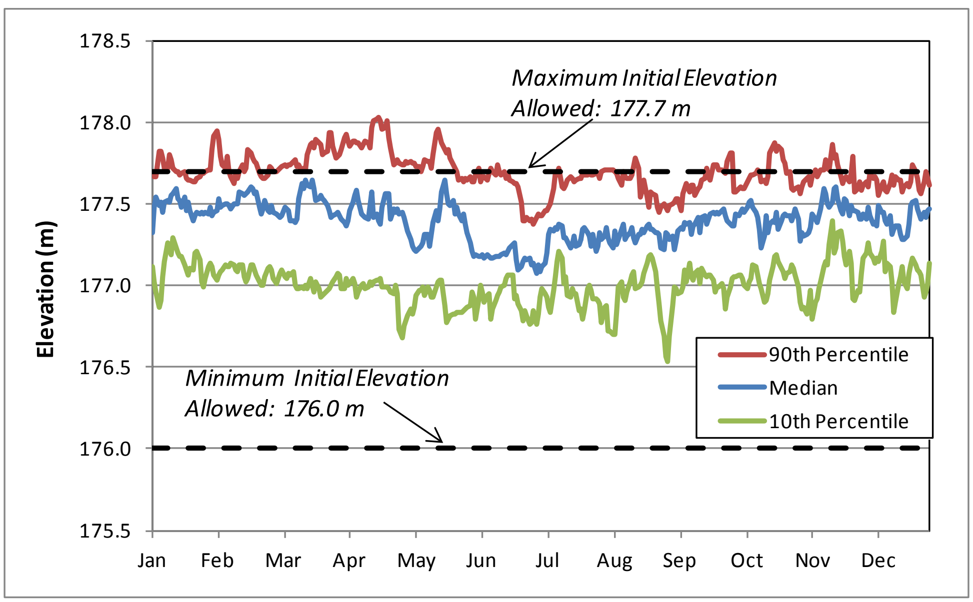

Figure 13b. Ladore Dam Initial Reservoir Elevation Data Summary January 1998 through September 2010, Used for Selecting Initial Reservoir Elevation

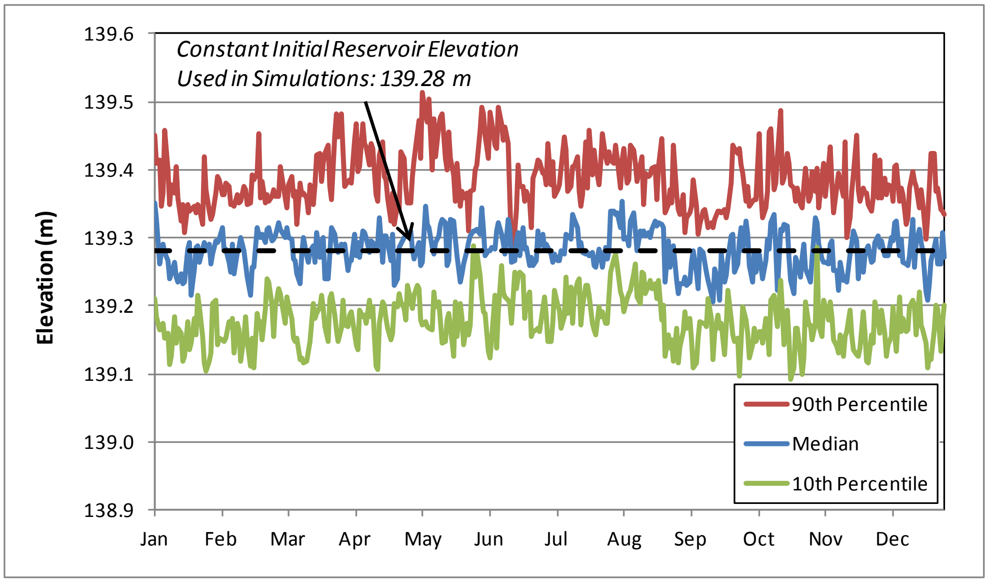

Figure 13c. John Hart Dam Initial Reservoir Elevation Data Summary
January 1998 through September 2010
(Constant Initial Reservoir Elevation of 139.28m used in all Simulations)

Simulation of Reservoir Operations During Floods

Flood routing simulations were performed in accordance with the current operational requirements. Reservoir releases at the Campbell River project depend on maintaining a flow rate of 453-cms at the town of Campbell River, when the Strathcona Reservoir is between 220-m and 222-m elevation. When the reservoir is above 222-m, then the discharge is set equal to the lower of the inflow or the maximum discharge capacity.

To determine the allowable release from the Campbell River project and maintain the required 453-cms downstream flow limit required an estimate of the local inflows between the Campbell River project and the town of Campbell River. Flow from the 278 km^2 Quinsam River basin is the dominant contributor of inflow to Campbell River between John Hart Dam and the town of Campbell River (Figure 14).

The Ladore basin has a similar size although higher mean elevation as the Quinsam basin. Flood peak discharge from Quinsam River is about 80% of local inflow to the Ladore reservoir (Hatch[7]). This value was determined by comparing the peak discharge magnitude-frequency estimates for the Ladore inflow with gaged flows at Quinsam. For each stochastic model run, the Quinsam flow was estimated by scaling the Ladore inflow hydrographs by 80%. When the Strathcona reservoir was between 220-m and 222-m, the discharge from Strathcona was set so that the sum of John Hart discharge plus Quinsam estimated discharge was at or below the 453-cms limit.

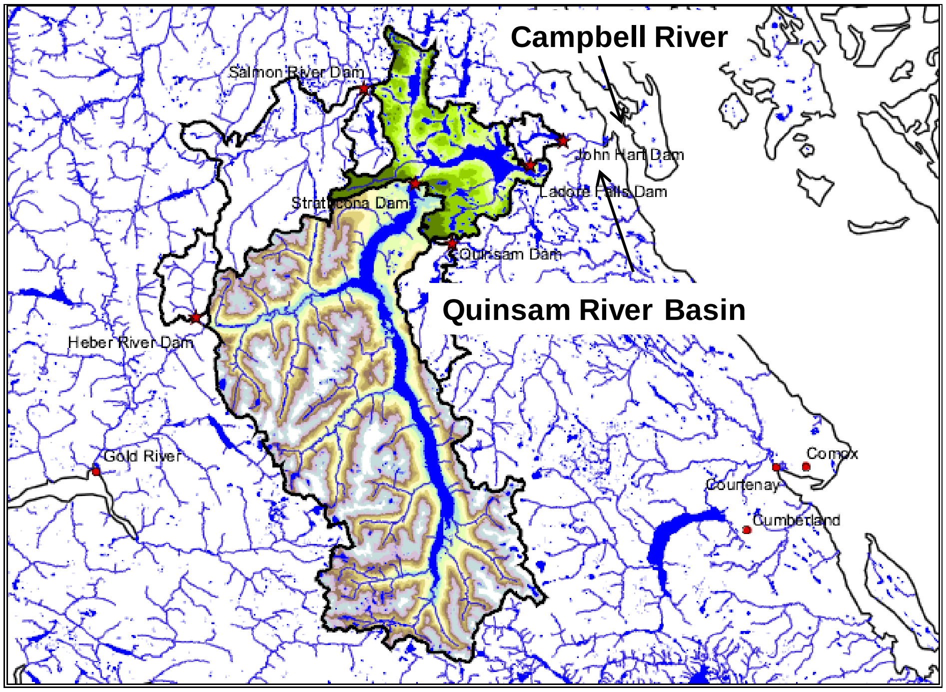

Figure 14. Vicinity Map Showing Campbell River Watershed, and City of Campbell River Where Flows Must be Maintained below 453cms when Upper Campbell Lake is between 220.0 and 222.0 m

SEFM Simulation Procedure

All simulations were conducted for end-of-month watershed conditions. This approach was adopted to reduce the amount of data analyses required for the hydrometeorological parameters and to simplify the simulation procedures. A flowchart for the stochastic simulation procedure for the Campbell River System is shown in Figures 15a and 15b, and the basic concepts of the simulation procedure are described below.

The stochastic simulation procedure can be grouped into five steps.

Step 1: Select date of storm occurrence

- Select end-of-month for storm occurrence based on historical seasonality of storm occurrences (Figure 4)

Step 2: Select all parameters associated with the occurrence of the storm event

- Select the magnitude of the 72-hour precipitation for Strathcona basin based on 72-hour basin-average precipitation-frequency relationship for Strathcona basin (Figure 6)
- Determine the 72-hour basin-average precipitation for the Ladore basin based on the 72-hour precipitation selected for Strathcona and the stochastic relationship with the Ladore basin.
- Select one of fifteen prototype storms for describing the temporal and spatial distribution of the storm, and scale the prototype storm templates to have the selected 72-hour basin-average precipitation amount

- Select 1,000-mb air temperature from physically-based probability temperature model for day of maximum 24-hour precipitation in selected prototype storm (Figure 10)
- Select air-temperature lapse-rate (Figure 11) and compute reference freezing level for day of maximum 24-hour precipitation for selected prototype storm based on 1,000-mb air temperature and air temperature lapse-rate
- Compute temperature temporal patterns using scaled 1,000-mb air temperature and freezing level temporal patterns for selected prototype storm and compute hourly temperature time-series for all elevation zones

Step 3: Establish antecedent watershed and reservoir conditions at onset of extreme storm

- Select UBC Watershed Model antecedent condition file for end-of-month that was selected for occurrence of extreme storm. This is selected from end of month antecedent condition files for the period 10/1983-9/2003. This sets the antecedent snowpack, soil moisture, and other model state variables.
- Select initial reservoir level for Strathcona and Ladore reservoirs. This is sampled from recorded reservoir level data for the period 1/1/1998-9/30/2010. The sampled year has similar antecedent precipitation as the year sampled for the UBC Model antecedent conditions. The sampled month and day corresponds to a 30-day period surrounding the sampled end of month (15-days before and 15-days after end-of month). The initial level for John Hart Dam reservoir is constant for each simulation because the reservoir level varies little throughout the year and from year to year.

Step 4: Conduct Watershed Modeling for each Dam

- Conduct rainfall-runoff and snowmelt modeling using the UBC Watershed Model. Reservoir inflows are saved for each simulation.

Step 5: Conduct Reservoir Routing of Inflow Flood

- Execute reservoir routing that implements current reservoir operational procedures. Routing is performed separately for each dam with all inflows routed in batch for each dam. Routing starts with the upstream-most dam (Strathcona) and proceeds with each subsequent dam downstream.

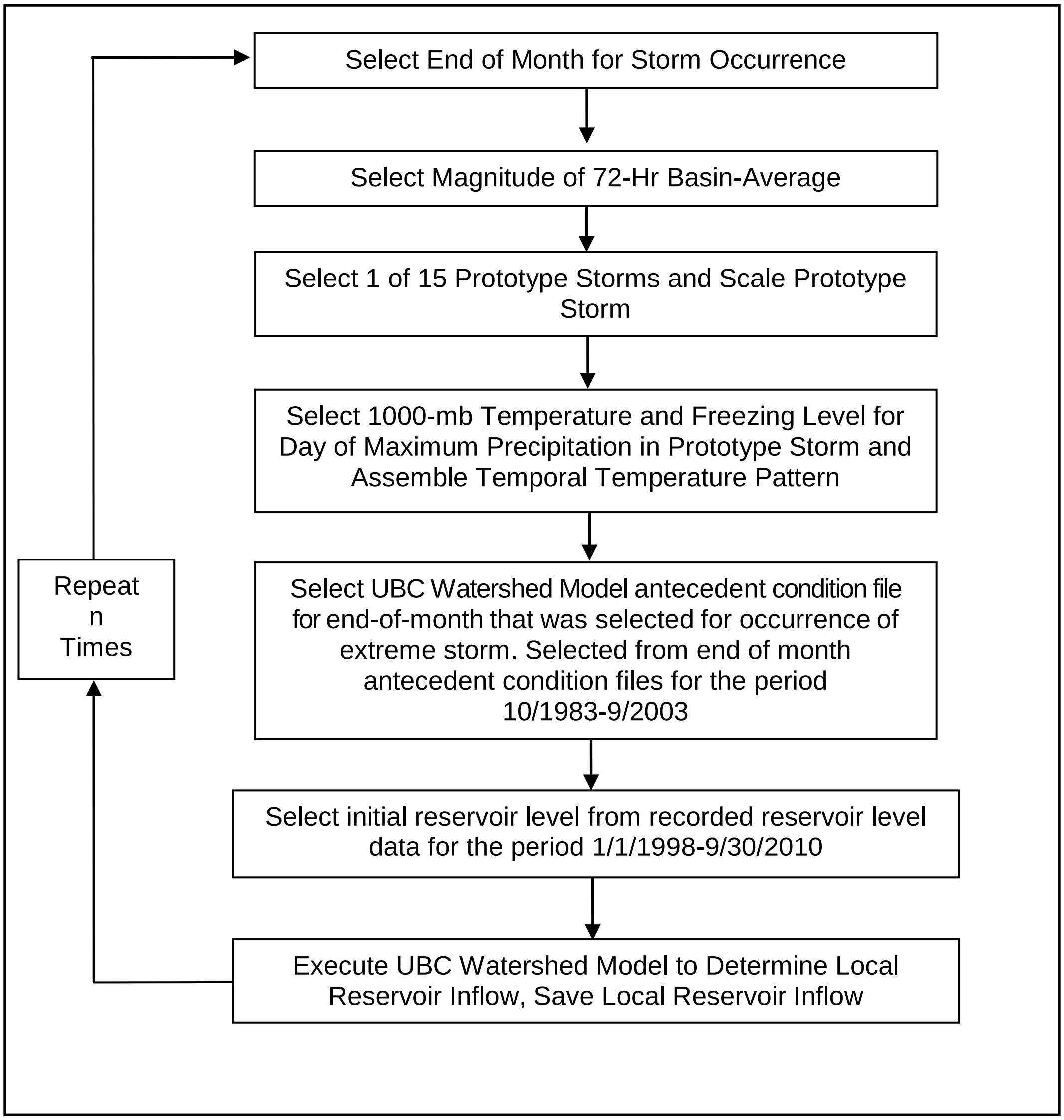

Figure 15a. Flow Chart for Stochastic Simulation Procedure Using the UBC Watershed Model for Strathcona and Ladore Dams (Steps 1-4)

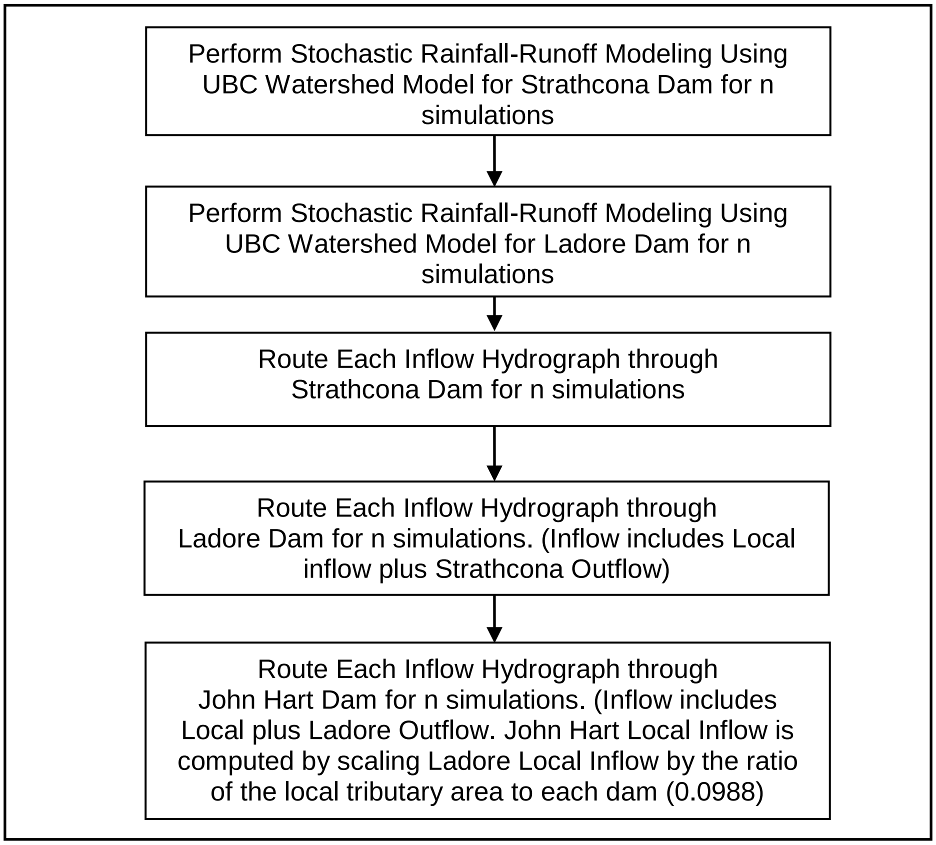

Figure 15b. Flow Chart for Hydrologic and Routing Simulation Procedure for Campbell River Watershed System (Steps 1-5)

Calibration of the UBC Watershed Model

The UBC Watershed Model was calibrated to observed inflow to the Strathcona reservoir as part of the Campbell River System Probable Maximum Flood analysis performed by BC Hydro[1]. The calibration utilized daily data with comparison of simulated and recorded mean daily inflow to the Strathcona reservoir for a 5-year period (October 1991 through September 1996). An additional 7-year period (October 1983 through September 1991) was used to validate the calibration. Because large floods are of interest for analysis of spillway adequacy, the UBC Watershed Model was also used to simulate hourly runoff for the six largest floods between October 1983 and October 2003.

The general goal of the daily calibration was to provide reasonable overall match between observed and calculated inflow on a long-term basis. Some individual events will, inevitably, be under or over-estimated. For extreme flood simulation, the daily calibration was enhanced by running the model at an hourly time step and focusing on extreme events for which good-quality hourly input data are available.

Results of the daily calibration for the 1996 water year are shown in Figure 16. The simulated annual water budget was within 1-percent for the calibration period, and 2-percent for the verification period. Generally, there was a slight bias towards underestimating several of the highest historical peak flows. This bias was removed during hourly calibration to the largest floods in the record.

Comparison of simulated and recorded discharge for the two largest floods in the calibration period is shown in Figures 17a and 17b. Overall, the calibrated hourly model replicated the peak and volume of the highest flow events well.

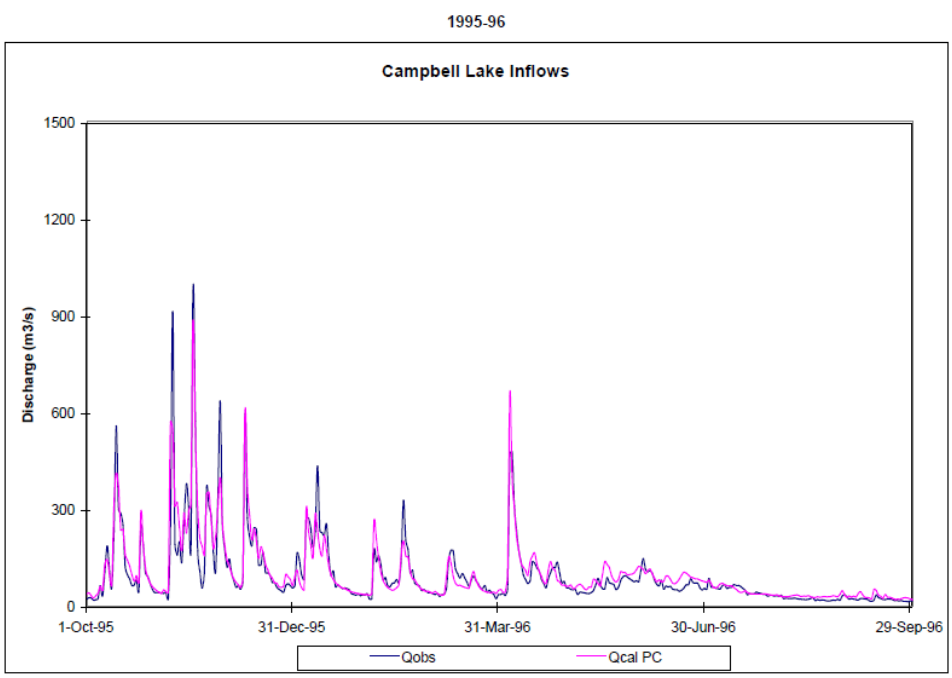

Figure 16. Comparison of Simulated and Recorded Inflow to Upper Campbell Lake (Strathcona Dam), Daily Calibration, Water Year 1996

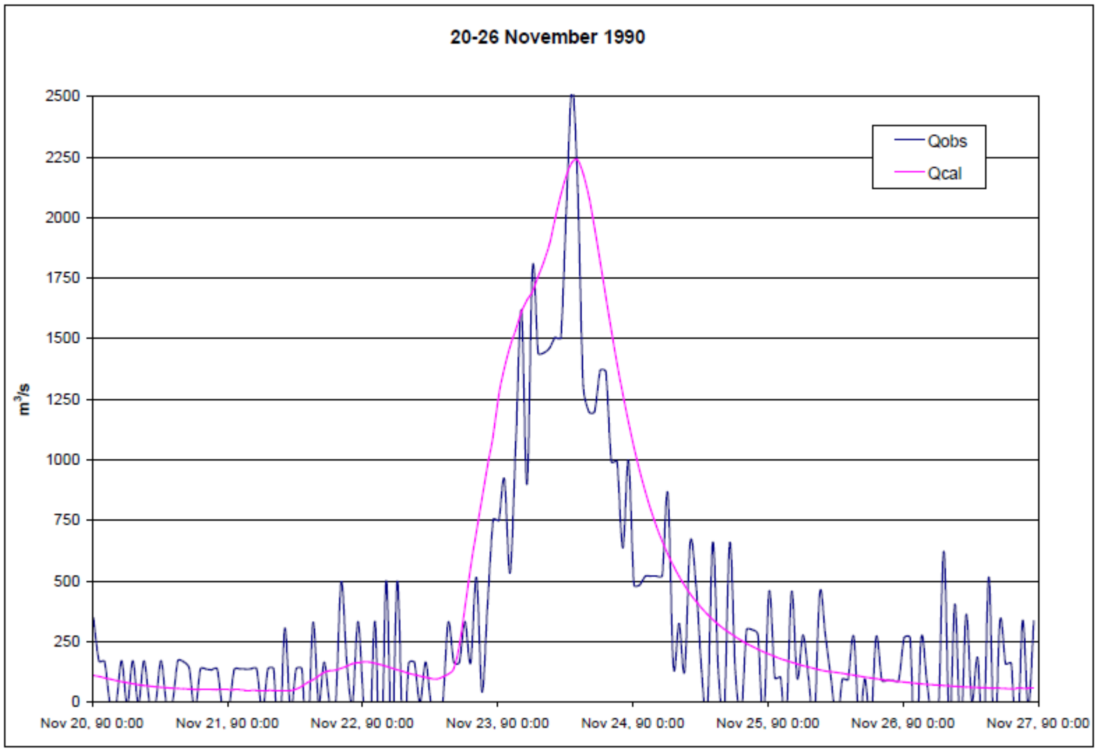

Figure 17a. Comparison of Simulated and Recorded Inflow to Upper Campbell Lake (Strathcona Dam), Hourly Calibration, November 20-26 1990

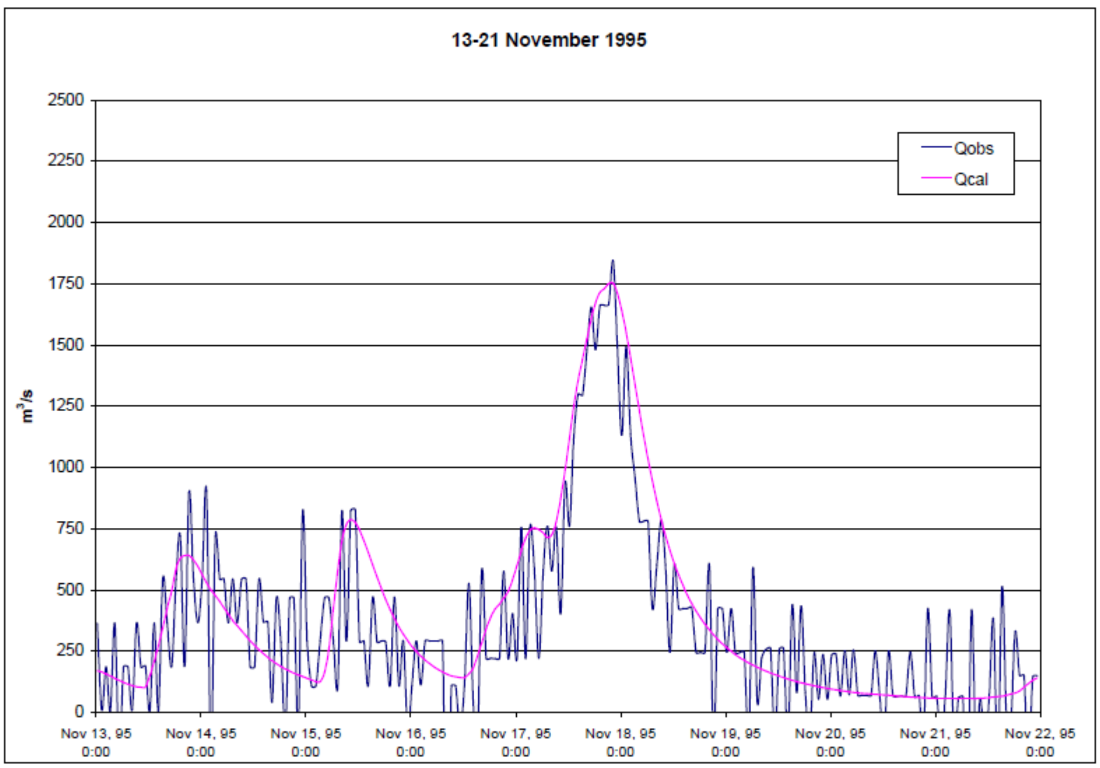

Figure 17b. Comparison of Simulated and Recorded Inflow to Upper Campbell Lake (Strathcona Dam), Hourly Calibration, November 13-21 1995

An additional calibration analysis was performed as part of this study to ensure that the flood-frequency characteristics predicted by SEFM were consistent with the behavior of observed flood volumes. Daily reservoir inflow data for Upper Campbell Lake were provided by BC-Hydro for the period 1963-2010. The inflows were computed by reverse reservoir routing given recorded reservoir discharge and water surface elevation. Annual maxima 3-day inflow volumes were computed for the period of record and exceedance probabilities determined using the Gringorten plotting position formula[8,9]. The 3-day annual maxima were scaled by 1.03 (standard adjustment for 3-day to 72-hour conversion) for comparison with the 72-hour runoff volumes produced by SEFM. A 72-hour duration was chosen because it is the critical duration for floods that influence reservoir level and 72-hour precipitation magnitude-frequency relationships were used as input to the stochastic model.

SEFM model parameters were adjusted to achieve calibration with the observed streamflows. Minor adjustments were made to parameters that are used to simulate storm temperatures along with a 2% downward adjustment of the basin-average mean value used to describe the 72-hour precipitation-frequency relationship. Overall, the adjustments made to the stochastic model parameters were minor and well within the uncertainty of parameter estimation. Final precipitation distribution parameters are shown in Table 4c.

After model calibration was completed, the 72-hour runoff volumes from the SEFM simulations closely matched the recorded frequency curve for common events in the range of 2-year to 5-year recurrence intervals (Figure 18). The slope of the SEFM frequency curve was slightly steeper than the observed 72-hour volumes, and the simulated and observed estimates diverge slightly at more rare recurrence intervals. This minor divergence can be attributed to natural sampling variability for the storms observed on the watershed in the historical record.

From the regional precipitation frequency analysis, it was found that the dataset of historical storms for the Strathcona basin was slightly under-representative when compared with the regional precipitation-frequency characteristics for locations on the leeward side of the Vancouver Island Mountains (Figure 19). Comparison of Figures 18 and 19 show similar behavior when comparing the 72-hour basin-average precipitation frequency relationship with the historical record for the Strathcona basin. The stochastic model draws samples from the precipitation-frequency relationship based on the regional characteristics from a very large sample set. This results in a slightly higher precipitation-frequency and resultant flood-frequency relationships relative to the observed values for the Strathcona basin.
The 72-hour PMP of 675-mm (Water Management Consultants[5]) for Strathcona Basin has an estimated annual exceedance probability of 10^{-7} based on the 72-hour basin-average precipitation-frequency relationship for the Strathcona Basin and is plotted on Figure 19 for comparison.

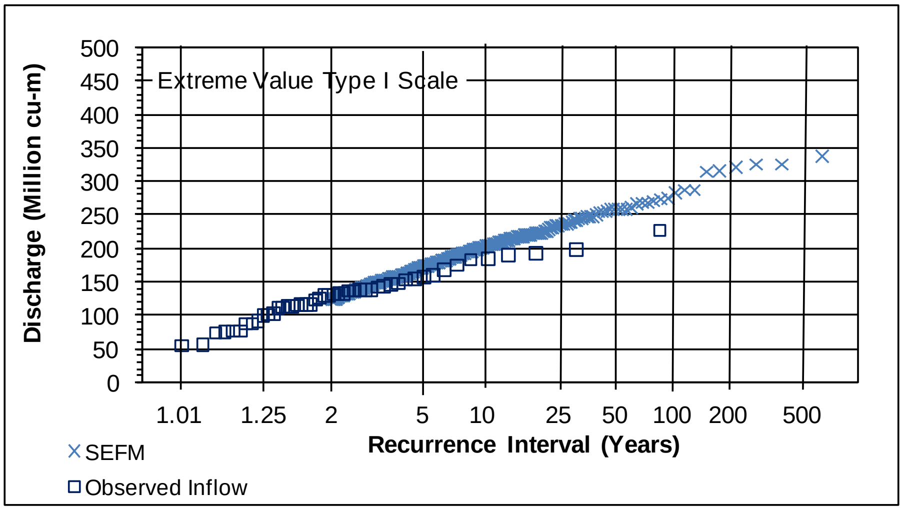

Figure 18. Upper Campbell Lake 72-Hour Inflow Magnitude-Frequency, SEFM and Observed Inflow

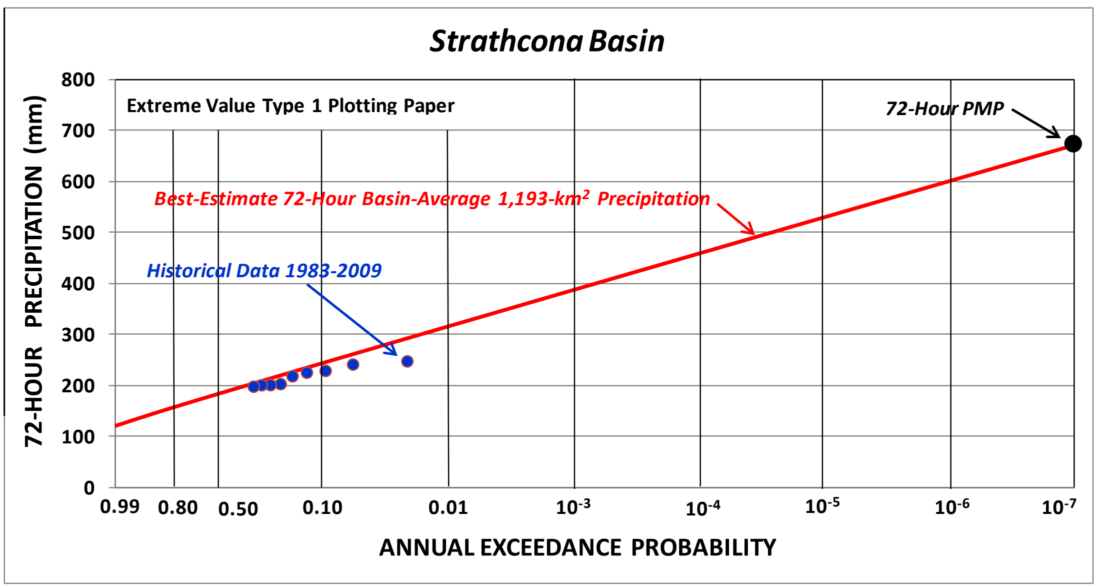

Figure 19. 72-Hour Basin-Average Precipitation-Frequency Relationship for Strathcona Basin and Comparison with Small Sample of Historical Storms for the Period from 1983-2009

Magnitude-Frequency Characteristics of Extreme Floods

SEFM Monte Carlo Simulation Approach

The results from the Monte Carlo computer simulations were used to develop magnitude- frequency relationships for reservoir elevation, peak inflow, peak outflow, and 72-hour reservoir inflow volume for each dam in the Campbell River system. These relationships were based on 60,000 computer simulations using a variation of latin-hypercube[10,11] censored sampling for the precipitation input that allowed the flood-frequency curves to be developed in a piecewise manner[12]. This greatly reduced the number of simulations that would otherwise have been required to develop the flood- frequency relationships.

The results of the simulations are presented as probability-plots using standard plotting position methods[8,9]. This approach avoids the problems often encountered in selecting and fitting a probability distribution to the model outputs. Outputs from the stochastic flood model were ranked in descending order of magnitude and the estimate of the annual exceedance probability (*Pex*) for each ranked flood output was obtained from the Cunane[8] plotting position formula using a Gringorten weighting factor of 0.44. Specifically:

$$P_{ex} = \frac{i - 0.44}{n + 0.12} \qquad (1)$$

where: *N* is equal to the record length of the annual maxima series being simulated (years) and equals the number of subdivisions for latin-hypercube sampling of 72-hour basin-average precipitation; and *i* is the rank of the flood output. A description of this procedure is contained in the SEFM Technical Support Manual[6].

Campbell River Flood Frequency Results using SEFM

Reservoir elevation, inflow, outflow, and inflow volume magnitude-frequency plots are shown below in the Figures 20a,b,c,d,e, 21a,b,c,d, and 22a,b,c,d. It should be noted that the step-like behavior of maximum reservoir outflow at Strathcona Dam and step-like behavior of maximum reservoir level and maximum reservoir outflow at Ladore and Hart Dams are the result of reservoir operation rule curves that are used for flood conditions. Annual maximum reservoir magnitude-frequency values for selected reservoir levels are listed in Tables 7a, 7b, and 7c.

Table 7a. Strathcona Reservoir Magnitude-Frequency Results for Critical Elevations

Elevation	Annual Exceedance Probability
Top of Lock Blocks: 226.30 m	1:5,500,000
Dam Crest: 225.55 m	1:415,000
Top of Impervious Core: 224.60 m	1:34,000

Table 7b. Ladore Reservoir Magnitude-Frequency Results for Critical Elevations

Elevation	Annual Exceedance Probability
Dam Crest Elevation: 179.35 m	1:960,000

Table 7c. John Hart Reservoir Magnitude-Frequency Results for Critical Elevations

Elevation	Annual Exceedance Probability
Dam Crest Elevation: 141.73 m	1:1,400,000
Top of Impervious Core, Slurry Wall, Sheet Piling: 140.50 m	1:65,000

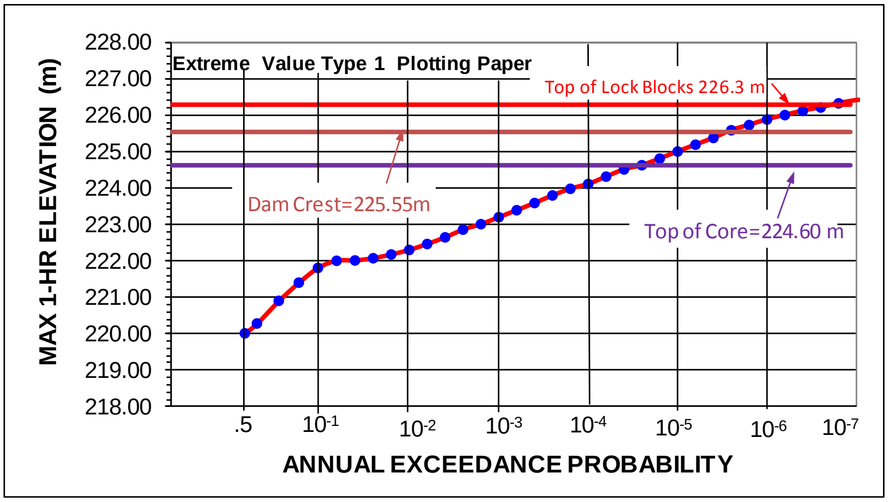

Figure 20a. Strathcona Dam, SEFM Simulated Reservoir Elevation Magnitude-Frequency

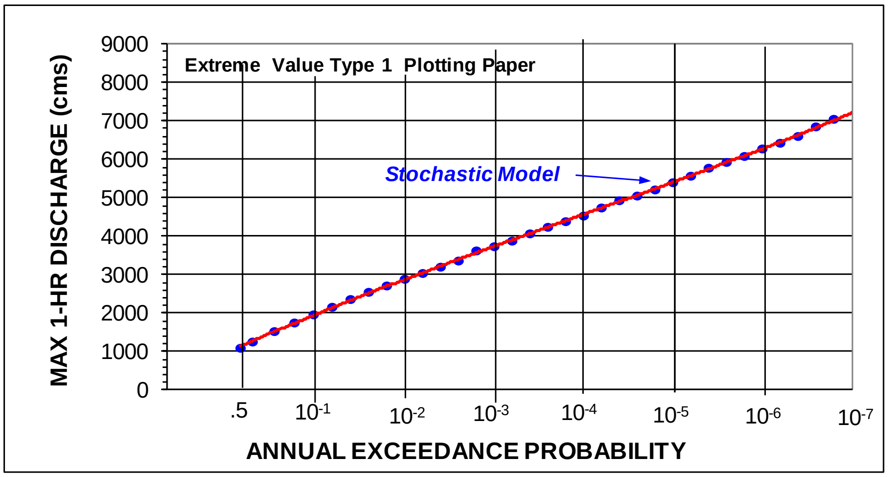

Figure 20b. Strathcona Dam, SEFM Simulated Reservoir 1-Hour Inflow Peak Magnitude-Frequency

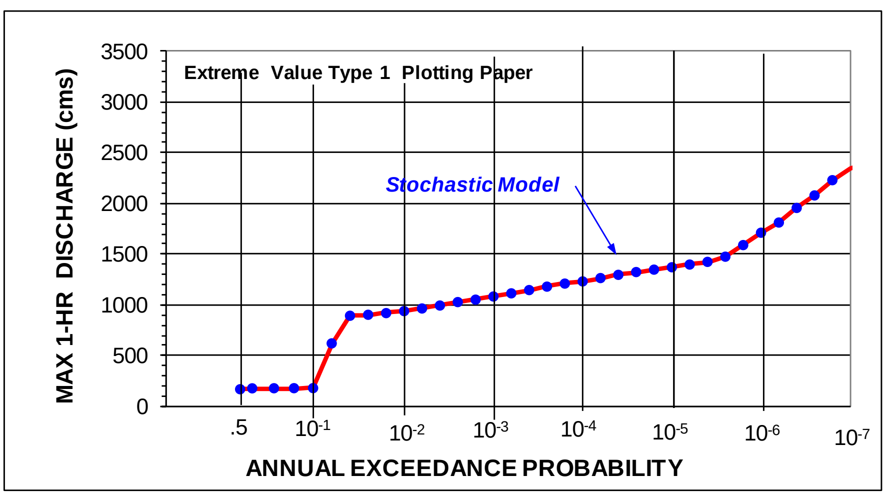

Figure 20c. Strathcona Dam, SEFM Simulated Reservoir 1-Hour Outflow Peak Magnitude-Frequency

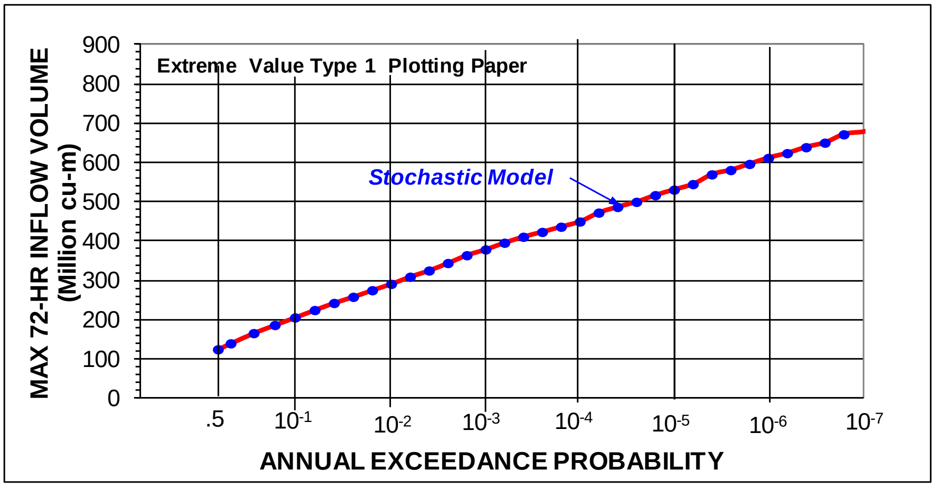

Figure 20d. Strathcona Dam, SEFM Simulated Reservoir 72-Hour Inflow Volume Magnitude-Frequency

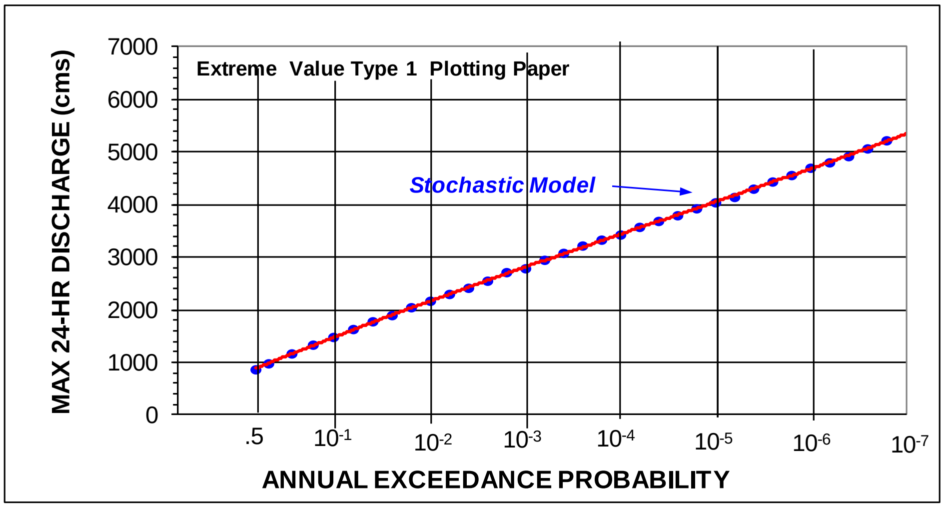

Figure 20e. Strathcona Dam, SEFM Simulated Reservoir 24-Hour Inflow Peak Magnitude-Frequency

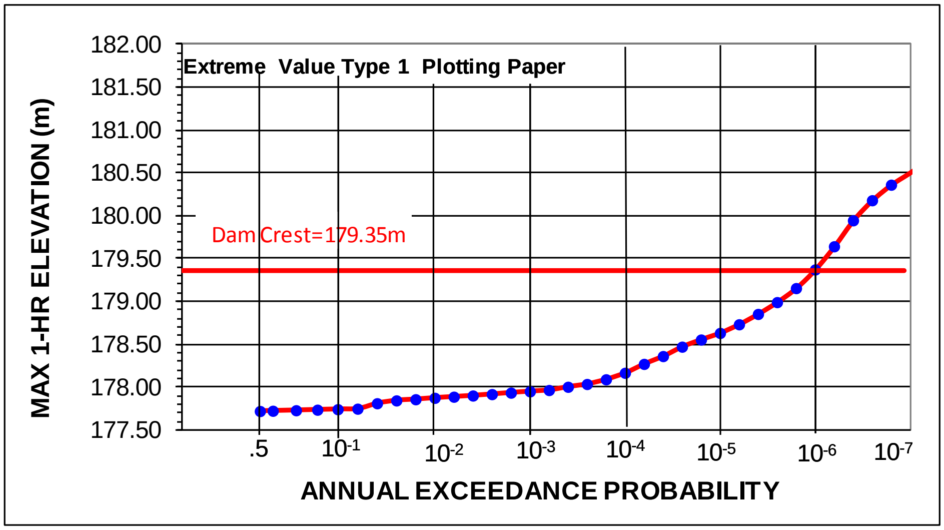

Figure 21a. Ladore Dam, SEFM Simulated Reservoir Elevation Magnitude-Frequency

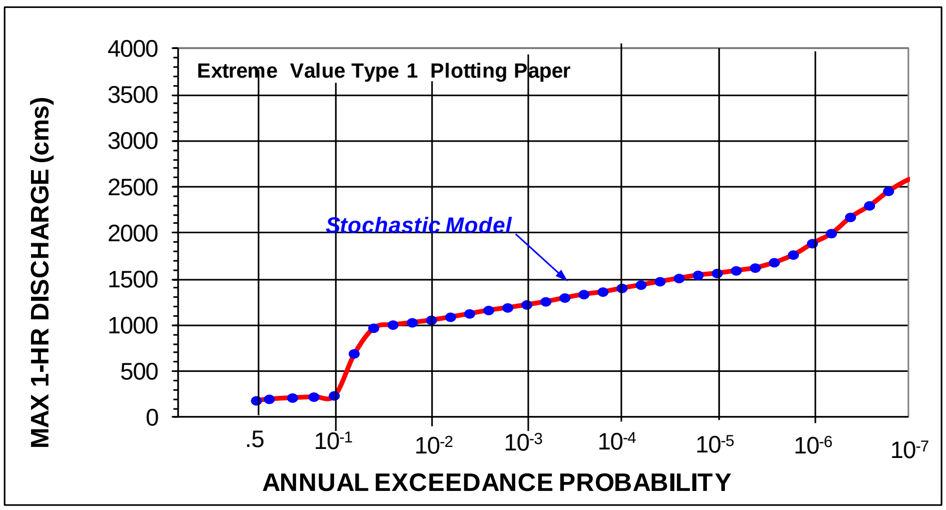

Figure 21b. Ladore Dam, SEFM Simulated Reservoir Peak Inflow Magnitude-Frequency

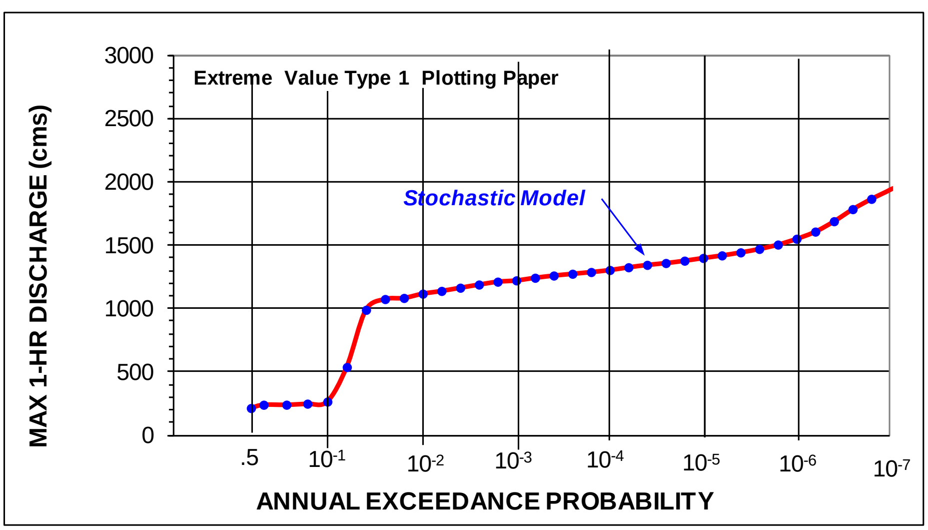

Figure 21c. Ladore Dam, SEFM Simulated Reservoir Peak Outflow Magnitude-Frequency

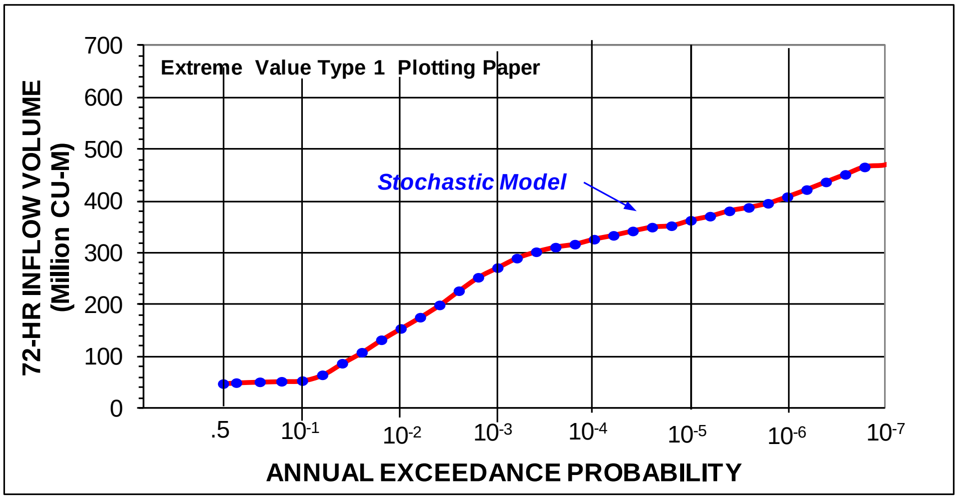

Figure 21d. Ladore Dam, SEFM Simulated Reservoir 72-Hour Inflow Volume Magnitude-Frequency

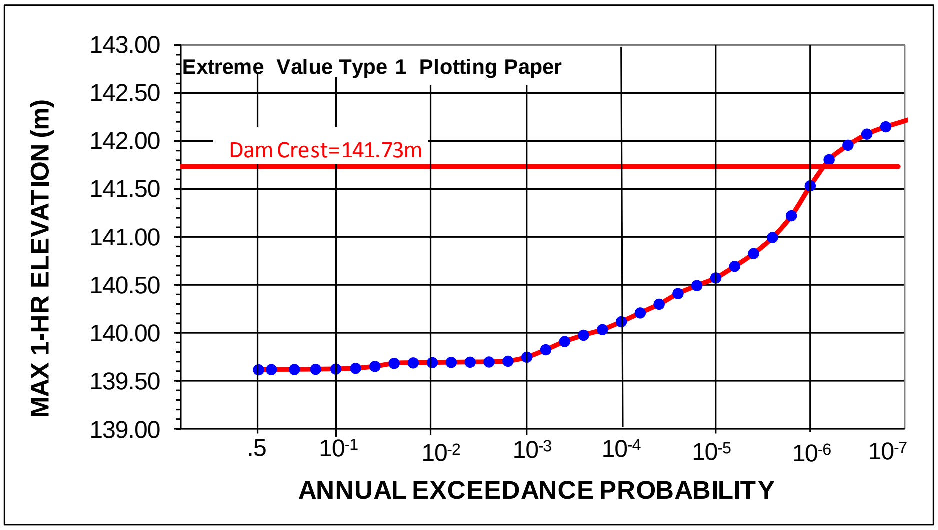

Figure 22a. John Hart Dam, SEFM Simulated Reservoir Elevation Magnitude-Frequency

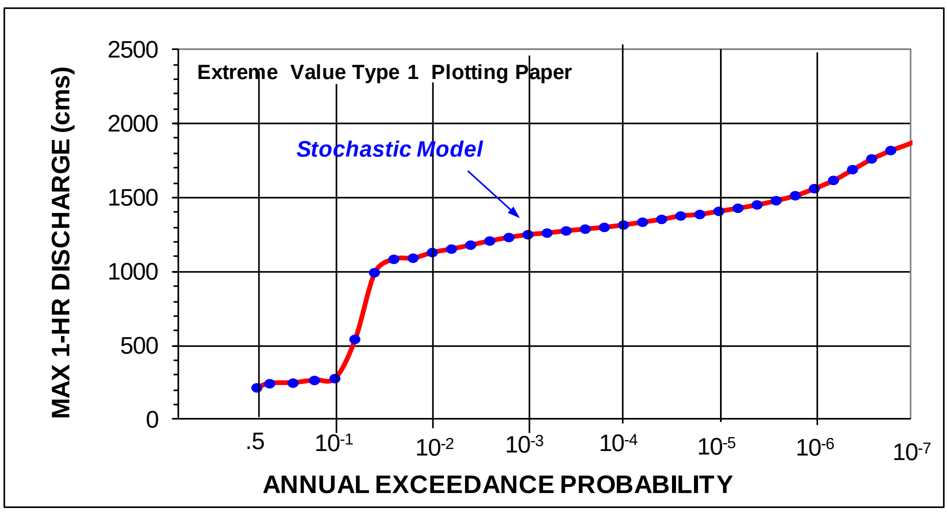

Figure 22b. John Hart Dam, SEFM Simulated Reservoir Peak Inflow Magnitude-Frequency

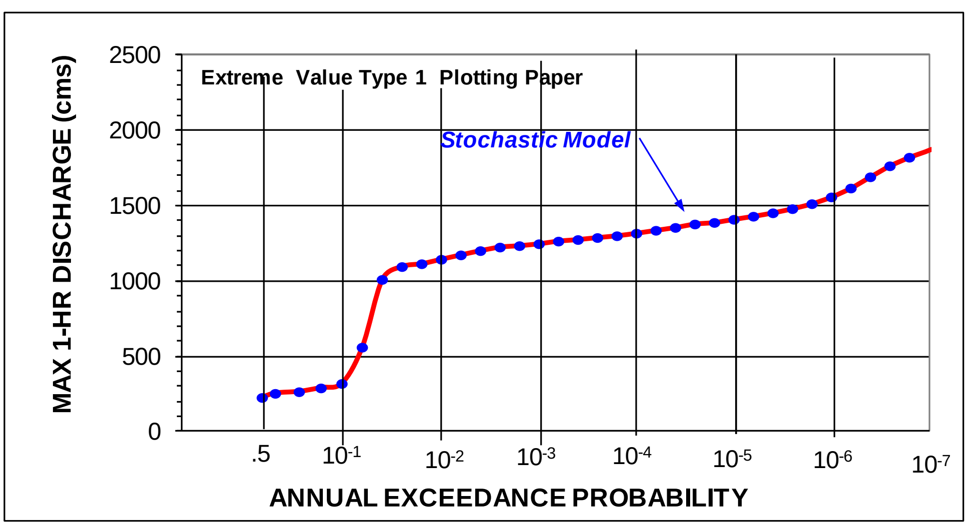

Figure 22c. John Hart Dam, SEFM Simulated Reservoir Peak Outflow Magnitude-Frequency

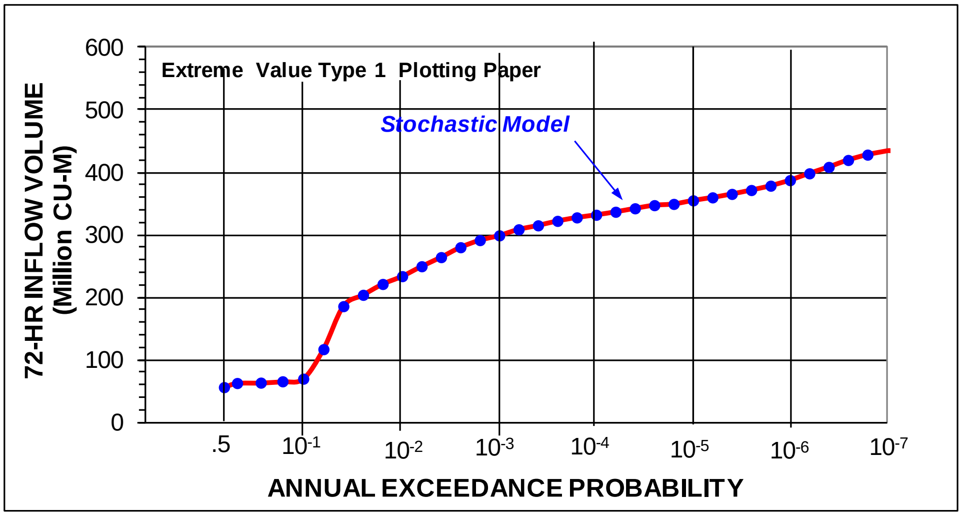

Figure 22d. John Hart Dam, SEFM Simulated Reservoir 72-Hour Inflow Volume Magnitude-Frequency

Summary

A stochastic flood model was developed for Strathcona, Ladore, and John Hart Dams on the Campbell River for use in developing flood-frequency estimates for extreme floods. The stochastic flood model utilized a deterministic flood computation model (UBC Watershed Model) and treated the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures were used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Hydrometeorological inputs that were treated as variables included: seasonality of storm occurrence; magnitude of extreme storm, temporal and spatial distribution of storms; temporal temperature pattern during the storm; sea-level and freezing level temperatures; hydrologic model antecedent conditions, and initial reservoir storage.

The flood-frequency relationships generated by the flood model were used to estimate the Annual Exceedance Probability (AEP) of selected flood characteristics. The AEP for flood waters reaching the top of the lock blocks on Strathcona Dam (226.30 m) was estimated to be 1:5,500,000 and the annual probability of flood waters reaching the top of the impervious core (224.60 m) was estimated to be 1:34,000. The annual probability of overtopping at Ladore Dam (179.35 m) was estimated to be 1:960,000. The annual probability of overtopping of John Hart Dam (141.73m) was estimated to be 1:1,400,000 and overtopping of the impervious core, slurry wall and sheet piles (140.50m) was estimated to be 1:65,000.

These flood magnitude-frequency curves are a valuable tool that bring the metric of a flood’s probability, including the PMF, into the decision making process in regards to dam safety conditions. Given the speed at which computer model simulations can now be conducted, there are methods of analysis that can be efficiently implemented to refine the estimated AEP associated with extreme floods. The SEFM method is one such method that can provide dam owners with useful information to aid in dam safety decision making.

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