Application of GIS in the Determination of Probable Maximum Flood

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The Probable Maximum Flood (PMF) is a hypothetical flood that is considered to be the most severe "reasonably possible" at a particular dam location. The UBC Watershed Model (UBCWM) was used to derive the PMF estimates for several BC Hydro dams in Southwestern British Columbia. The UBCWM uses the concept of area-elevation bands and point-input precipitation data. This means that a watershed is split into several elevation bands and the precipitation measured at a point (usually at one or two meteorological stations) is distributed to the elevation bands using the orographic precipitation gradients. However, the Probable Maximum Precipitation causing the PMF was provided in a rectangular-grid format of 3.5 km^2 resolution, and as such could not be used as the UBCWM input. ArcView 3.2 with the Spatial Analyst extension was utilised to enable the UBCWM to use the gridded precipitation input and derive the corresponding PMF estimates.

INTRODUCTION

BC Hydro is a large electric utility in Canada that, through its various facilities, generate between 43,000 and 54,000 GWh (gigawatt hours) of electricity annually, depending on prevailing water levels. Almost all of British Columbia's electricity demand is met with BC Hydro hydroelectric installations. Approximately 90% of the electrical energy produced by BC Hydro is provided by 30 hydroelectric generating stations.

Figure 1 shows the names and location of BC Hydro dams. Many of these structures, particularly the smaller ones, were constructed before the design concept of the Probable Maximum Flood (PMF) was in use. The development of the PMF concept was dependent on the availability of meteorological tools/methods required to estimate the upper limit to storm rainfall for a given region, commonly known as the Probable Maximum Precipitation (PMP). The first usage of the PMP concept in establishing a PMF for the design of BC Hydro dam was in 1962. Such early PMF estimates were subjected to external review due to the paucity of streamflow and meteorological data on which they were based and the novelty of the concept (BCH Report No. H2531). Since that time, methods for PMF estimating have advanced in a number of ways, including modified approaches for PMP estimation and improved hydrological models. Furthermore, there are more than 40 years of additional hydrometeorological data to assist in the analyses.

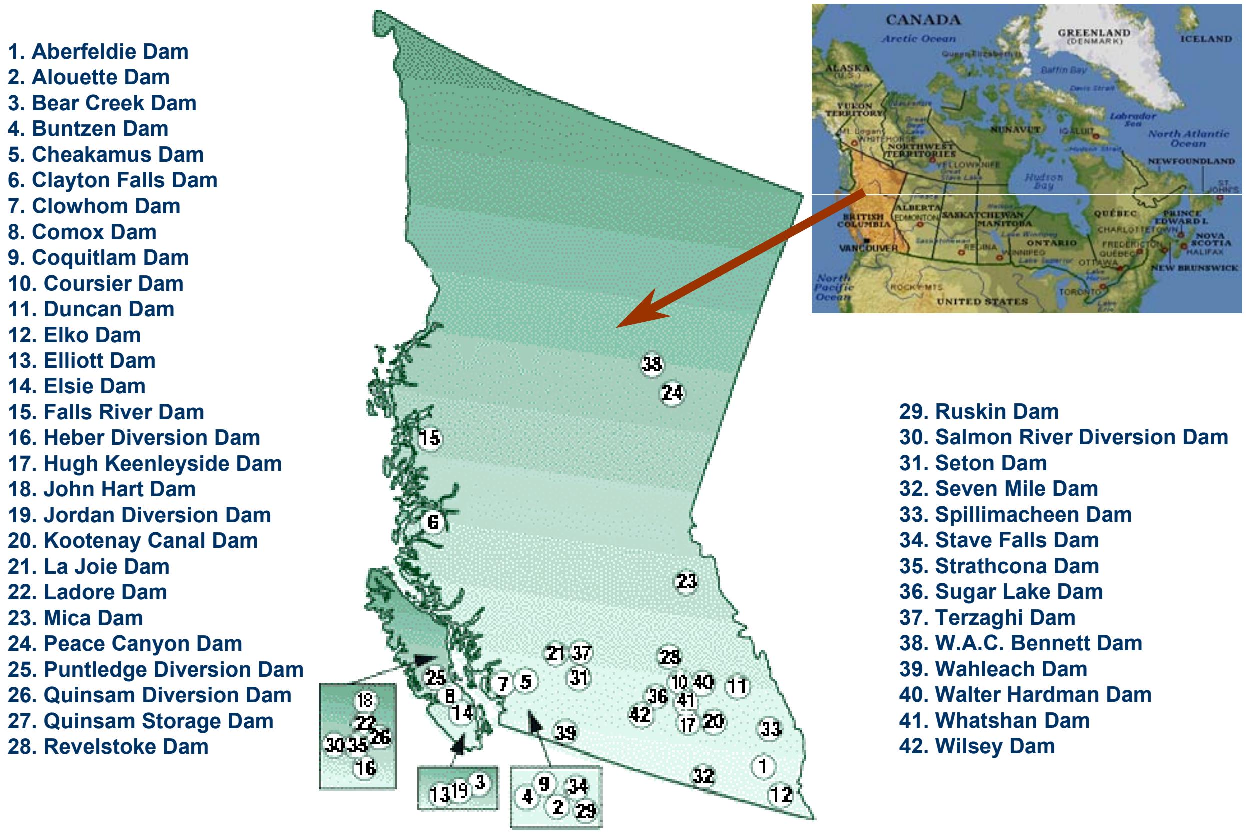

Figure 1: BC Hydro Dams

WATERSHED MODEL

Physical processes producing inflows to a reservoir formed by a dam have to be simulated using some kind of watershed model that converts precipitation input into runoff from a watershed. Watershed model should provide an accurate representation of watershed hydrological behaviour, and this is typically checked by comparing measured and model simulated streamflow at the watershed outlet. The Probable Maximum Flood scenarios are then calculated using an accurate watershed model with appropriate inputs, i.e., most severe "reasonably possible" combinations of extreme precipitation, snow accumulation, air temperatures, and antecedent conditions.

Some of the main reasons to choose the University of British Columbia Watershed Model (UBCWM) over other hydrological models for BC Hydro PMF studies were:

- ***Proven track record***. This model has been successfully applied to many of BC Hydro's developments, as well as numerous international projects.
- ***Minimal data requirements.*** The UBC Watershed Model runs with only daily or hourly temperature and precipitation input at a point.
- ***Existence of daily calibration.*** BC Hydro uses the UBCWM to forecast daily inflow in almost every BC Hydro reservoir.

The UBC Watershed Model (Figure 2) calculates watershed outflow using point measurements of precipitation and temperature data combined with physical watershed characteristics as input. The model was designed primarily for the calculation of streamflow from mountainous watersheds where streamflow consists of snowmelt, rain and glacier outflow. Since the hydrological behaviour of the mountainous watershed is a function of elevation, the model uses the area-elevation bands concept. This concept accounts for orographic gradients of precipitation and temperature, which are assumed to behave similarly for each storm and are dominant gradients of behaviour in mountainous areas. Besides the daily streamflow estimates, the UBCWM provides information on area of snow cover, snowpack water equivalent, energy available for snowmelt, evapotranspiration and interception losses, soil moisture, groundwater storage and surface and sub-surface components of runoff. All this information is available for each elevation band separately as well as for the whole watershed (average values).

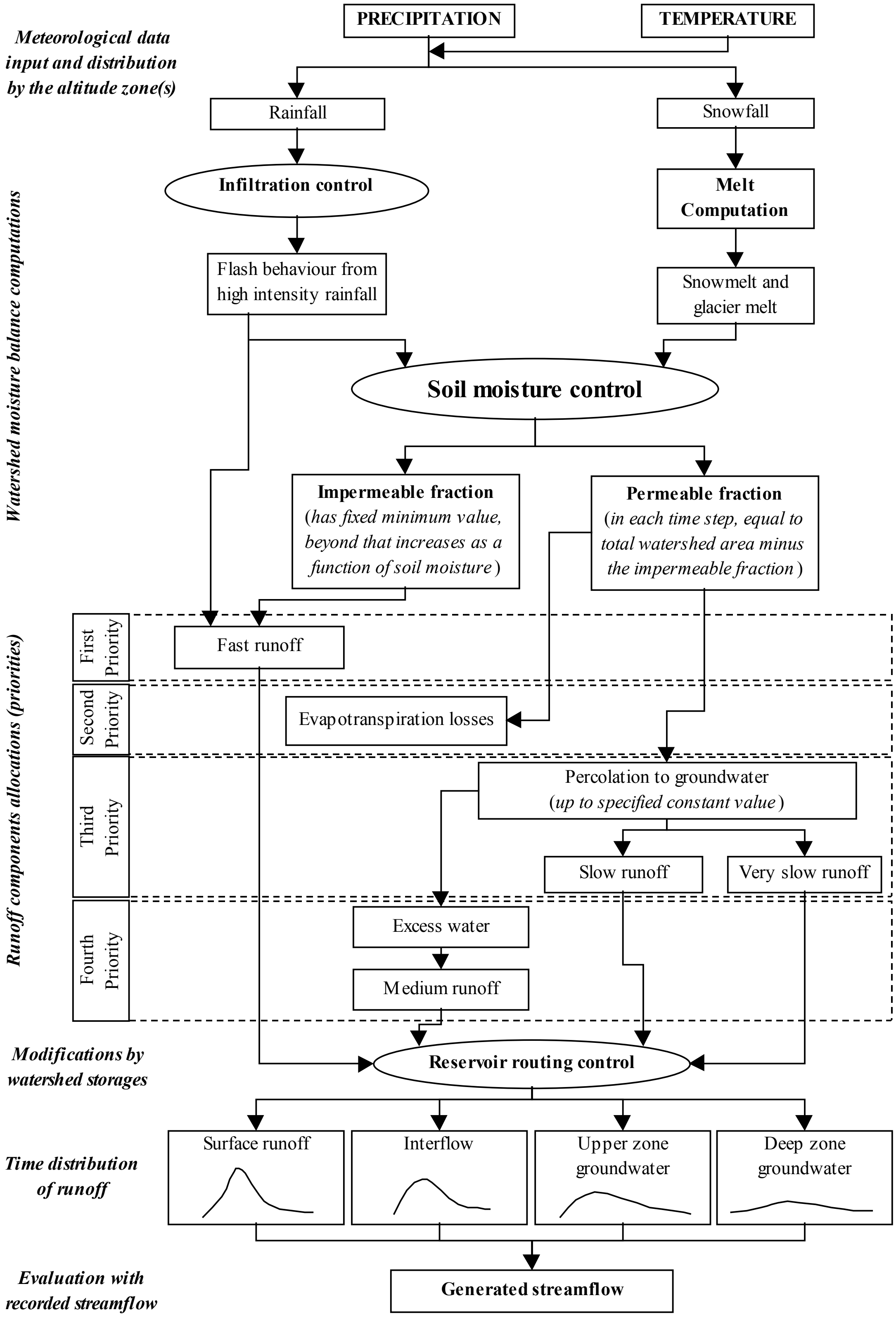

Figure 2: Diagram of UBC Watershed Model structure

The UBCWM is a continuous hydrologic model, which means that it will provide streamflow output as long as meteorological input is available. The physical description of a watershed is given for each elevation band separately in the form of different variables such as area of the band, forested fraction and forest density, glaciated fraction, band orientation and fraction of impermeable area. The UBCWM was designed to run from a minimum of meteorological and flow data, because these data are often sparse in the mountainous regions. In addition, most of these sparse data are from the valley stations. As a result of these constraints, an important aspect of the model is the elevation distribution of data. The current version of the UBC Watershed Model is made up of several sub-models as described in Micovic and Quick (1999):

- The meteorological sub-model *distributes the point values of precipitation and temperatures to all elevation zones of a watershed*. The variation of temperature with elevation controls whether precipitation falls as rain or snow and also controls the melting of the snowpacks and glaciers.

- The soil moisture sub-model *represents the non-linear behaviour of a watershed*. All the non-linearity of the watershed behaviour is concentrated into this soil moisture sub-model which sub-divides the water input (rain and snowmelt) into four components of runoff namely, fast, medium (interflow), slow (upper groundwater) and very slow (deep groundwater). An important aspect of the soil moisture sub-model is the “impermeable area” - fast responding region of a watershed which is assumed to be adjacent to a well developed stream channel system. This area changes as a function of soil moisture deficit and is used to describe three aspects of fast responding watershed runoff behaviour. Part of the watershed may be rocky, and therefore impermeable, producing overland flow. Part of the watershed soils will become saturated, and will then become “impermeable”, so fast runoff will occur; this region is usually riparian and the runoff usually occurs as “pipe-flow” within the soil matrix. Lastly, during high intensity rain, infiltration will be limited, and runoff will go directly to the fast runoff system. Within the soil moisture sub-model, these three types of fast runoff are controlled by the “impermeable fraction”, by the soil moisture deficit, and by the flash runoff threshold for the extreme rain, infiltration limiting runoff.

- The routing sub-model - *routing is linear which leads to great simplifications of model structure*. It guarantees conservation of mass and a simple and accurate water budget balance.

It should be mentioned that the majority of the parameters in the UBCWM are pre-calibrated and are kept constant. These parameters include all snowmelt, evapotranspiration and interception parameters. The snowmelt algorithm uses an energy approach, which is discussed in detail in Quick (1995) and can account for forested and open areas, aspect and latitude. Glacier melt is also computed using this same method and pre-calibrated parameters.

PROBABLE MAXIMUM PRECIPITATION

The Probable Maximum Precipitation (PMP) is "the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a given time of year" as defined in the US National Weather Service 1994 Hydrometeorological Report No. 57 (HMR-57).

The regional PMP study for Southwest British Columbia was recently completed by Water Management Consultants (WMC, 2003). This study provided recommendations for basin average PMP, spatial, temporal, and seasonal distribution, and storm temperatures. The methodology used for PMP estimation followed many of the procedures used in HMR-57 (storm separation with orographic enhancement), with some adjustments for historical storm analyses.

As shown in Figure 3, the spatial distribution of PMP was provided in a rectangular grid format of 3.5 km^2 resolution, and as such could not be used with the UBCWM, which, as mentioned earlier, uses point-input precipitation. Therefore, the ArcView GIS software had to be utilised to enable the UBCWM to use the gridded precipitation input and derive the corresponding PMF estimates.

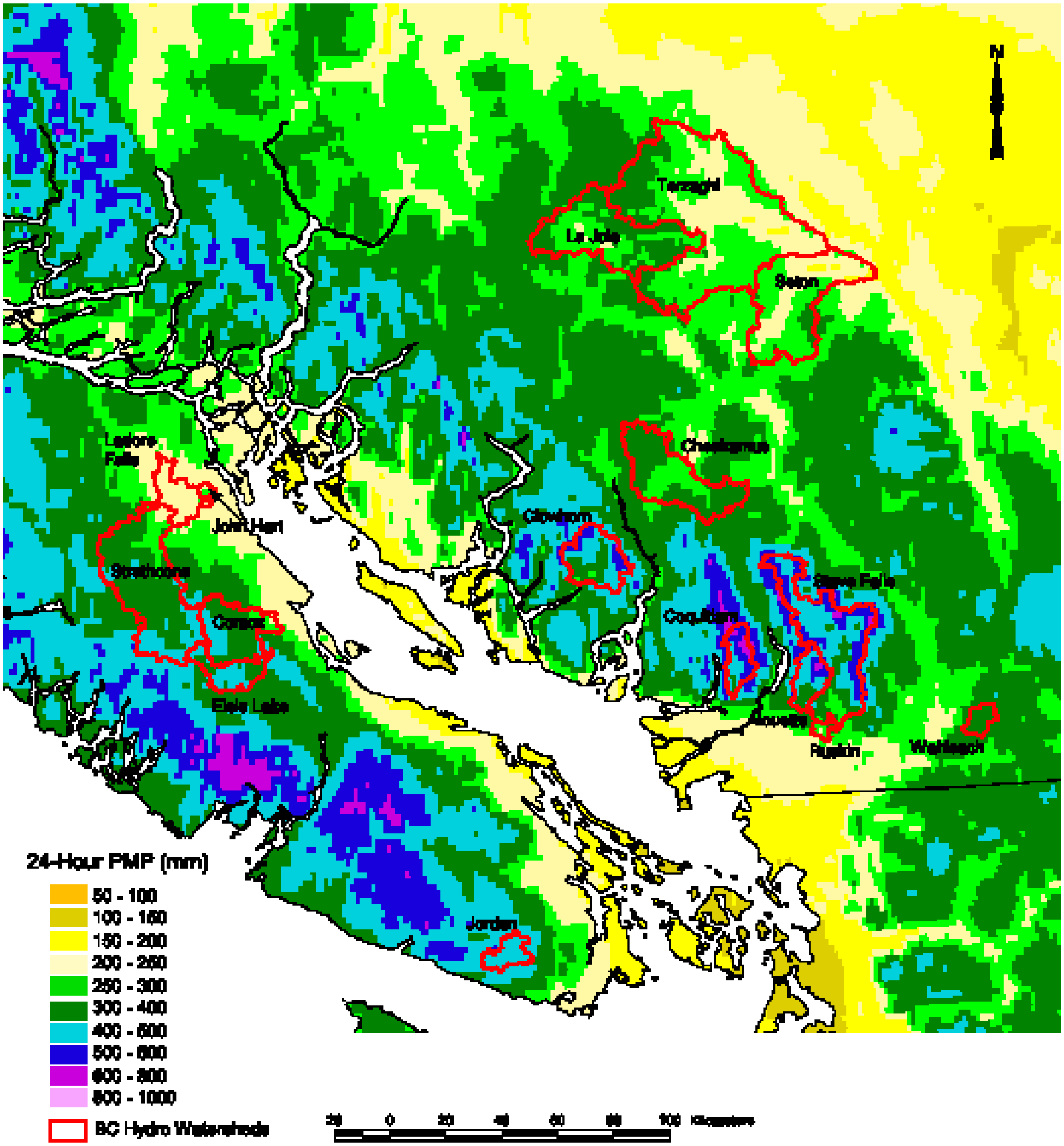

Figure 3: 24-hour PMP for Southwestern British Columbia

DERIVATION OF PROBABLE MAXIMUM FLOOD

The Campbell River system (Figure 4) will be used as an example in outlining the methodology for derivation of the PMF with UBCWM and gridded PMP input. The Campbell River system is comprised of three reservoirs in a row plus three diversions. It is located on the east side of the Vancouver Island mountains and drains to the north and east into the Strait of Georgia. The basin above the Strathcona Dam is very rugged with peaks rising to 2200 m and small areas of permanent snowpack. The mean basin elevation is 950 m and the basin area is 1193 km^2. The reservoir formed by Strathcona Dam is about 50 km long and up to 5 km wide. The creeks feeding the reservoir tend to be short and steep. The reservoir above the Strathcona Dam provides storage for the 66 MW Strathcona generating station, which discharges into Ladore Dam reservoir. Below the Strathcona Dam the terrain is much less rugged with rolling, heavily forested hills. The local basin area between Strathcona Dam and Ladore Dam is 245 km^2 and the mean basin elevation is 250 m. The Ladore Dam reservoir provides storage for the 47 MW Ladore generating station, which discharges into John Hart Lake that serves as the reservoir for the 126 MW John Hart generating station. The local basin area between Ladore Dam and John Hart Dam is only 25 km^2.

The critical months of the year for heavy precipitation in the Campbell River watershed are October through March. In this period frontal storms arriving from the southwest off the Pacific Ocean are associated with strong, moist winds that bring very heavy precipitation for durations of a few hours to 4 days. During these large winter storms the air temperature may be above freezing at all altitudes in the basin. Consequently, the accumulated snowpack may vary appreciably especially at low elevations.

The UBCWM is used to simulate inflows to Strathcona Dam and Ladore Dam watersheds. Consequently, within the UBCWM setup, the Strathcona and Ladore watersheds were divided into nine and five elevation bands, respectively. Due to its relatively small size, the John Hart Dam watershed was not modelled by the UBCWM, and its local inflow is assumed to be 10% of Ladore watershed local inflow, based on their area ratio.

The general location of the Campbell River System and UBCWM altitude bands setup were shown in Figure 4.

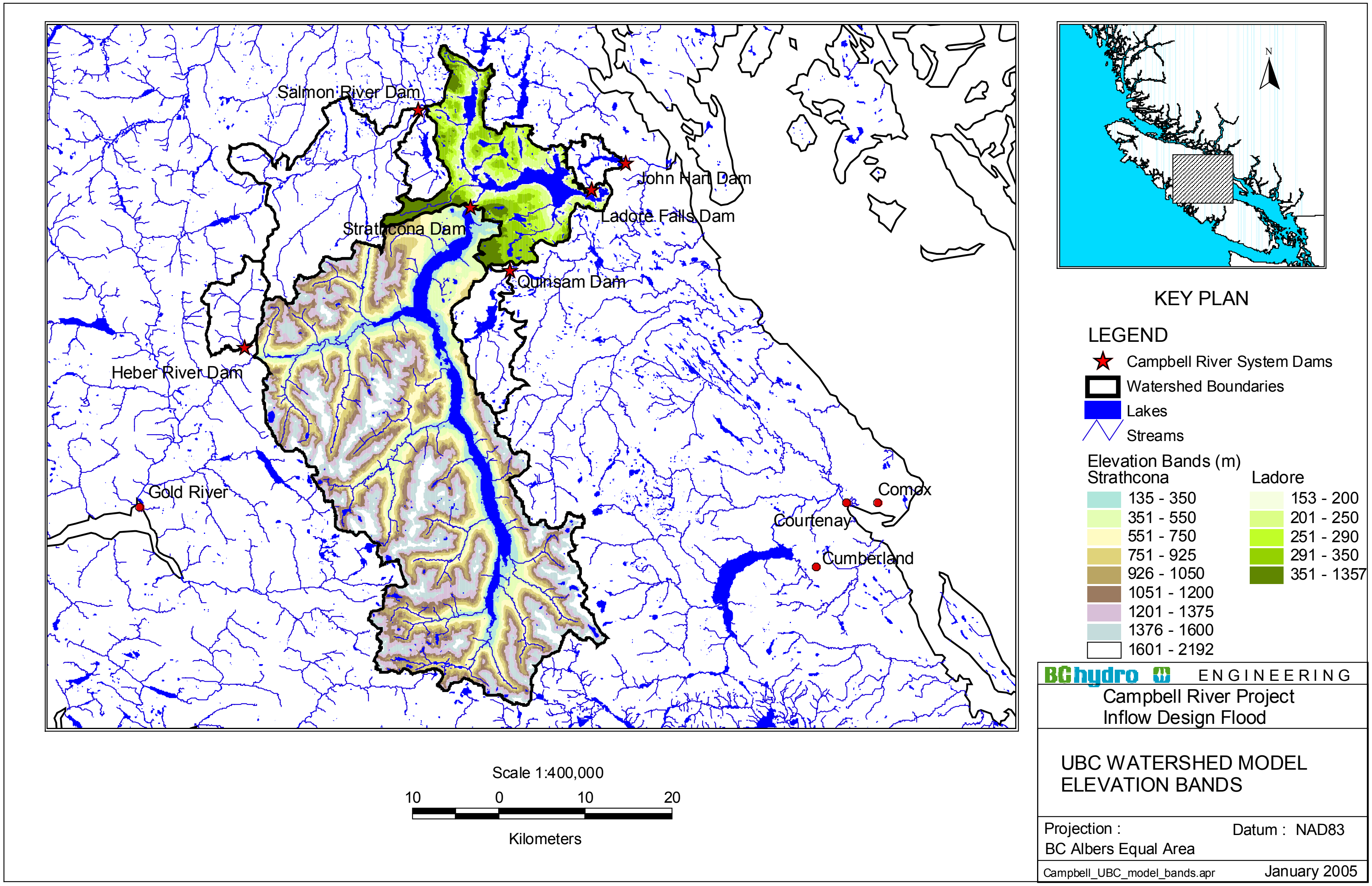

Figure 4: Campbell River System and UBCWM elevation bands

One of the main advantages of the UBC Watershed Model is a very simple input data requirement. As mentioned earlier, the precipitation data used are point measurements and thus, have to be distributed over the watershed, because in mountain regions precipitation increases as a moist air mass is driven by wind across mountain barriers. This orographic enhancement of precipitation is, within the UBCWM, modelled by the precipitation gradient parameters. For example, the precipitation gradient value of 5 represents 5% increase in measured point-precipitation per each 100 meters of altitude gain. As a result, each elevation band has its unique precipitation input that is equal (in the case of zero gradient) or greater than the input for elevation bands below it.

To match both the basin average PMP input and its spatial distribution for each watershed (Figure 3), it was necessary to create precipitation input targets for the UBCWM elevation bands which reflected the grid-element distribution. This was achieved in two steps:

1. The first step was to calculate the average 24-hour PMP for each of the UBCWM elevation bands for both Strathcona and Ladore watersheds. This was achieved by overlaying elevation band boundaries from Figure 4 on the 24-hour PMP grid elements from Figure 3 using GIS software. The Strathcona watershed example with band #2 (elevation 351 m to 550 m) is shown in Figure 5. The analysis resulted in the 24-hour PMP target input values for each elevation band, as shown in Table 1.

2. The second step required a trial-and-error procedure to adjust hourly precipitation values in the UBCWM point-input file and the associated precipitation gradients so that the UBCWM produced precipitation amounts in each band are as close as possible to the prescribed target values from Table 1. The results for Strathcona watershed are shown in Figure 6.

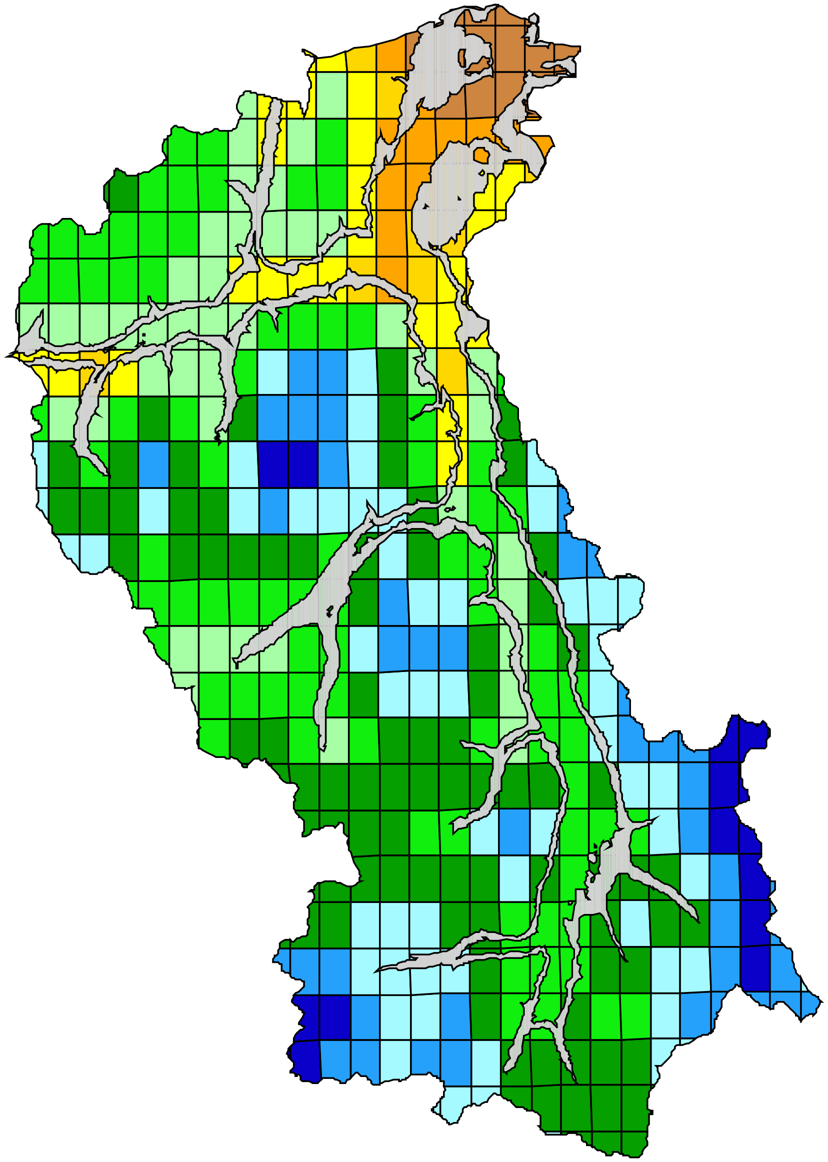

Figure 5: Calculation of average 24-hour PMP for an elevation band (Strathcona, elevation band #2)

Table 1: Elevation-band distribution of 24-hour PMP

Strathcona Dam Watershed		**Ladore Dam Watershed**	
Elevation Band	24-hour PMP (mm)	Elevation Band	24-hour PMP (mm)
1	290.0	1	203.7
2	300.6	2	204.0
3	315.4	3	204.2
4	326.6	4	205.5
5	333.5	5	214.8
6	337.7		
7	342.3		
8	346.9		
9	357.0		

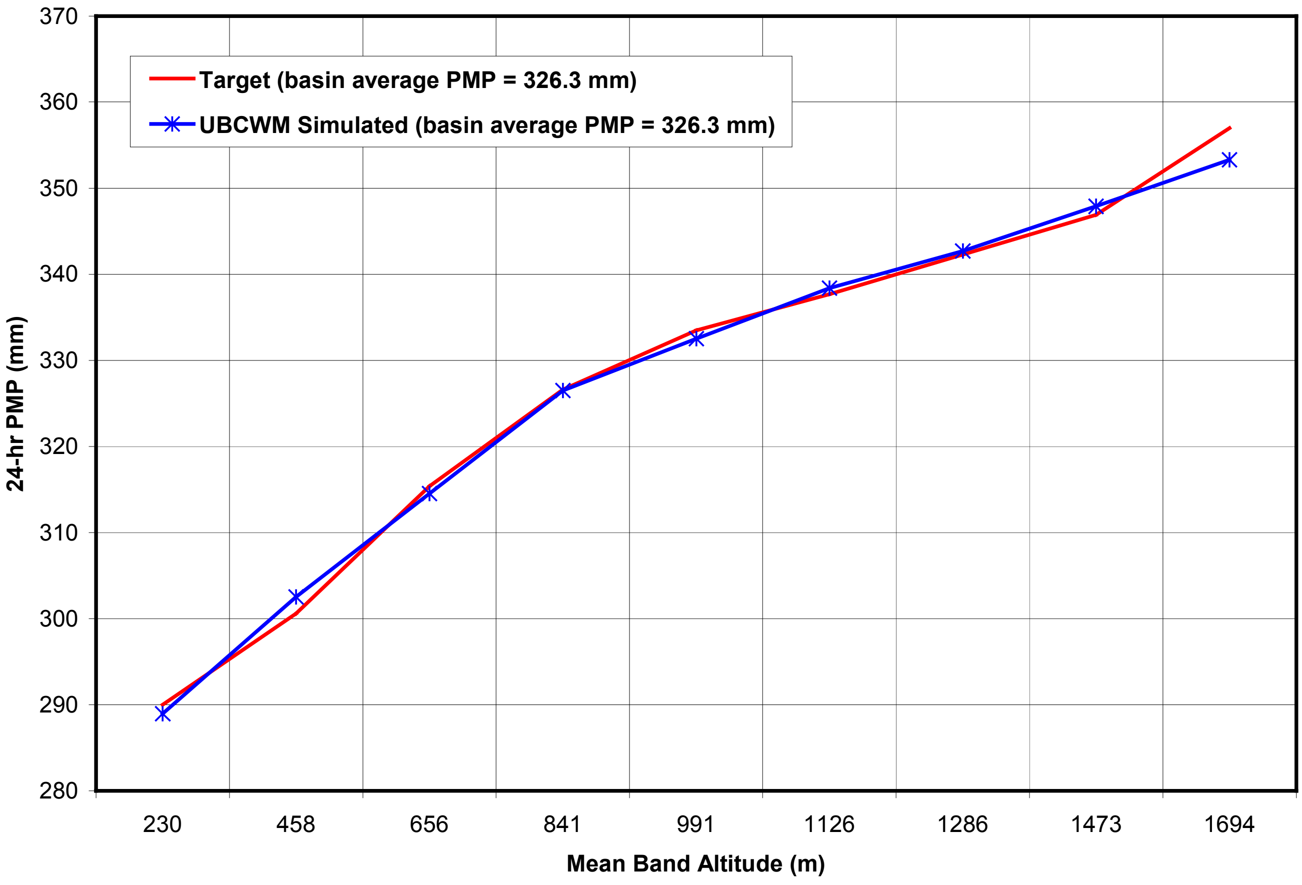

Figure 6: Achieved 24-hour PMP distribution by UBCWM elevation bands (Strathcona)

Once the UBCWM was capable of achieving prescribed spatial distribution of PMP as well as its basin-average value for each watershed, it was relatively easy to produce the Probable Maximum Flood. The point precipitation input producing the prescribed PMP was combined with critical snowpacks, air temperatures and antecedent soil conditions within the UBCWM. The resulting output hydrographs shown in Figure 7 are Probable Maximum Flood for these two watersheds.

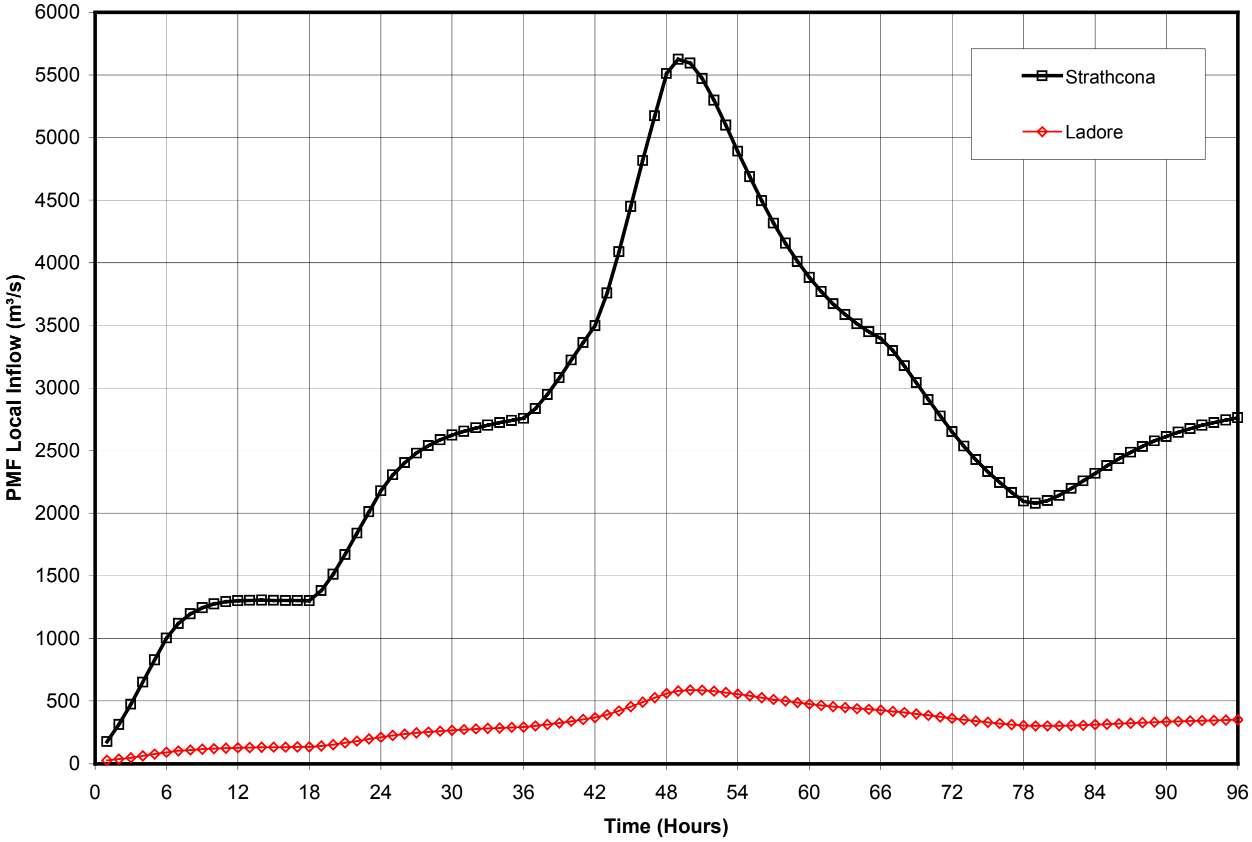

Figure 7: Calculated PMF hydrographs

SUMMARY

The presented work shows coupling of a conceptual watershed model that has simple input data requirement with the more complex, spatially distributed data set, using GIS software tools. The methodology is applied to the development of Probable Maximum Flood estimates, but the same principles can be used in other hydrological modelling studies when the model input data requirements do not match spatial extent of the available data.

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