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BULLETIN 2022-6-MetPortal

British Columbia Extreme Flood Project

Draft MetPortal Application Guidance for Freshwater Dams

PREFACE AND ACKNOWLEDGMENTS

The BC Ministry of Forests and BC Oil & Gas Commission are the regulators of freshwater dams in the province. The construction and safe operation of these dams are regulated through the British Columbia *Water Sustainability Act* (WSA) and the Dam Safety Regulation (the Regulation). Authorization for construction of a dam is obtained through issuance of a water licence. The design of the dam must be accepted by a WSA Engineer who is qualified in the area of dam design. Alternatively, acceptance of a design may be completed by a Dam Safety Officer (DSO) who is supervised by a WSA Engineer or the design has been reviewed by an Independent Engineer who has made a recommendation for a regulator to accept the design. **A key component of the design is a defensible determination of the hydrologic loading (flood) on the dam.**

The Regulation requires that the owner of a high, very high or extreme failure consequence dam conduct a Dam Safety Review (DSR) at the frequency specified by the Regulation. The Regulation indicates the DSR must be completed **in accordance with the requirements** of the Comptroller or Water Manager and the DSR report must be in **the form and with the content** specified by the Comptroller or a Water Manager. The DSR report must be submitted to a DSO for acceptance. **A key component of any safety assessment is an evaluation of the hydrologic loading design for the dam and an update of the design if there have been significant improvements in methodology, changes in watershed characteristics, and/or changes in climate forcings in the region.** The Regulation also indicates that a DSO may request an owner of a dam submit any information and records that the DSO considers necessary to evaluate the hydrological hazard that may act on the dam.

The following guidance paper is the 6th document in a series referred to as the BC Extreme Flood Project. The document provides an indication of the level of effort required for the five different dam failure consequence classifications specified in the Regulation and discusses both deterministic and probabilistic approaches. This guidance document is intended for both hydrologists completing flood studies as well as regulators who are evaluating the adequacy of a submitted report.

There have been several costly and dangerous flood events in British Columbia in recent years that have also unfortunately, in some cases, resulted in fatalities. The intention of the development of government funded regional flood and hydrometeorological studies, as well as hydrology guidance documents, is to mitigate the impact of these flood events through improved design of structures. This document references applicable dam safety guidelines from other jurisdictions. Practitioners should not hesitate to seek out and utilize other high-quality guidelines that are suitable for the specific requirements of the project under study. The Qualified Professional conducting the flood analysis should decide the appropriateness of all guidelines and data used for their study and is responsible for the final product.

I would like to acknowledge Leanna King and Zoran Micovic of BC Hydro for assistance with the preparation of this report and various other guidance documents and papers that have greatly contributed to the science of hydrologic loading on dams.

This document is being released as a draft as we welcome comments and suggestions from practitioners who are using the BC MetPortal for completing any type of dam reservoir flood study or other types of hydrotechnical flood assessments in BC. Please send all comments to the Ministry of Forests Dam Safety Program at dam.safety@gov.bc.ca

Robert K McLean, P.Eng.
Senior Dam Safety Engineer

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Prepared for

BRITISH COLUMBIA
Ministry of Forests

Prepared by

RTI INTERNATIONAL | Center for Water Resources
Driving Sustainable Use of Water

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

In cooperation with

MGS Engineering Consultants, Inc.

MGS Engineering Consultants, Inc.

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Executive Summary

Accurate estimates of the magnitude of flood events are critical information for the safe operation of dams and any other water management structure. This requires the assessment of the reservoir peak inflow rate and total volume of inflow during flood events for a selected probability of occurrence and/or the Probable Maximum Flood (PMF). In British Columbia the Ministry of Forests are the regulator of freshwater dams. The Ministry of Forests requires that the inflow design flood for freshwater storage dams is based on the failure consequence of the dam as specified in the Canadian Dam Association guidelines.

This guidance document was primarily developed to assist users of the BC MetPortal who are preparing a flood study for a freshwater dam in BC. Considerable user documentation (bulletins 2020-2 through 2020-5) was provided when the BC MetPortal was released in 2021. In addition, a recent publication by BC Hydro documents the approach taken to develop a PMF study for the Cheakamus Dam in BC utilizing data and information from the BC MetPortal. The purpose of this guidance document is to provide additional information and discussion for using the BC MetPortal with a watershed model to estimate the magnitude of a flood event when designing or conducting a safety assessment for any water management structure including dams, spillways, dikes and river crossings. This document also discusses appropriate approaches for estimating the magnitude of a flood event at a Low failure consequence dam. The intent of the document is to:

- communicate the level of effort required to complete a suitable flood study commensurate with the failure consequence of the dam,
- discuss the two basic approaches to completing a study (i.e., deterministic and probabilistic),
- summarize basic concepts of watershed modeling,
- discuss the importance of utilizing numerous types of data/information when modeling flood processes, including rainfall magnitude, storm characteristics, temperature sequences, dew point temperatures, etc. and
- provide options for assessing uncertainty of estimates, including climate change.

Sections of the guidance document generally include a discussion that address the *Purpose* of the section, *Available Options* when completing a flood study, *Recommended Minimum Hydrologic Analyses*, *Experience* of the authors with regards to the section under discussion, and *Details* of developing hydrologic models and conducting hydrologic analyses.

The Ministry of Forests have no prescriptive design code to follow and allows hydrologists to utilize appropriate guidelines from the Canadian Dam Association as well as international dam safety organizations or other regulatory agencies. The Ministry of Forests also have no specific requirements when assessing the uncertainty of the flood estimate for a reservoir, including the allowance for climate change. The Ministry of Forests, however, recognize this is extremely important and requires evaluation of the uncertainty in an appropriate manner. Hydrologists are encouraged to seek out appropriate methods of assessing uncertainty and to document them in their study.

Dam owners and regulators should have confidence in the magnitude of flood best estimate, and an adequate analysis and/or discussion of the uncertainty with the estimate should be provided, commensurate with the failure consequence of the structure. This information is necessary for many instances, when the dam owner and regulator are required to make decisions regarding construction, operation and/or modifications to the dam or spillway.

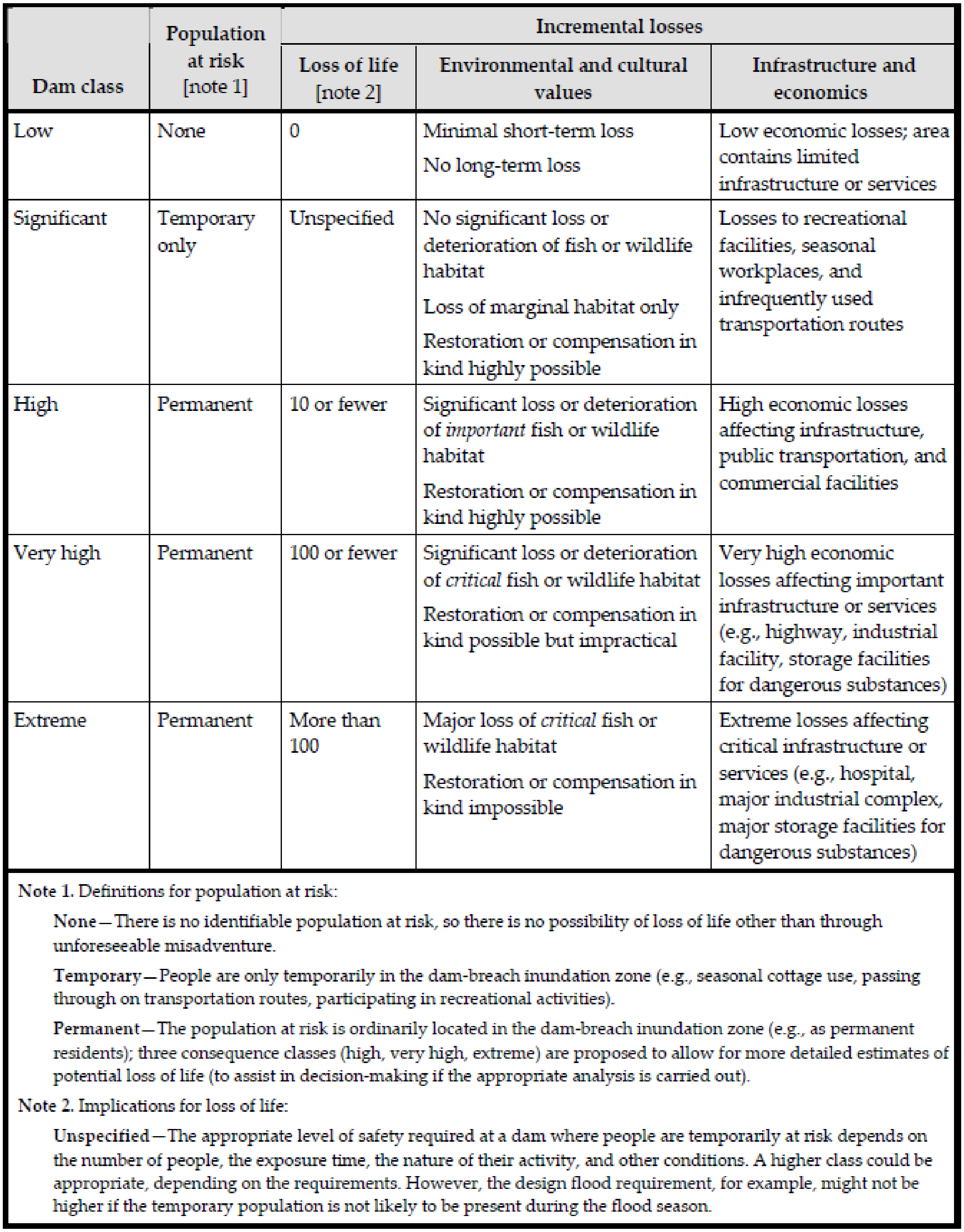
1 Introduction

The purpose of this guidance document is to assist hydrotechnical practitioners who are tasked with estimating the magnitude of flood peak flow rates and volumes in British Columbia for the design of dams, spillways, dikes, and stream crossings. Specifically, this document provides guidance on the use of the British Columbia (BC) MetPortal which contains calculated values of Probable Maximum Precipitation (PMP), Annual Exceedance Probability (AEP) rainfall depths, temperature sequences, storm seasonality and observed storm temporal rainfall distributions. Information contained within the BC MetPortal is based on observed data and does not include considerations for natural climate cycles or anthropogenic climate change.

The focus of this document is to provide options/methods to meet the intent of the Canadian Dam Association (CDA) guidelines through the use of watershed rainfall and snowmelt runoff models. The CDA guidelines provide recommendations for the Inflow Design Flood (IDF) and corresponding spillway capacity based on the dam failure consequence classification (the classification) of a dam. The classification of the dam is based on loss of life, environmental and cultural values, as well as economic losses as shown in Table 1.

The IDF target levels for fresh water dams in BC are summarized in Table 2 below. Information regarding flood design for tailings dams in BC are located in EMLI (2021) and CDA (2019).

Table 1: Canadian Dam Association Dam Failure Consequence Classification System (from CDA, 2007)



Dam class	Population at risk [note 1]	Incremental losses		
		Loss of life [note 2]	Environmental and cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss No long-term loss	Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat Loss of marginal habitat only Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of *important* fish or wildlife habitat Restoration or compensation in kind highly possible	High economic losses affecting infrastructure, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of *critical* fish or wildlife habitat Restoration or compensation in kind possible but impractical	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of *critical* fish or wildlife habitat Restoration or compensation in kind impossible	Extreme losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances)

Note 1. Definitions for population at risk:

None—There is no identifiable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure.

Temporary—People are only temporarily in the dam-breach inundation zone (e.g., seasonal cottage use, passing through on transportation routes, participating in recreational activities).

Permanent—The population at risk is ordinarily located in the dam-breach inundation zone (e.g., as permanent residents); three consequence classes (high, very high, extreme) are proposed to allow for more detailed estimates of potential loss of life (to assist in decision-making if the appropriate analysis is carried out).

Note 2. Implications for loss of life:

Unspecified—The appropriate level of safety required at a dam where people are temporarily at risk depends on the number of people, the exposure time, the nature of their activity, and other conditions. A higher class could be appropriate, depending on the requirements. However, the design flood requirement, for example, might not be higher if the temporary population is not likely to be present during the flood season.

Table 2. IDF Target Levels for Water Dams (CDA)

Dam Classification	IDF Water Dam[1]
Low	100yr
Significant	between 100yr and 1000yr
High	1/3 between 1000yr and PMF
Very High	2/3 between 1000yr and PMF
Extreme	PMF

Notes: 1 - IDF target levels for initial consideration and consultation between owner and regulator, table modified from page 17 of CDA (2007)

IDF evaluated for instantaneous peak flow and/or volume of flood

100yr is a short form notation for the flood with a 1 in 100 Annual Recurrence Interval (ARI), the inverse of the AEP (i.e., ARI = 1 / AEP).

Note that Table 2 is with respect to the magnitude of ***flood flows*** as determined using both a flood-frequency based approach as well as the deterministic PMF approach, and not the respective ***rainfall events***. The flood event produced by a rainfall event of a specified AEP can vary considerably based on the storm characteristics, the watershed characteristics, and the pre-storm watershed antecedent conditions that often includes snowpack and soil moisture saturation. This is discussed further below.

The focus of this document is on drainage areas less than 100 km^2, though similar techniques are applicable to larger watersheds.

The terms common, rare, very rare and extreme are used throughout the report and the respective range of AEPs are defined in Table 3, as adapted from the Australian Rainfall and Runoff Guidelines (Nathan & Weinmann, 2019).

Table 3: Terminology for different magnitudes of storms and floods

Descriptor of Storms and Floods	Range of AEP
Common	More likely than 1:5
Rare	From 1:5 to 1:100
Very Rare	From 1:100 to 1:2,000
Extreme	Rarer than 1:2,000 to beyond 1:10^6

1.1 Deterministic versus Probabilistic Approaches

Various factors affect the magnitude of large floods and the impact on reservoirs, including:

1. The magnitude of a storm event (e.g., the total precipitation depth over a 48-hour period)
2. The spatial and temporal distribution of the storm
3. The corresponding temperatures during a storm (when snowmelt is involved)
4. The watershed conditions at the start of the storm (snowpack, soil moisture, and reservoir levels)

Floods of a specific magnitude can be produced by various combinations of these factors. For instance, a 3-inch, high intensity storm on a ripe snowpack may produce the same peak runoff as a 6-inch, lower intensity storm following a prolonged dry period. The 100-year flood event (1:100 AEP) is intended to represent the flood magnitude with a 1 in 100 ARI, regardless of the mechanism causing the event, and should reflect the true natural variability of conditions causing the event.

Two basic methods can be used to estimate floods:

1. **Deterministic modeling approaches**: With deterministic modeling, a hydrologic model is used with a single sequence of meteorological inputs (precipitation and temperature) to simulate the runoff response. The PMF is typically simulated using deterministic approaches, and simplified methods for simulating the 100-year (1:100 AEP) and 1000-year (1:1000 AEP) flood rely on deterministic modeling.

   One challenge with deterministic approaches is appropriately selecting meteorological inputs and antecedent conditions such that the deterministic IDF is representative of the natural variability that occurs in a watershed. This challenge is discussed further in Section 5.

2. **Probabilistic approaches**: With a probabilistic approach, the natural variability of key inputs (e.g., storm volume, storm spatial and temporal patterns, temperature sequence, and antecedent conditions) is first characterized. Stochastic modeling approaches utilize a large set of these key inputs based either on direct use of historical data or probabilistic models fit to historical data. A watershed model is then executed for each of the combinations of inputs (e.g., Figure 1). The results are then aggregated and used to generate probability-plots for key flood characteristics such as reservoir inflow flood peak, reservoir inflow volume, maximum reservoir level, maximum reservoir and spillway discharge, depth and duration of dam overtopping, etc. These probability-plots are collectively termed Hydrologic Hazard Curves (HHCs) and are used to provide an estimate of the 100-year (1:100 AEP), 1000-year (1:1000 AEP) and rarer floods in a manner that strives to reflect the true probability of different combinations of conditions. The resulting HHCs are then used to provide inputs to the Risk Informed Decision Making (RIDM) process described in the CDA guidelines.

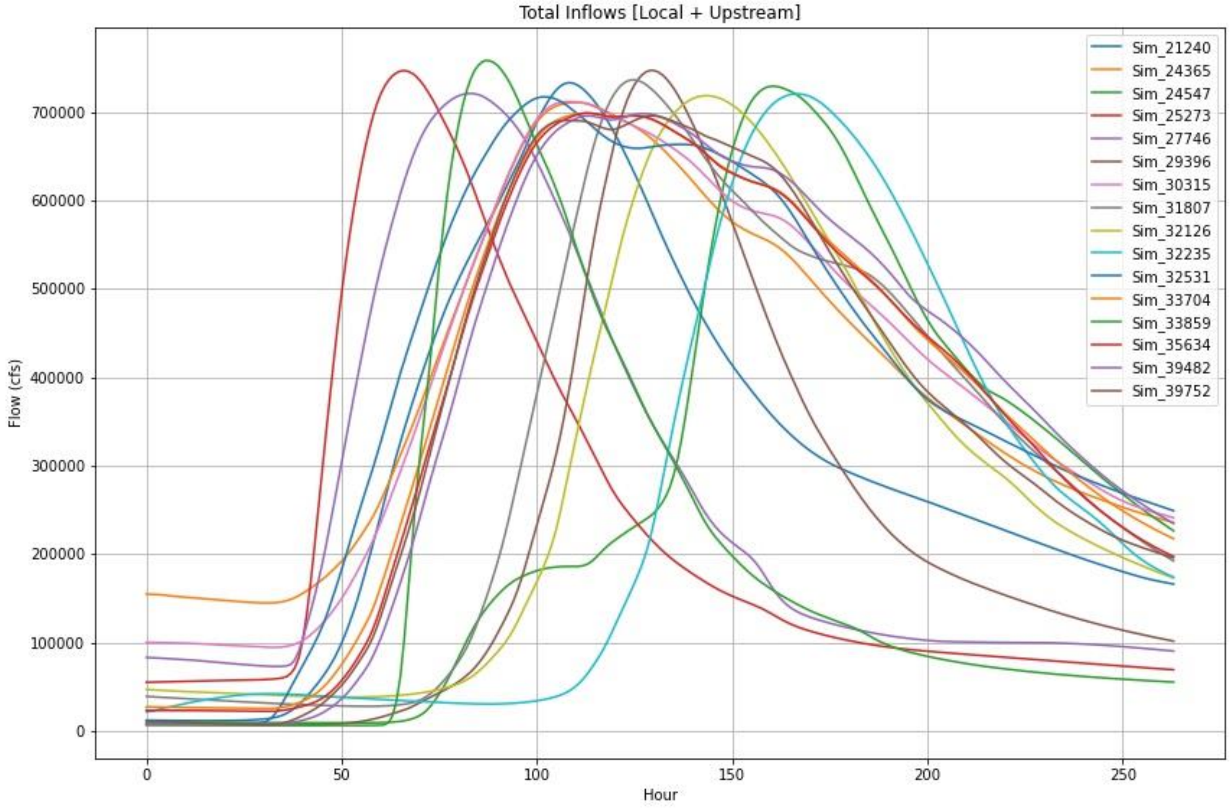


Figure 1. Suite of inflow hydrographs for a large watershed. Each hydrograph results in similar peak pool elevations, but have varied hydrograph shapes and peaks.

1.2 Key Considerations

The following are key takeaways:

- The CDA guidelines provide a general framework for assessing flood magnitude, leaving latitude for specific applications in different contexts. This guidance document describe **options and methods to meet the intent of CDA Guidelines**. With respect to PMF calculations, this guidance document includes recommendations from the example IDF computations described in King and Micovic (2022), which expanded upon the basic approach contained within the CDA guidelines.
- The intent of assessing the PMF is to identify the *probable* maximum flood. One challenge is identifying an appropriate degree of conservatism. This guidance document **focuses on identifying plausible combinations of hydrometeorological inputs** versus applying blind conservatism, recognizing that a blind application of conservatisms can lead to excessive compounding effects. Attention is given to controlling the compounding of conservatisms of inputs and model parameters.
- Different factors will have greater or less influence on results for a particular situation. The guidance document highlights these factors where appropriate:
    - Identify differences in hydrometeorological inputs for dams/reservoirs sensitive to **flood peak vs. flood volume**
    - Recognize the influence of storm seasonality with respect to the values of **hydrometeorological inputs**
    - Recognize the influence of storm seasonality with respect to **reservoir levels and reservoir operations**

1.3 Climate Change

Information contained within the BC MetPortal is based on observed data and does not consider future anthropogenic climate change or naturally occurring climate cycles.

King and Micovic (2022) consider the impacts of climate change on PMP (and subsequently PMF) in a relatively straightforward manner by considering the theoretical relationship between the moisture holding capacity of the atmosphere and temperature. The theoretical Clausius-Clapeyron relationship suggests a ~7% increase in moisture carrying capacity per ºC change in temperature. King and Micovic (2022) rely on information available from Cannon et al. (2020) to determine changes in mean temperatures. Using regional climate models for Canada, Cannon et al. (2020) relate shifts in global mean temperature to shifts in mean temperature for locations throughout Canada. Cannon et al. (2020) also relate shifts in global temperature to different time horizons under different emissions scenarios, providing a means of relating planning horizons to shifts in temperature, recognizing uncertainties in climate modeling.

The approach followed by King and Micovic (2022) represents one means of accounting for climate change impacts. However, there is not consensus in the scientific community regarding how climate change may impact rare to extreme precipitation. For instance, Wasko et al., 2021 summarize various approaches presented in the literature for incorporating climate change into extreme flood estimation and recommends an adaptive approach for managing risks associated with climate change. Similarly, Salas et al., 2020 review approaches employed to adjust PMP estimates under climate change. Designers of hydrotechnical structures in BC are referred to the Engineers & Geoscientists BC Climate Change Information Portal https://www.egbc.ca/Practice-Resources/Programs-Resources/Climate-Sustainability/Climate-Change-Information-Portal for additional information.

1.4 Existing Guidance for Using the BC MetPortal

The data available from the BC MetPortal was developed as a part of the BC Extreme Flood Project. In addition to the BC MetPortal website (https://dtn-metportal.shinyapps.io/bc_region/) supporting documentation includes:

1. A BC MetPortal User's Guide (DTN and MGS Engineering, 2020a)
2. Technical reports
    a. PMP development (DTN and MGS Engineering, 2020b)
    b. Storm analyses used to support the PMP development (DTN, 2020)
    c. Precipitation-frequency development (DTN and MGS Engineering, 2020c)

BC Hydro documented the application of data available from the BC MetPortal to estimate the PMF for Cheakamus Dam in BC (King and Micovic, 2022). The comprehensive PMF analysis described in Section 8.1 recommends employing the methodology outlined in this paper for a detailed assessment of PMF.

The Colorado-New Mexico Regional Extreme Precipitation Study (MetStat and MGS Engineering, 2018) resulted in similar regional PMP and precipitation datasets. The State of Colorado developed guidelines for risk assessments and risk informed decision making (RIDM; CO SEO, 2021a), including a section on the application of these datasets to assess flood risks at dams (CO SEO, 2021b). The Colorado guidelines are focused on probabilistic flood estimates but also discuss evaluation of the PMF and include recommendations for modeling considerations as well as reasonableness checks.

1.5 Document Organization

The guidance document is organized as follows:

- **Section 2** of the document focuses on considerations related to the development of watershed models for the simulation of extreme floods.
- **Section 3** discusses input datasets available from the MetPortal website.
- **Section 4** focuses on estimation of the 100-year (1:100 AEP) flood, pointing to the complementary streamflow-frequency data available for BC.
- **Section 5** discusses estimation of the 100-year (1:100 AEP) to 1000-year (1:1000 AEP) flood and presents considerations surrounding meteorological inputs and watershed modeling.
- **Section 8** turns to estimation of the PMF. Considerations for both a comprehensive and simplified analysis are presented.
- **Section 7** discusses interpolation between the 1000-year (1:1000 AEP) and PMF flood for high- and very high- failure consequence dams.
- **Section 9** provides an overview of Probabilistic Flood Hazard Analysis (PFHA) approaches to support Risk Informed Decision Making (RIDM)
- **Section 10** presents concluding remarks

The various sections of the document generally include the following sub-sections:

1. **Purpose**: This sub-section provides an overview of the analysis component described in the section and discusses the objective the analysis component is attempting to achieve. This is intended to give context to the reader in understanding how this section and the analysis component fit into the overall scheme of conducting hydrologic analyses and meeting the CDA guidelines.

2. **Available Options**: This sub-section identifies alternative approaches that may be employed to achieve the objectives of the hydrologic analysis.
3. **Recommended Minimum Hydrologic Analyses**: If applicable, this sub-section identifies a minimum level of analysis that would satisfy the intent of the CDA guidelines.
4. **Experience**: This sub-section discusses important considerations and experience to-date associated with different analysis components to help analysts in developing hydrologic models and conducting hydrologic analyses.
5. **Details**: For those analysis components involving greater complexities, this sub-section discusses important details of developing hydrologic models and conducting hydrologic analyses.

2 Watershed Modeling Considerations for All Failure Consequences

Purpose

We refer to ***watershed modeling*** throughout this guidance document. A watershed model consists of the combination of hydrologic, hydraulic, and reservoir routing models used to simulate the snowmelt, soil infiltration and runoff, transformation of runoff to streamflow, and channel flow resulting in an inflow hydrograph to a reservoir. If a reservoir routing model is included, the response of the reservoir level to the inflow event is determined, and can include operation of any gated outlets. If there are upstream reservoirs of significance, the watershed model would include representations of these reservoirs as well.

Section 1.1 discusses the difference between deterministic and probabilistic watershed modeling-based approaches. Both methodologies involve the development of rare to extreme storm meteorological inputs (the purpose of the BC MetPortal), the development of a watershed model to represent the watershed response to those meteorological inputs, and the development of initial conditions associated with the watershed. The specific meteorological inputs and initial condition inputs will differ depending upon the implemented approach as discussed in the sections below, but the same underlying watershed model can be used in both cases.

The following are some key elements that should be considered when developing a watershed model:

1. ***Watershed delineation, subdivision, and elevation zones***: The first step in modeling involves deciding upon the delineation and subdivision of the watershed. Watershed models may be classified as lumped, distributed, or semi-distributed. Lumped models characterize the hydrologic response of delineated sub-basins within a watershed using a single set of hydrologic parameters per sub-basin. Distributed models utilize a gridded representation of watersheds with unique computations performed for each grid cell, and semi-distributed models may sub-divide a watershed into many sub-areas (sub-basins) based on soil type, elevation range, or similar characteristics. The watershed response may be effectively characterized using any of these methods if applied appropriately. For watersheds less than 100 km^2 and a limited elevation range, the runoff response can often be adequately characterized using a single lumped watershed approach.

   For larger watersheds, and where there are notable differences in soil/runoff characteristics across the watershed, sub-basins should be considered for significant unique tributaries to represent differences in runoff response from each sub-basin. Elevation zones should be considered for sub-basins where elevation and snowpack vary sufficiently that it is necessary to account for differences in temperature and associated snowmelt response.
2. ***Snowmelt modeling***: The snowmelt response is an important factor affecting flooding for many watersheds. For basins with significant snow accumulation and melt, a model capable of simulating the major snow energy exchange processes should be used, but should rely solely on temperature (and precipitation) inputs because other meteorological inputs (radiation, similar) are

not available from the BC MetPortal for events. The temperature index snow model associated with the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software, the University of British Columbia (UBC) snow model, and the National Weather Service (NWS) snow accumulation and ablation model (SNOW-17) are all appropriate models.

3. ***Soil moisture modeling***: The infiltration rates during rare to extreme events will influence the resulting runoff response. Different hydrologic models represent infiltration in different ways. If fixed infiltration rates are employed, the expected differences in infiltration during common and rare to extreme events needs to be considered; typically, infiltration rates will be lower during high rainfall intensities as the soil zones become saturated.
4. ***Runoff to streamflow transform***: Different hydrologic models have different methods for translating a depth of runoff into flow at the outlet of a sub-basin or watershed, including simple unit hydrographs, quasi-distributed methods such as the ModClark transform in HEC-HMS, and 2D dynamic routing methods available in HEC-HMS. Potential differences in routing characteristics for extreme events should be considered. For instance, the USACE recommends increasing the peak of unit hydrographs by 25 to 50 percent when evaluating IDF events to account for the fact unit hydrographs are normally derived from historical events (USACE, 1991). Although dynamic routing methods are not typically employed, one advantage of these methods is that differences in runoff response between low and high flows will be implicitly represented. Dynamic methods become less practical for larger watersheds and for probabilistic methods due to the increases in computation time.
5. ***Channel routing***: For larger watersheds with longer river reaches (e.g., >25-30 km), hydrologic or hydraulic routing models will be required to translate flow from upstream to downstream locations. As river reaches become larger, the dynamic lag and attenuation effects become more pronounced. Some hydrologic routing methods can represent nonlinear behavior at higher flows, although parameterizing the methods can be more subjective, requiring judgment decisions to capture differences in response characteristics. By contrast hydraulic models rely on channel geometry to simulate flow lag and attenuation at higher flows. However, hydraulic models require more data (e.g., bathymetric information) and effort to develop. For smaller watersheds with shorter river reaches, the impacts of channel routing are minor compared to other modeling factors and meteorological inputs and basin transform methods may be employed to represent the translation of runoff depth to flow at the basin outlet.
6. ***Reservoir operations and routing***: Ultimately, when considering extreme flooding, the primary interest is in how the resulting IDF impacts reservoir levels. A reservoir model may be employed to simulate the operation of outlet structures over the course of an event and the attenuation of flow in the reservoir. Typically, level pool routing assumptions are adequate, but in some situations the slope of the reservoir surface introduces additional water storage. This can be represented using a hydraulic model (e.g., HEC-RAS), or with some alternative reservoir models (e.g., RiverWare). In cases with upstream reservoirs, these should be incorporated in the watershed model if the reservoir can store a significant amount of runoff or substantially attenuates flows for large events.

   One consideration when assessing the impact of extreme floods on reservoirs is the potential for inoperable outlet structures or debris blockage. When applying the IDF, scenarios should be included that assess gate outages or partial blockage of spillways by debris.

<u>Available Options</u>

Many hydrologic models and modeling systems are available to support development of IDF hydrographs. Two commonly applied systems are listed below along with some key features, although there are many others that may be employed

- ***HEC-HMS***: The HEC-HMS model includes a wide range of methods to simulate snowmelt, infiltration and runoff response, basin transform, and channel routing. HEC-HMS recently added the 2D diffusion wave model from the HEC River Analysis System (HEC-RAS) to simulate overland flow routing, though 1D hydraulic modeling is not possible using HEC-HMS; for larger rivers, if 1D hydraulic modeling is necessary, this would need to be modeled using a separate model such as HEC-RAS. The model currently includes a basic reservoir element; future versions of HEC-HMS will incorporate complex reservoir operations to further expand the modeling capabilities. HEC-HMS includes methods to represent uncertainty in parametric inputs (e.g., starting soil moisture states), and includes Bayesian Markov Chain Monte Carlo functionality to characterize model uncertainty if observed flows are available for model calibration.

- ***Raven***: The Raven hydrologic modeling system is another flexible modeling system. This includes a variety of model elements and includes emulating capabilities to replicate various commonly used continuous hydrologic models, including the UBC snow and soil moisture models.

Recommended minimum hydrologic analyses

The minimum hydrologic models required to simulate extreme events will vary depending upon the influence of snowmelt, size of watershed, and elevation range. For 100 km^2 watersheds and smaller, the recommended minimum hydrologic model components, when using the HEC-HMS or Raven framework, are as follows:

- Use a single lumped watershed approach. If elevation ranges in the watershed are significant and there is a marked change in snowmelt contribution with elevation, subdivide the watershed or sub-basin into unique elevation zones.
- Temperature index snowmelt model
- Deficit and Constant loss method
- Snyder, SCS or Clark unit hydrograph transform method (although the ModClark transform method allows for the use of either gridded or scalar precipitation inputs)
- For small watersheds, the selected baseflow method should have a minor impact on results (see note below)
- The reservoir routing available in HEC-HMS may be employed to simulate unregulated outlet structures and simulate reservoir routing effects. If gated operations need to be modeled, an alternative method currently would need to be employed (though the HEC plans to add complex reservoir operations to HEC-HMS in the near future).

Experience

- ***Model calibration***: If historical flow observations are available at the site (either from a stream gage or back-calculated reservoir inflows), these data should be used to calibrate the watershed model . The performance evaluation should focus on the largest historical events and should include evaluation of performance for multiple events for event-based watershed models.
- ***Uncertainty of meteorological data for watershed model calibration***: Historical meteorological data (most commonly precipitation and temperature) are typically developed using meteorological station data. Through the calibration process, recognize that uncertainties in the meteorological inputs are often a driving source of uncertainty in calibration of the watershed model, particularly in data-sparse areas. When adjusting model parameters, consider whether precipitation or temperature data errors may be causing an event to be over- or under-simulated to avoid distorting model parameters to unreasonable values.
- ***Ungaged locations***: For locations without observed flow data, the hydrologic model development will rely more heavily on underlying watershed characteristics. The NRCS TR55 methodology may be employed to determine initial time of concentration estimates for small watersheds and loss rates set to a minimum for the underlying soil group (NRCS, 1986). The runoff response can

also be assessed by comparing the watershed-generated peak flows and flow volumes to hydrographs from nearby watersheds scaled to the same basin area, or to peaks and volumes derived from regional regression solutions (NHC, 2020).

- ***Most influential parameters***: When simulating rare to extreme events, the most influential model parameters controlling the watershed response are those affecting the transform of runoff to streamflow, channel routing, and infiltration rate. Parameters determining snowmelt response are also often sensitive. Particular care should be given to determining these parameters.
- ***Adjustments for more extreme events, sensitivity tests, and reasonableness checks***: Consider uncertainties in how a watershed would respond to storms larger than those used for model calibration. Basic sensitivity tests should be applied to assess the influence of those parameters that are expected to be most influential. If parameters are sensitive, this should be noted, and somewhat conservative parameters should be employed to evaluate results. The 100-year (1:100 AEP) or 200-year (1:200 AEP) peak flows/volumes may be compared to peak flows/volumes derived from regional regression solutions for reasonableness and to confirm that any parameter adjustments are not overly conservative (or under-conservative).
- **Baseflow mass balance:** If the “ratio to peak” baseflow method is used in the hydrologic model it may be amplified during the PMF event since it is based on a ratio of the hydrograph peak for the sub basin. In these cases, the baseflow volume produced for the event will be greater than the precipitation volume that infiltrates into the ground. The baseflow ratio may need to be adjusted so that proper mass balance is achieved between the infiltration and baseflow.

3 Meteorological Data from MetPortal for Watershed Modeling

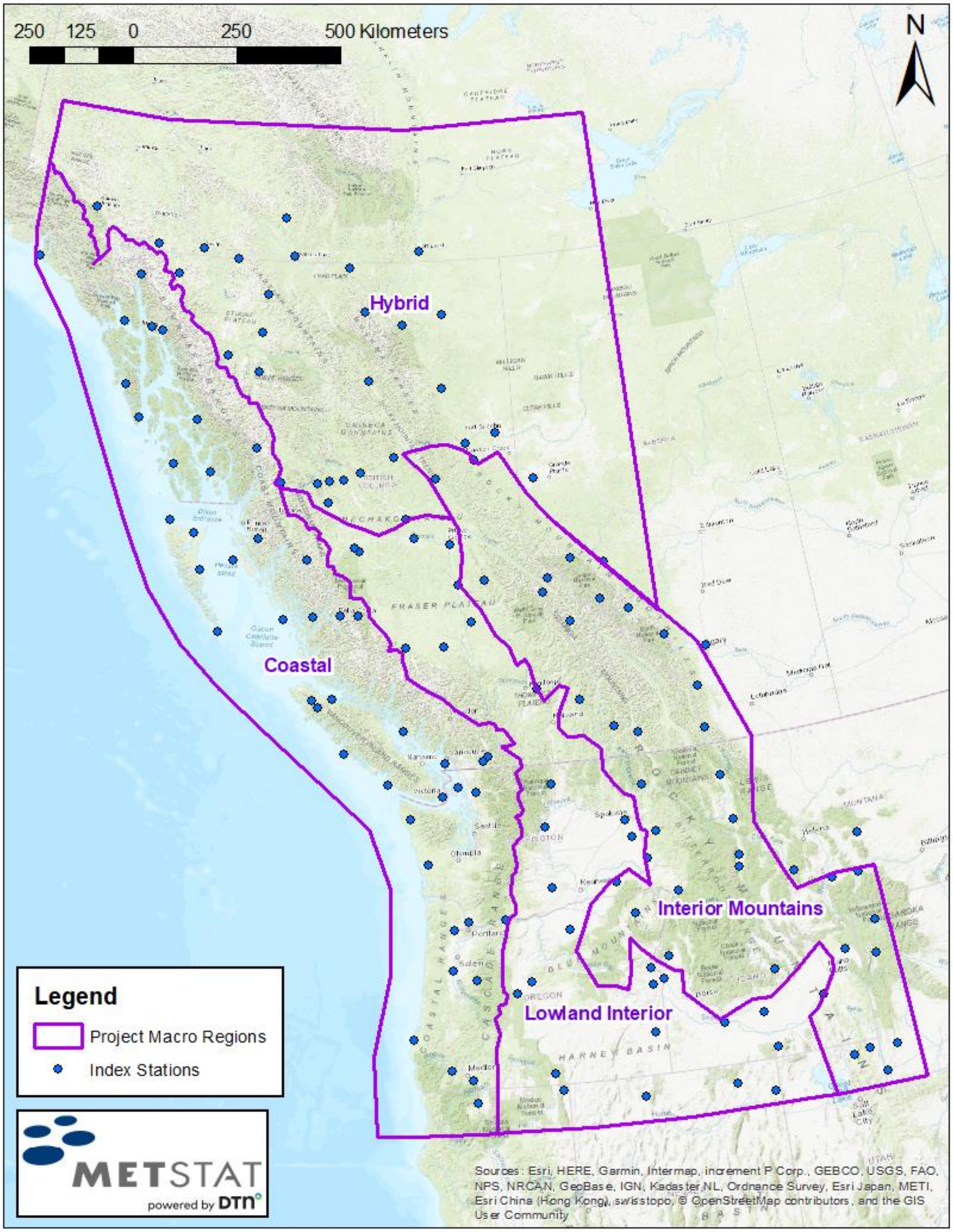
Purpose

The BC MetPortal provides regionally consistent estimates of key meteorological inputs needed to compute IDFs and PMFs for dams. The BC MetPortal provides key outputs at regularly-spaced points over the entire BC province (see references in Section 1.4 for additional detail on the datasets and data access). Datasets available from the BC MetPortal include:

1. ***PMP-related datasets***: At each grid point, the BC MetPortal provides PMP estimates for the controlling storm and second-largest storm, recognizing that different storm depths and temporal patterns can result in different estimates of the PMF hydrograph. The user can select between four durations (24, 48, 72, and 96-hour), select a location, and select a season of interest. The tool outputs:
    a. ***PMP depths*** for 10 km^2, 100 km^2, 1,000 km^2, and 10,000 km^2 watersheds for the PMP and the secondary storm. Note that different historical storms may control for different area sizes.
    b. ***Seasonally adjusted depths***, applying a simple scaling factor to reduce the PMP depth for months when atmospheric conditions are deemed to produce a storm that is some percentage of the PMP. Seasonal adjustment factors are defined based on four climate macro regions across the province (see Figure 2 and Table 4).
    c. ***Storm Data***: The PMP depths for different durations, watershed sizes, and locations result from different storms. The BC MetPortal allows the user to download the underlying storm data associated with each PMP event, including:
        i. ***Gridded time series*** of precipitation corresponding to the PMP and secondary PMP events transposed to the selected grid point for specified durations and watershed sizes. Note that maximization factors have been applied to these storms.

    ii. ***Temperature time series*** associated with the controlling/secondary PMP storm in the form of 1000-mb (sea level) temperature and freezing level height. Note these are temperatures associated with the *original* storm and have not been increased to reflect PMP conditions.

d. ***Scaling factors for uncertainty***: The underlying analysis used to develop PMP focused on determining the PMP based on large regional storms. A separate analysis was conducted to assess uncertainty in PMP based on uncertainty in the primary inputs to the PMP process (see Chapter 11 of the BC MetPortal Technical Report [DTN and MGS Engineering, 2020b]). The analysis concluded that uncertainties in inputs used to derive the PMP would generally result in higher PMP estimates than those determined using the standard procedures employed by MetPortal, and as such yield substantially higher PMP values. 5th, median, and 95th percentile scaling factors are available in the BC MetPortal user guide for the four macro regions in BC (Table 5).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 2. BC MetPortal macro climate regions (from DTN and MGS Engineering, 2020b)

Table 4. Seasonal PMP scaling factors
(adopted from Table 9 of the Technical Report [DTN and MGS Engineering, 2020b])

Date	Coastal North	Coastal South	Lowland Interior	Interior Mountains	Hybrid
1/1	100%	100%	100%		
1/15	100%	100%	100%		
2/1	100%	100%	100%		
2/15	**95%**	100%	100%		
3/1	**85%**	**95%**	100%		
3/15	**80%**	**85%**	**85%**		
4/1	**75%**	**80%**	**75%**	**60%**	
4/15		**75%**	**80%**	**75%**	
5/1			100%	**85%**	**70%**
5/15			100%	100%	**75%**
6/1			100%	100%	100%
6/15	**60%**		100%	100%	100%
7/1	**65%**	**60%**	100%	100%	100%
7/15	**70%**	**65%**	100%	100%	100%
8/1	**75%**	**70%**	100%	**85%**	100%
8/15	**80%**	**75%**	100%	**85%**	100%
9/1	**95%**	**80%**	**90%**	**85%**	**95%**
9/15	100%	**95%**	**85%**	**90%**	**90%**
10/1	100%	100%	**85%**	**95%**	**95%**
10/15	100%	100%	**90%**	**95%**	100%
11/1	100%	100%	100%		
11/15	100%	100%	100%		
12/1	100%	100%	100%		
12/15	100%	100%	100%		

Table 5. PMP uncertainty scaling factors (from DTN and MGS Engineering, 2020b)

Project Macro Region	5th Percentile	Median	95th Percentile
Coastal	1.056	1.265	1.528
Lowland Interior	1.027	1.237	1.493
Interior Mountains	1.023	1.236	1.494
Hybrid	1.030	1.332	1.727

2. ***Precipitation-frequency related datasets***: The BC MetPortal also provides probabilistic meteorological inputs, including:
    a. ***Maps of precipitation depths*** at specific AEPs

b. ***Precipitation-frequency relationships*** and uncertainty bounds associated with 24, 48, 72, and 96-hour durations for the Mid-Latitude Cyclone (MLC) storm type in tabular form. The precipitation-frequency relationships are associated with ***point*** precipitation (in contrast to precipitation-frequency associated with different watershed sizes).

c. ***Temporal patterns*** for multiple storms (3 to 6 per macro region) based on historical storms and representing front, center, and back-loaded storms. The tool will scale the precipitation to a selected AEP storm (e.g., 1000y storm) such that the depth over the selected duration equals the best estimate depth for that AEP/storm duration. Gridded storm patterns are not available for use with the precipitation-frequency information, although Section 5.1 discusses how to introduce spatial variability for watersheds.

d. ***Temperature time series*** associated with each of the storm patterns in the form of 1000-mb (sea level) temperature and freezing level time series. Note that temperature time series are only available from the *Download MetStorm Reports* tab in BC MetPortal via the *Select Temperature Pattern to Download* pull-down menu.

e. ***Storm seasonality*** relationships in the form of Probability Density Functions depicting the likelihood of storms occurring in different half-month periods in a year. These are available in the precipitation-frequency technical report (DTN and MGS Engineering, 2020c).

The datasets may be used to create time series of precipitation and temperature corresponding to the PMP or to a storm of a particular frequency, as discussed in Sections 5.1 and 8.1.

Experience

- **Diversity of storms**: Storms naturally have a wide range of spatial/temporal characteristics, and this natural variability can produce varied runoff responses. For both evaluation of the PMF and evaluation of 100-year (1:100 AEP) to 1000-year (1:1000 AEP) storms, analysts should consider multiple storm patterns.
    - **PMP**: For a given location and watershed size, different transposed storms could produce the PMP for different durations. The underlying gridded PMP data may be accessed for each storm. Note that the gridded storm patterns associated with the PMP reflect underlying topographic and orographic effects and should not be spatially shifted to align with the watershed of interest (see King and Micovic [2022] for additional discussion).
    - **Storm patterns for frequency-based storms**: BC MetPortal provides a select set of front, center, and back-loaded temporal patterns that can be used to evaluate differences in storm timing. The temporal patterns from these storms are available for download from the tool.
    - **Importance of storm intensity versus volume**: The storm patterns from BC MetPortal reflect true historical storms. For smaller reservoirs and reservoirs located on smaller watersheds, shorter, higher-intensity storms generally will produce the highest flood peaks with the greatest impact on the reservoir. In contrast, volume-driven storm patterns tend to produce higher peaks for large watersheds or large reservoirs.
- **Areal reduction factors for precipitation-frequency relationships**: The precipitation-frequency relationships included in BC MetPortal represent ***point*** precipitation-frequency as opposed to the precipitation-frequency for different watershed sizes. As the watershed size increases, the watershed averaged precipitation depth that can be produced at a given AEP over the watershed will decrease. The reduction in precipitation-frequency will be non-linear in nature, typically with larger reductions for rarer precipitation events. Section 5.1 discusses how to translate point precipitation frequency information into watershed-average precipitation frequency estimates.

- **Convective storms**: The BC MetPortal was developed focusing on large-scale mid-latitude cyclones and currently does not include data to support the analysis of small, convective storms. For small watersheds, convective storms may be a significant contributor to flood risk for inland areas. To understand this risk, analysts would need to collect short-interval (hourly and shorter) precipitation data from the nearest airport precipitation gages (or similar). As a starting point, the annual maximum hourly precipitation totals may be assessed to determine the seasonality of short-duration precipitation events. The largest events should be reviewed to determine if these appear to be isolated, short-duration events in summer months (indicating possible convective events) versus a part of larger-scale storms. Lightning strike data may also be used to assess the prevalence of convective events. If convective storms appear to be important, the analyst would need to perform a regional frequency analysis on an hourly or 2-hour basis to assess low frequency events (100 year to 1000 year). The resulting depths could be used to compare the resulting flood response from these events to those produced by the longer-duration events that are provided as a part of MetPortal.

4 Estimation of 100-year Flood (Low Failure Consequence)

Purpose

Determine the 100-year flood inflow using a regional flood frequency analysis approach (observed flood-frequency curve) and determine the corresponding reservoir stage that would be produced given this inflow rate and volume. Estimation of the flood event using only hydrometric data (i.e., observed streamflow or reservoir data) is less time consuming than developing rainfall-runoff and snowmelt models, and in most regions of BC will provide defensible results for a 100-year return interval flood.

An observed flood-frequency curve is also useful for calibration of rainfall-runoff and snowmelt models. The 100-year flood event represents the flood magnitude with a 1 in 100 ARI, regardless of the mechanism causing the event, and should reflect the true natural variability of conditions causing the event. That is, the flood event may be caused by rainfall, snowmelt, or a combination of factors and also incorporates the unique characteristics of the watershed into the analysis. CO SEO (2022) provides information on using observed flood-frequency curves for the calibration of models.

Available Options

If sufficient hydrometric data is available in the region, determine the IDF using only hydrometric data. There are different approaches available for completing a regional flood frequency analysis. Two common methods used in BC are the Index Flood (IF) method (also called the peak-flow method) and the Regional Regression Equations (RRE) method (also referred to as the direct quantile regression and the multiple regression method). For details of the methods see for example CDA (2007), Viessman and Lewis (1996), and Watt et al. (1989).

The BC Ministry of Environment and Climate Change Strategy provide streamflow inventory studies for all regions of the province. An ArcGIS map with links to the reports and data sheets, can be accessed at the BC Data Catalogue or by using the following url:

https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=9ac7f138fcf9437b90d3304f7eff600c.

The reports provide streamflow statistics, watershed area and median elevation, and regional flood quantile-watershed area plots for active and discontinued Water Survey of Canada (WSC) hydrometric stations in BC. Flood frequency analysis of single hydrometric station data was completed using the annual maximum **instantaneous** discharge values. The peak flow frequency analysis results are summarized by return period as a ratio to the 10-year return period peak flow, thereby presenting the data in a suitable form to be utilized with the IF method. The reports provide a frequency analysis of all hydrometric stations **without regard for natural or regulated streamflow status** or other factors that may require close scrutiny of the data when incorporating the information into a study.

The BC Ministry of Forests initiated a regional flood frequency analysis study using the RRE method (NHC, 2021). Single station frequency analysis was completed for selected hydrometric stations in BC and the surrounding province, territories, and states that met the study **natural flow definition**. Flood frequency analysis of single hydrometric station data was completed using the annual **daily** maximum discharge values. The gauge reports for each hydrometric station analyzed include several physical and hydroclimatic characteristics of the respective watersheds. Regional flood quantile equations were developed using the RRE method. Regional analysis procedures were proposed using different available information for determining homogeneous regions.

Alternative methods include the development of a rainfall-runoff model and snowmelt model used in combination with storm and temperature information taken from the BC MetPortal. Depending on the end use of the study, construction of models can provide complementary information to increase confidence in estimates.

Recommended Minimum Hydrologic Analyses

Apply regional regression relationships found in NHC (2021) if available for the region, to determine flood peak flow estimates as well as some type of check on the validity of the results.

For small reservoirs, spillways can be sized to pass the 100-year inflow flood peak without consideration of routing effects through the reservoir. If flood attenuation from reservoir storage is considered important, a flood hydrograph will be needed for reservoir routing. A flood hydrograph can be obtained either from scaling a historical gauged flood from a hydrologically similar watershed to meet flood peak and volume targets or watershed modeling can be conducted. Reservoir routing can then be conducted for sizing of the spillway(s).

Experience

Regional flood frequency analysis methods generally provide defensible estimates of flood quantiles but must be used with caution in BC as the province has considerable variety of climate, topography, and landcover.

Use of two different methods to estimate the peak flow will increase confidence in the final design. Examples of two different methods to estimate the 100-year flood in NHC (2021) include use of Table 2-19 and drainage area scaling (Section 2.2.7).

Hydrologists need to be aware of the limitations of any analysis completed by others when incorporating it into a design. For example, the number of years of data used to estimate a flood quantile, the suitability of the data for frequency analysis, presence of data gaps, etc.

5 Estimation of 100-year to 1000-year Floods (Significant Failure Consequence)

Purpose

Determine reservoir inflow floods in the range of 100-year to 1000-year ARI and corresponding maximum reservoir stage that would be produced given these inflows.

Flood magnitudes in the range of 100-year (1:100 AEP) to 1000-year (1:1000 AEP) are used for sizing spillways for dams in the significant consequence classification. The 1000-year flood hydrograph is also used as a component in computing an IDF for a dam in the high and very-high consequence classification and is discussed in Section 6.

Available options

Inflow Design Flood of 100-year to 200-year ARI: Several flood-frequency methods may be used when the 100-year or 200-year inflow flood is the design target. In some cases, streamflow data may be available for the watershed/dam of interest and conventional statistical flood-frequency analysis may be employed. More commonly, streamflow data are not available for a given dam. In this case, flood-frequency information can be obtained from NHC (2021) using either regional regression equations or from transposition methods using a nearby watershed with streamflow records that is hydrologically similar to the watershed of interest.

Flood-frequency information for the flood peak can be adequate for spillway sizing when the reservoir volume is relatively small and little flood attenuation is anticipated during the IDF. Conversely, when flood attenuation by reservoir storage is to be considered, an inflow flood hydrograph is needed to conduct reservoir routing and confirm spillway adequacy.

Inflow Design Flood of 200-year to 1000-year ARI: Flood magnitudes rarer that 200-year ARI may be assessed based on conventional statistical flood-frequency analysis if adequate streamflow data are available, but otherwise will require execution of a watershed model along with rainfall-runoff modeling to develop an inflow flood hydrograph. An inflow flood hydrograph will be required to develop the 1000-year (1:1000 AEP) flood for use with the high and very-high consequence classes. Both deterministic and probabilistic watershed modeling approaches can be used (Section 1.1) to produce reservoir inflow hydrographs. The Simplified SEFM approach (Schaefer and Barker, 2019) provides several simplifications for watershed modeling that allows for some natural variability to be considered.

Conventional flood-frequency analysis may also be employed to assess 200-year to 1000-year ARI inflow volumes if historical streamflow data are available for a given watershed/dam. The Risk Management Center Reservoir Frequency Analysis (RMC-RFA) software developed by the US Army Corps of Engineers (USACE) may then be used to assess the combined impact of inflow volume, inflow shape, and starting pool elevations on the resulting headwater frequency for dams with a significant consequence classification (Smith et al., 2018; RMC, n.d.). This stochastic model uses a combination of an inflow volume-frequency relationship, representative flood hydrograph shapes, and representative starting pool elevation data to develop HHCs for maximum reservoir stage and reservoir discharge. It is a practical choice when 50 years or more of streamflow data are available for a given watershed/dam.

Recommended Minimum hydrologic analyses

Conventional statistical flood-frequency analysis may be used for IDF design targets in the range of the 100-year to 200-year ARI for dams in the significant consequence classification. When the design target IDF is rarer than 200-year ARI (1:200 AEP) and insufficient streamflow data are available to complete a flow-based analysis, watershed modeling is needed and a deterministic approach using an AEP Neutral approach (Section 5.2) would be the simplest approach to obtain the target IDF. Stochastic modeling with consideration of flood sensitivities to meteorological inputs (Section 5.3) of a Simplified SEFM approach would provide increased confidence in achieving the design target AEP by assessing the flood response for plausible combinations of the meteorological inputs.

Details for selection of IDF

Watershed modeling of all temporal storm patterns from MetPortal should be conducted in the process of selecting the IDF for the target AEP whether using a deterministic or stochastic watershed model. The IDF hydrograph chosen should be the flood hydrograph that best replicates the mean of the flood peaks and flood volumes from the flood simulations.

In addition, the sensitivity of the flood peak, volume, timing and flood hydrograph shape should be examined with some level of sensitivity analysis. Aspects of sensitivity analyses are discussed in Section 5.3.

5.1 Meteorological Inputs for Watershed Modeling

Purpose

Information is needed for the meteorological inputs needed for deterministic and stochastic watershed modeling of floods. Identifying the range and typical values of meteorological variables is important for understanding the seasonal flood response of the watershed to various storm magnitudes and various antecedent watershed conditions.

Available options and details for obtaining meteorological inputs

Meteorological inputs are described in the following subsections.

Watershed precipitation magnitude for 48-hour duration

For small watersheds less than 10-km^2, the best-estimate watershed precipitation frequency can be taken as point precipitation frequency and obtained directly from the MetPortal using the geographical coordinates of the watershed centroid. For larger watersheds, the recommended approach is to download the gridded 48-hour precipitation datasets from the MetPortal and intersect the watershed shape file with the gridded precipitation field to obtain areal-average point precipitation. The resulting areal-average point precipitation should then be multiplied by the areal-average point quantile estimates for the watershed by the precipitation frequency Areal Reduction Factor (PF-ARF) for the MLC storm type (Figure 3) to produce the watershed precipitation frequency relationship (Figure 4). The same process should be repeated to obtain the 90% uncertainty bounds for the best-estimate watershed precipitation frequency relationship (Figure 5).

The 90% uncertainty bounds depicted in Figure 3 for the PF-ARF would be used if an uncertainty analysis were to be conducted usually for the case where a detailed probabilistic approach was used for a RIDM process. The PF-ARF uncertainty bounds could also be used as part of a sensitivity analysis for use with either a deterministic or stochastic watershed modeling approach.

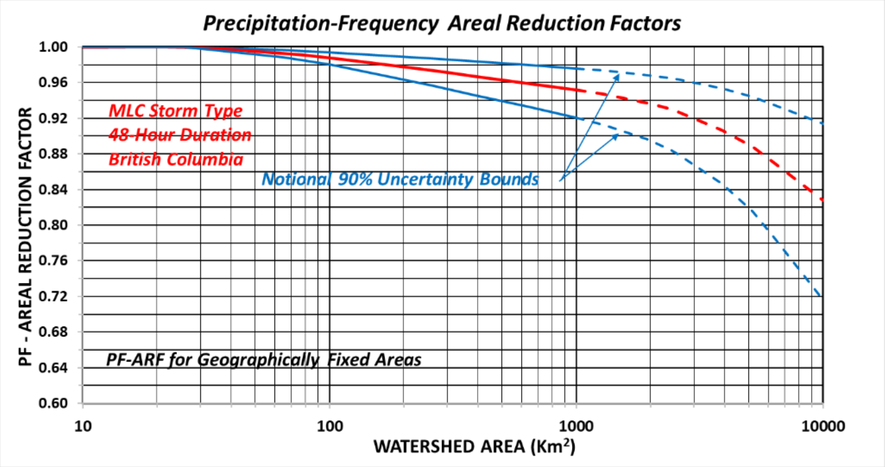


Figure 3. PF-ARFs for geographically fixed areas for the MLC storm type and 48-hour duration

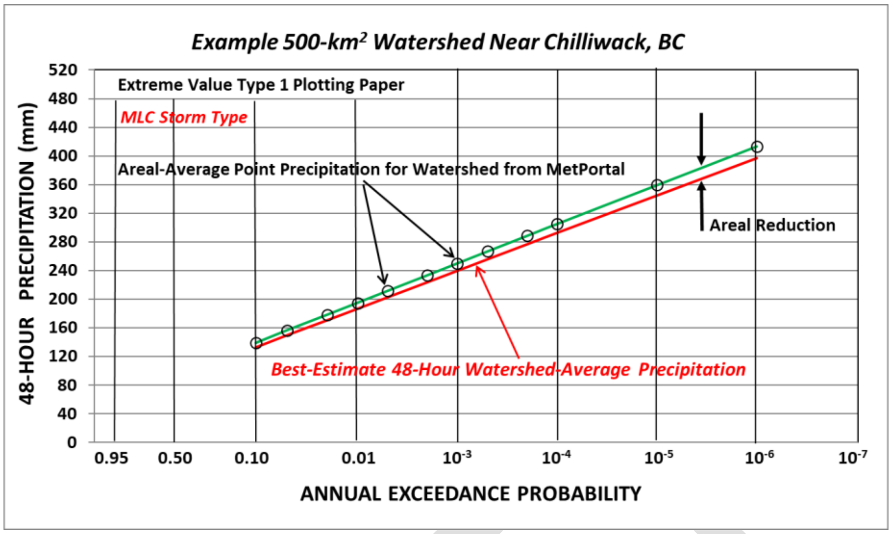


Figure 4. Application of PF-ARF to 48-hour areal-average point precipitation for a 500-km^2 watershed near Chilliwack BC to produce the areal-average watershed frequency relationship for the MLC storm type

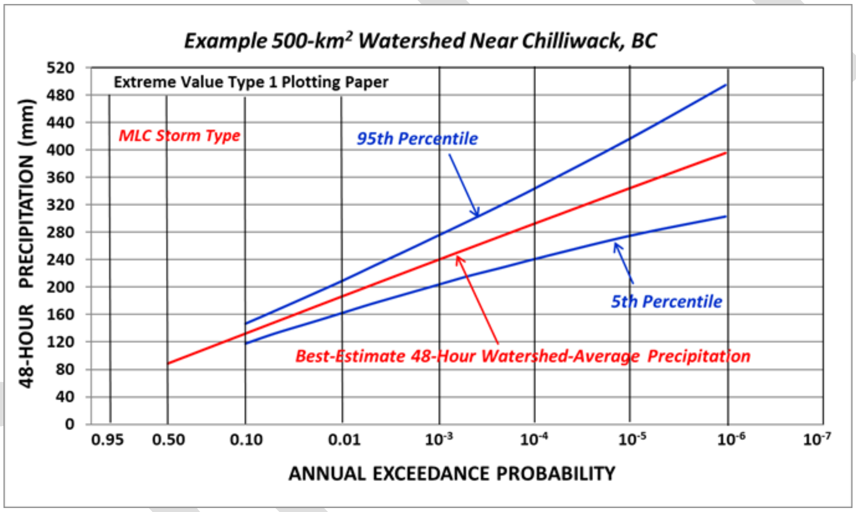


Figure 5. Watershed 48-hour precipitation-frequency relationship and 90% uncertainty bounds for the MLC storm type for a 500-km^2 watershed near Chilliwack, BC

Storm temporal patterns

Storm temporal patterns representative of a user-identified location can be obtained directly from the MetPortal. There are suites of noteworthy storms in the MetPortal. The MetPortal has functionality to automatically scale a temporal pattern to have the 48-hour precipitation for the user-specified AEP. The hourly time series of both incremental precipitation and mass-curve precipitation can be downloaded directly in csv file format for input into a watershed model. An example of a scaled temporal pattern is shown in Figure 6 for the watershed near Chilliwack BC, where the maximum 48-hour precipitation occurs from hours 22 through 69.

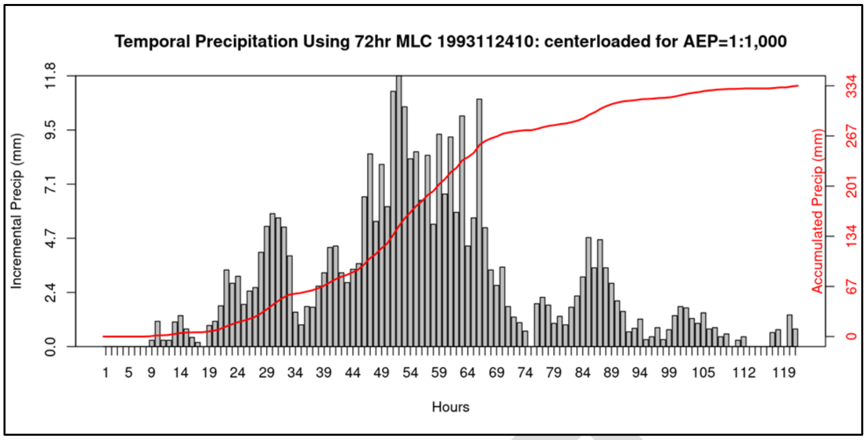


Figure 6. Temporal pattern for November 24-28, 1993 storm scaled to contain 1:1000 AEP areal-average 48-hour precipitation for watershed near Chilliwack, BC

<u>Storm spatial patterns</u>

Storm spatial patterns are not usually needed for watersheds with an area less than 100-km^2, which is the focus of these guidelines. Areal-average precipitation can be used for these watersheds. For larger watersheds, or if a spatial pattern is desired, the watershed shape file may be intersected with the gridded 48-hour precipitation field for a 1:10 AEP. This will provide a spatial pattern for the subbasins which would then be normalized to yield subbasin adjustment factors that would aggregate to an areal-average of 1.00 for the watershed. The subbasin adjustment factors would then be used to rescale the temporal storm pattern so that each subbasin would have the appropriate 48-hour precipitation. This approach does not address variation in the sub-basin temporal storm patterns which reflect storm movement. Variation in storm temporal patterns would be considered in detailed flood analyses for much larger watersheds.

<u>Storm seasonality</u>

Storm seasonality for the MLC storm type was analyzed as part of the precipitation frequency study for British Columbia. Storm seasonality histograms may be obtained directly from Figures 6-9 in the BC_RPFA Technical Report. Figure 7 depicts the seasonality of 72-hour maxima which exceeded a 10-year ARI for a collection of long-term, widely separated stations, in the Coastal region. The use of 72-hour duration and a 10-year ARI effectively constrained the data to MLC storms. This histogram is for the entire Coastal Region and some shifting of seasonality into the late summer and early-fall can be expected for the most northerly coastal areas.

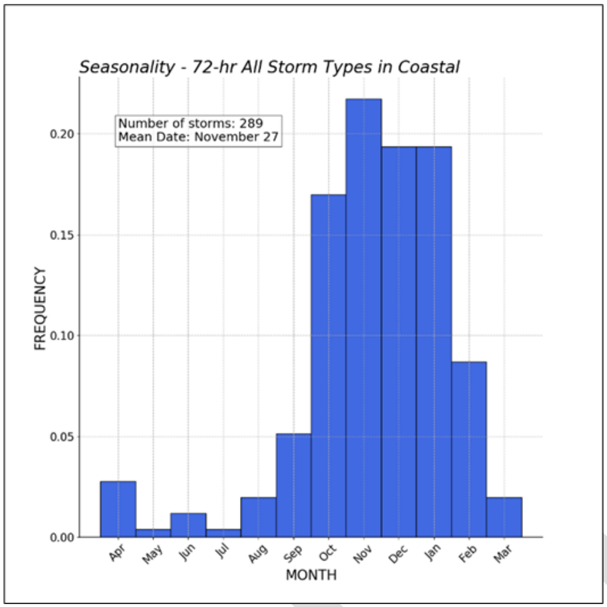


Figure 7. Seasonality of MLC storms in the coastal region of BC

<u>Air temperatures and freezing levels to accompany storms</u>

1000-mb air temperature (°C) and freezing level height (meters) hourly time series are available for 44 storms contained within the MetPortal and are graphically presented in downloadable S*torm Reports (e.g.,* Figure 8). The hourly 1000-mb (near sea-level) and freezing level height time series are downloadable in digital format in csv file format for use with the temporal patterns selected for watershed modeling.

Air temperature time series can be developed for various elevation bands in the watershed model by linear interpolation between the 1000-mb air temperature (nominal elevation of zero) and the freezing level elevation for each timestep. The historical air temperature and freezing level height time series can generally be used as observed for watershed modeling for the 100-year and 200-year ARI floods. For floods rarer than 200-year ARI, the 1000-mb air temperature and freezing level height time series should be scaled upward. This is done recognizing that higher levels of atmospheric moisture are needed to support larger precipitation magnitudes and warmer atmospheres are needed to support higher levels of atmospheric moisture. Scaling of these time series for different 1000-mb air temperature and freezing level heights can be done by simple addition. A constant temperature (°C) can be added to the 1000-mb time series and a constant elevation (m) can be added for the freezing level height time series. Selection of the increase in 1000-mb air temperature and freezing level height is discussed in Section 6.

The freezing level time series should be checked to confirm that precipitation is falling as rain throughout the majority of the storm event. Many of the temporal patterns are associated with cold-front passage near the end of the storm which can result in snowfall at higher elevations in mountainous terrain. The watershed model results should be checked to confirm the freezing level is sufficiently high to produce rainfall throughout the majority of the storm event. The freezing level may be scaled higher to produce rainfall and not snowfall. Where appropriate, meteorologists should be consulted to obtain advice on adjustments to observed air temperature and freezing level height time series.

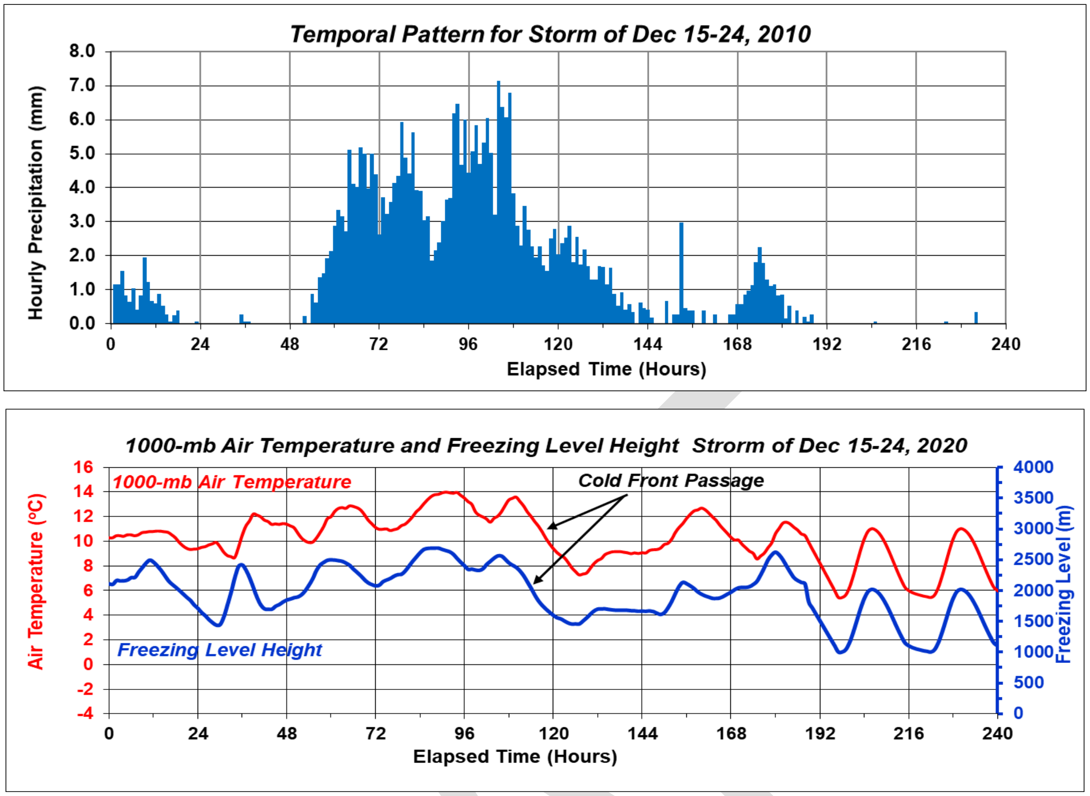


Figure 8. Storm temporal pattern and 1000-mb air temperature and freezing level height for a December 15-24, 2010 storm on the west coast of the US

Available options and details for developing initial conditions

In addition to the characteristics of storms, the initial conditions of the watershed (reflecting the effects of snow accumulation, melt, and previous storms) can have a significant impact on the resulting flood from a storm event. These initial conditions are discussed in the following subsections.

Flood seasonality

Flood seasonality can also be used to inform the choice of storm seasonality for watershed modeling. The dates of major floods can be examined for stream gaging sites in the same climatic region as the watershed of interest. This information will assist in identification of flood types of concern, whether primarily rainfall-driven floods, rain-on-snow floods, and floods during the spring snowmelt season.

Seasonal snowpack

The seasonal variation of snowpack in the watershed can be assessed using conventional frequency analysis for snowpack data obtained from nearby snow-courses. The Log-Normal and Gumbel probability distributions have commonly been found to provide a reasonable fit to snow-water equivalent (SWE) data. It may be necessary to use a mixed distribution for some lower elevation sites, particularly in the early winter months when the ground may be snow-free during some climatic years. The mixing parameter in the mixed distribution accounts for the fraction of time the ground is snow-free in a given month. Some low elevation sites may not have snow course data available, and the best option is to obtain snow-on-ground data from Environment Canada precipitation measurement stations and then make adjustments to convert to SWE. Typical values of snowpack (SWE) are of interest for use with the deterministic AEP Neutral approach (Section 5.2), whereas a broader range of SWE values are needed if a simplified stochastic flood modeling approach is to be used (Section 5.2).

Seasonal soil moisture

The seasonal variation of soil moisture can be assessed by conducting a monthly water budget for soils in the watershed using the soil moisture storage capacity of the soils, and monthly precipitation and evapotranspiration for a range of dry, normal and wet climatic years. The soil moisture budget can also assist in identifying transition periods when soils are wetting up or drying out and when floods are more likely because soils are in the wettest state. This information can help inform the choice of the months of the year for conducting flood simulations and selecting representative values of soil moisture, snowpack, and for scaling of air temperature time series for snowmelt computation.

Initial streamflow for reservoir inflow

Streamflow inflow to the reservoir is needed as an input to the watershed model. Streamflow magnitudes vary seasonally and provide the baseflow upon which flood flows reside. Representative monthly streamflow magnitudes can be obtained either from nearby streamflow gaging stations or from streamflow records for hydrologically similar watersheds in the region. Some scaling for differences in watershed area and climatic differences may be required to produce representative monthly streamflow rates.

Initial reservoir levels

Information of reservoir levels is needed for setting the initial reservoir level for starting reservoir routing of floods. Historical records of reservoir level on a daily or sub-daily basis are often available and can be used to compute summary statistics for mean, median, and various percentiles for reservoir level on a monthly basis (e.g., Figure 9). It is anticipated that many of the small reservoirs in BC will not have systematic records available for historical reservoir level. In these cases, anecdotal information and intermittent records of particularly low or high reservoir levels may be of value in determining representative reservoir levels on a monthly basis or conservative estimates of monthly reservoir levels.

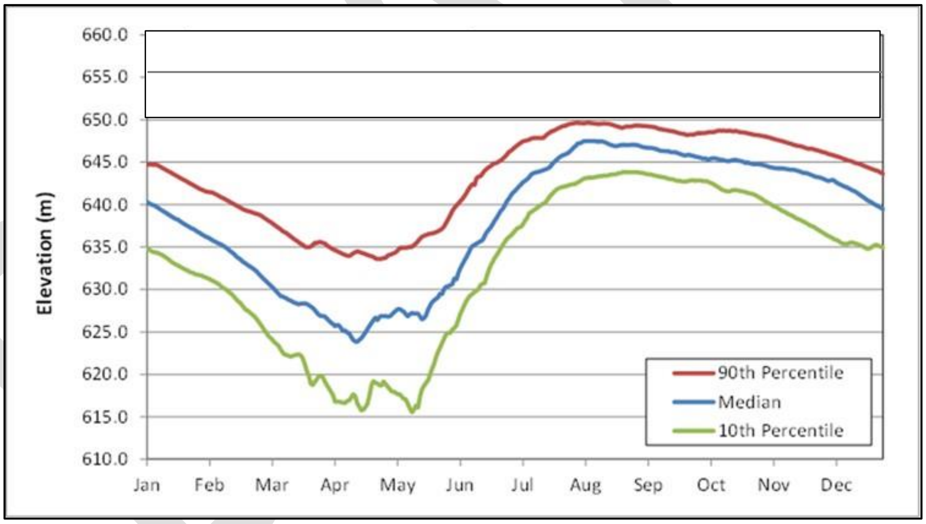


Figure 9. Example of median and 10th and 90th percentiles for monthly reservoir level

5.2 AEP Neutral Approach

Purpose

The AEP Neutral concept strives to generate a 1:N AEP flood using a 1:N AEP storm. Emphasis is usually placed on the flood peak in matching AEPs. However, for dam safety applications, a flood hydrograph is usually needed for flood routing and spillway sizing. Ideally, the flood hydrograph generated from watershed modeling would meet what Cudworth (1989) termed a *balanced hydrograph* where the volume of the flood hydrograph at various durations would also have a frequency of 1:N AEP.

In reality, both storms and floods are multi-dimensional with various combinations of peaks, volumes and temporal shapes (hyetographs and hydrographs). As such, the AEPs for individual storm and flood characteristics differ for a given storm/flood and the 1:N AEP labeling for a storm/flood varies depending on what characteristic is being emphasized. Nonetheless, it is still common practice in the engineering and lay communities to label a flood based solely on the ARI of the flood peak.

In short, AEP Neutral is a convenient and useful engineering concept that is challenging to achieve in practice and rarely occurs in nature.

Experience

The challenges of implementing an AEP Neutral approach can be envisioned by considering the manner in which floods are produced in nature and the manner in which flood probabilities are computed.

Flood characteristics of flood peak, volume and hydrograph shape are determined by a large number of meteorological variables that can vary seasonally, spatially and temporally and by storm type. This includes:

- Magnitude, spatial and temporal characteristics of the storm for a given storm type
- Seasonality of storm occurrence
- Soil moisture conditions at the time of storm occurrence that can vary spatially by elevation, soil type and ground cover (monthly precipitation and evapotranspiration vary with elevation)
- Air temperatures and freezing level during storms for generating snowmelt that vary seasonally
- Snowpack magnitude that varies seasonally and with wet-dry-normal climatic years

Flood-frequencies for peaks and volumes are typically computed from an annual maxima series where the dataset is comprised of the largest flood peak, or volume (for a given duration) for each year. The flood maxima are chosen from several rainfall-runoff events that occur each year that were produced by the mix of meteorological conditions that generated the floods. For example, similar flood peak magnitudes can be produced by a rare storm on dry watershed conditions and a more common storm on wet watershed conditions. The assembled datasets and estimated flood probabilities therefore represent a wide variety of combinations of the meteorological conditions that generated the floods.

Recognizing the large number of variables and the effect on flood magnitude (Section 5.1), it is difficult to a priori choose the combination of meteorological inputs that would achieve AEP Neutrality.

Available options

Deterministic Watershed Modeling: Past standard practice for deterministic watershed modeling has been to use conservative values of meteorological inputs for design applications. The CDA Guidelines have frequency-based design targets for dams in the significant consequence classification. The frequency-based design targets lead to the need for a watershed modeling approach that strives to achieve the AEP for the design targets.

The recommended approach for deterministic flood modeling is to use the AEP Neutral approach where typical values of the meteorological variables are used as inputs to the watershed model. Typical values of meteorological variables would be selected from the central body of historical data as represented by mean and median values. Conservatism can be imparted, if desired, by selecting values of the meteorological inputs that are more conductive to flood generation than median or mean values. The flood outputs from the watershed model for peaks and volumes can be compared with regional flood-frequency information from NHC (2021) to confirm the reasonableness of the proposed IDF.

Stochastic Watershed Modeling: The discussion above highlights the challenges in choosing the combination of meteorological values to meet CDA frequency-based design targets. The alternative to deterministic flood modeling is to explicitly consider the natural variability in the meteorological inputs and to evaluate the floods produced by plausible combinations of the meteorological inputs. This can be done in several ways including:

- evaluating flood sensitivities to various meteorological variables (Section 5.3);
- conducting flood simulations with various combinations of the dominant meteorological inputs (Simplified SEFM approach); and
- developing a detailed stochastic flood model to comprehensively incorporate the natural variability of the meteorological variables and to develop HHCs.

The first two options are practical for dams in the significant consequence classification, whereas the third option would be appropriate where a detailed risk analysis is proposed, leading to a RIDM process.

Details for Stochastic Watershed Modeling

Stochastic watershed modeling provides a flexible approach to assessing flood sensitivity to plausible combinations of the meteorological inputs. The basic idea using the Simplified SEFM approach is to use the target areal-average best-estimate 48-hour storm magnitude for the watershed obtained from the MetPortal and create input datasets for plausible combinations of selected meteorological inputs. Flood simulations would be conducted for each of the input datasets and the flood outputs would be analyzed to obtain mean estimates for flood peak and runoff volume. If reservoir routing is included in the watershed model, a mean value for the maximum reservoir level for a proposed spillway(s) could also be computed.

As described earlier, the reasonableness of the mean estimates of flood peak and flood volume can be evaluated by comparison to regional flood-frequency estimates for flood peak and volume.

The simplest form of stochastic flood modeling would be to include the suite of temporal patterns applicable to the project location that are listed in the MetPortal scaled to the target AEP for the 48-hour duration. Additional meteorological variables and initial conditions could be added based on the anticipated or analyzed flood sensitivity to the various meteorological parameters/initial conditions described in Section 5.1. Latin hypercube sampling methods can be used to assemble the input datasets for combinations of parameters. Alternatively, when there is only a single additional meteorological parameter to consider with a few values of interest, then input datasets can be assembled by hand to consider all possible combinations. For example, 5 storm temporal patterns and 3 soil moisture conditions would result in 15 possible input datasets for flood simulations using the watershed model.

5.3 Sensitivity Analysis and Evaluation

Purpose

Epistemic (knowledge) uncertainties are present to some extent in every meteorological and hydrometeorological variable that is input to the watershed model. Epistemic uncertainties are also present in the various hydrological modeling processes and model parameterizations that comprise the watershed model.

Sensitivity analyses are a convenient way to assess the sensitivity of flood response (peaks, volumes, timing, hydrograph shapes) to changes in the magnitudes of the various meteorological and hydrometeorological inputs and model parameters. This process allows an assessment of the importance of the various inputs and model parameters to the flood outputs and allows for decisions to be made if changes are needed to the modeling configuration to better meet the intent of the CDA design targets or the desired conservatism of a decision-maker.

One-at-a-time (OAT) sensitivity analyses are compatible with deterministic watershed modeling. This analysis is done by first defining a baseline watershed model configuration for a selected combination of inputs and model parameters. The baseline may be for all inputs and model parameters set at median. mean or judged typical conditions or the baseline may be for a selected model configuration such as for a candidate IDF. Then vary selected inputs and model parameters one-at-a-time over a preselected range to evaluate the flood sensitivity to that input or model parameter.

A global sensitivity analysis is possible with the stochastic watershed modeling approach where numerous sample sets are created with various combinations of inputs and model parameters. Flood simulations are conducted using the sample sets and scatterplots are created for each input or model parameter plotted against the flood characteristic of interest (peak, volume, timing) which allows an evaluation of the sensitivity of that flood characteristic to the input or model parameter. This approach has the advantage of being able to examine interactions of inputs and model parameters that are not possible with the OAT approach.

For the case of a stochastic watershed modeling approach, a global sensitivity analysis is often used as a first step in identifying inputs and model parameters to be included in an uncertainty analysis that allows development of a mean-frequency curve and 90% uncertainty bounds for HHCs. The HHCs are then used in risk analyses and ultimately in RIDM. Details on HHCs are discussed in Section 9.

Recommended Minimum Analysis

As discussed previously, flood simulations should be conducted for all storm temporal patterns applicable to the location of the project as identified in the MetPortal. This should be done as the basis for selecting the IDF for the low and significant consequence classes and for development of the 1000-year flood for scaling of the 1/3 and 2/3 design targets for the high and very high consequence classes.

Assess the sensitivity of flood peaks and volumes to the various initial meteorological and hydrometeorological conditions which are known or anticipated to be important for a particular watershed or climatic setting

Assess the sensitivity of flood peaks, volume and timing to the various model parameters, such as for soil moisture storage, quickflow and interflow, which are known or anticipated to be important for a particular watershed or climatic setting

Experience

The natural hydrologic processes involved in flood generation are quite complex with natural climatic variability affecting many factors that determine flood magnitude. This includes meteorological factors such as storm magnitude (depth); spatial and temporal storm pattern; storm seasonality that in turn affects antecedent soil moisture, snowpack magnitude and condition, and air temperature during the storm for snowmelt. In addition, the transformation of rainfall-runoff and snowmelt-runoff to a flood hydrograph requires a watershed model with parameters that can emulate the natural hydrologic processes.

This high level of natural variability and the complexity of watershed model formation results in many challenges for a deterministic approach to yield a 1:N AEP flood hydrograph from a 1:N AEP storm (the AEP Neutral approach). For this reason, stochastic flood modeling is often preferred where the natural variability of the meteorological model inputs can be explicitly incorporated into the flood analysis.

The following observations about flood sensitivity can be made based on experience with floods and watershed modeling of floods:

- Storm magnitude is always an important factor in determining flood magnitude and becomes more dominant with increasing rarity of the storm magnitude
- The temporal pattern of the storm is always an important factor for the small watersheds considered here where the shape of the hyetograph (front-loaded, middle-loaded or back-loaded) and the magnitude of precipitation intensities are important considerations
- The seasonality of storm occurrence determines the likely watershed antecedent conditions when major storms occur. In general, watersheds in arid and semi-arid climates have greater variability with regard to antecedent watershed conditions for soil moisture and snowpack magnitude. This natural variability increases the difficulty in applying an AEP Neutral approach.

- For the small watersheds considered here, snowmelt runoff typically contributes to the flood volume for an IDF, but the flood peak is more sensitive to the magnitude of runoff produced by the storm.
- Air temperatures during the storm for snowmelt generation can be important, particularly when air temperatures are near the freezing point where the precipitation may occur as rainfall or snowfall. Air temperatures and freezing levels during storms vary seasonally and should be considered when assessing storm seasonality.
- The mix of quickflow and interflow runoff responses can also be dominant factors, particularly for mountainous watersheds where coarser soils are common, and the level of fracturing of the surficial bedrock often increases interflow which delays the timing of the streamflow response.
- The majority of small watersheds in British Columbia will not have streamflow data for calibration of the watershed model. It would be prudent to compare results from the watershed model with flood-frequency statistics for hydrologically similar watersheds to confirm the reasonableness of flood outputs for flood peak and flood volume.

6 Estimation of 1000-year Flood (High and Very High Failure Consequence)

Purpose

The 1000-year flood hydrograph is needed as part of the process of developing the 1/3 and 2/3 IDF targets for the high and very high consequence classes. There are some differences in development of the 1000-year flood for this application compared to the prior section for the significant consequence class in order to provide compatibility with the PMF for scaling of flood hydrographs. Those differences and constraints are discussed below.

Available options for development of 1000-year flood compatible with scaling of PMF hydrograph

The following constraints are appropriate in development of the 1000-year flood to provide compatibility of scaling with the PMF hydrograph and consistency with the incremental intent of the CDA Guidelines:

1. No pre-storm
2. Same temporal storm pattern as used for PMP in PMF watershed modeling (without pre-storm)
3. Same month of storm occurrence as used in PMF development

There are additional elements of deterministic watershed modeling of the 1000-year flood that would provide consistency with the incremental transition to the PMF hydrograph:

4. Use of AEP Neutral concepts that would result in typical soil moistures and snowpack magnitudes for the month used in PMP development (item 3 above)
5. The 1000-mb air temperature and freezing level hourly time series should be increased beyond what was observed in the historical storm template. This is consistent with a warmer atmosphere to support larger precipitation magnitudes. See prior discussion in Section 5.1. One simple and practical approach is to increase the 1000-mb air temperature and freezing level height incrementally between the maximum values observed in the observed time series for the temporal pattern and the PMP dewpoint. Use of ¼ the difference between observed and PMP conditions would be a simple and practical adjustment and consistent with later application of the 1/3 and 2/3 IDF targets. Specifically:

$$\Delta C = 0.25*(C_{PMP} - C_{MAXobs}) \qquad (1)$$

$$\Delta FL = \Delta C/0.0050 \qquad (2)$$

where: ΔC is the change in 1000-mb air temperature for adjustment of the 1000-mb air temperature time series (Celsius); C_{PMP} is the PMP dewpoint temperature for the month of the storm (Celsius); C_{MAXobs} is the maximum 1000-mb air temperature observed in the historical storm during the 24-hour period of maximum precipitation for the chosen storm temporal pattern; ΔFL is the change in freezing level height for adjustment of the freezing level height time series; and 0.005 for the air temperature lapse rate (-0.50°C/100-meters) which is near the pseudo-adiabatic lapse rate.

6. Consider using quickflow response (e.g., FRTK parameter in the Raven UBC model) and interflow response (e.g., IRTK parameter in the Raven UBC model) parameters that result in a slower response than the typically conservative timing parameters used in PMF development.

If a stochastic watershed modeling approach is taken for development of the 1000-year flood, the process would proceed similarly to that described in Section 5.2 for stochastic watershed modeling. Items 1, 2, 3, 5 and 6 described above for deterministic watershed modeling would be retained. The difference would be in the manner in which the variability of the hydrometeorological variables is considered and the choice of a flood hydrograph that best replicates the mean of the flood peaks and flood volumes from the collection of flood simulations.

7 1/3 and 2/3 IDF Targets between 1000-year Flood and PMF (High and Very High Failure Consequence)

Purpose

The high and very high consequence classes in the CDA Guidelines identify IDF targets that are 1/3 and 2/3 of the span between the 1000-year flood and the PMF flood, respectively. Flood hydrographs are needed for flood routing and sizing of spillways and therefore the 1/3 and 2/3 IDF targets require development of hydrographs that have the desired flood peaks and volumes.

There are a number of implications inherent in the development of the flood hydrographs for the 1/3 and 2/3 IDF targets. The scaling process implies that several conditions are incrementally changing in the scaling process between the 1000-year flood and the PMF. This would include:

- Temporal pattern of storm that is producing the larger floods is increasing in magnitude
- Pre-storm is increasing from no pre-storm for the 1000-year flood to full pre-storm for the PMF
- Soil moisture conditions may be getting progressively wetter (climate dependent)
- Snowpack SWE in the watershed is getting progressively larger
- Air temperatures are getting progressively warmer and freezing level height is increasing
- Reduction in quickflow and possibly interflow timing parameters are producing flashier flood responses
- Both flood peaks and flood volumes are getting progressively larger

Details of the scaling process

It is likely that differences in meteorological and hydrometeorological inputs and watershed model parameters in computing the 1000-year flood and PMF hydrographs will result in non-linearities in the shapes of the flood hydrographs in progressing from the 1000-year flood to the PMF. The scaling process has been devised to accommodate the possibility of non-linearities in the flood response and flood hydrograph shapes. The scaling process to develop the 1/3 and 2/3 IDF flood hydrographs proceeds as follows.

1. Determine the flood peak magnitude that corresponds to the 1/3 and 2/3 points ($Q_{peak1/3}$ and $Q_{peak2/3}$) between the 1000-year flood peak (Q_{p1000}) and PMF peak (Q_{pPMF}).
2. Multiply the ordinates of the 1000-year flood hydrograph by $Q_{peak1/3}/Q_{p1000}$ to scale to the 1/3 IDF target and $Q_{peak2/3}/ Q_{p1000}$ to scale the 1000-year flood hydrograph to the 2/3 IDF target.
3. Multiply the ordinates of the PMF flood hydrograph by $Q_{peak1/3}/ Q_{pPMF}$ to scale to the 1/3 IDF target and $Q_{peak2/3}/ Q_{pPMF}$ to scale the PMF to the 2/3 IDF target.
4. Synchronize the two 1/3 IDF target flood hydrographs so the timing of the flood peaks match. Now average the flood hydrograph ordinates on a timestep-by-timestep basis. This will preserve the flood peaks at the IDF target value and produce a flood volume that is a composite of the two hydrograph shapes and implicitly satisfies the conditions for the 1/3 IDF target described in the purpose section above.
5. Repeat the same process for the 2/3 IDF target.

An example of the scaling process for the 1/3 and 2/3 IDF targets is shown in Figure 10 through Figure 12. The February PMF hydrograph and watershed model from the Cheakamus watershed (King and Micovic, 2022) was used for this example and minor modifications were made to the watershed model inputs, consistent with criteria listed above, to develop the 1000-year flood.

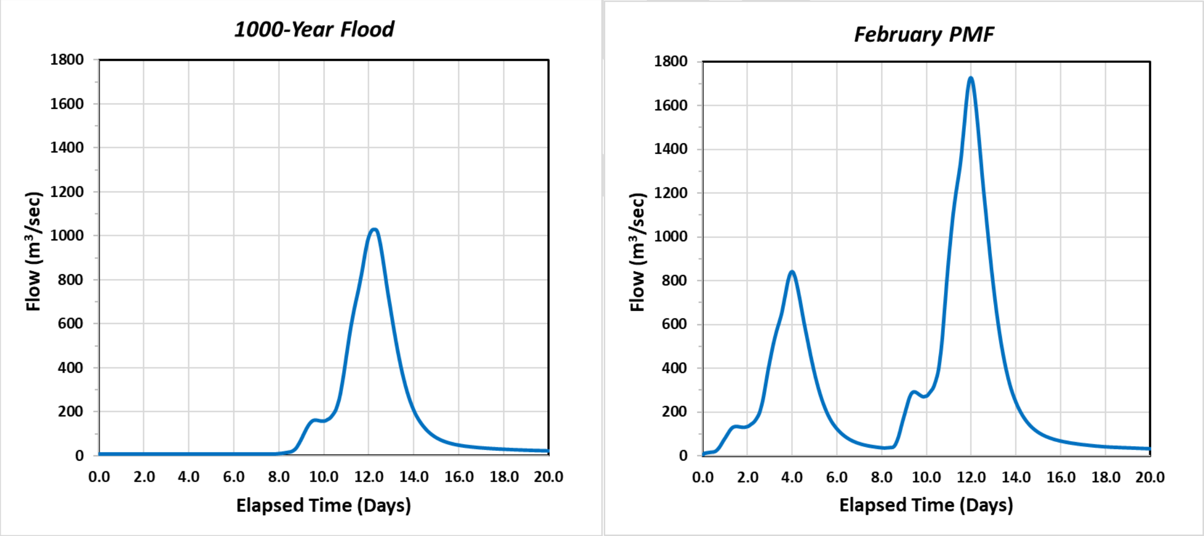


Figure 10. 1000-year and February PMF flood hydrographs

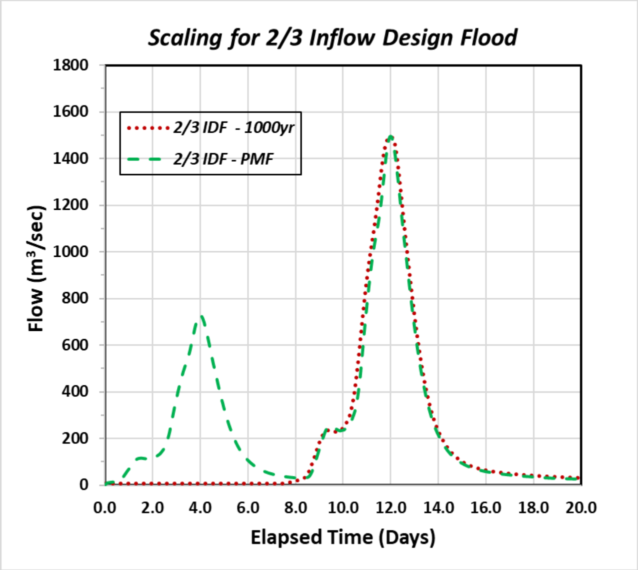


Figure 11. Scaling of 1000-year and PMF hydrographs to flood peak magnitude for 2/3 IDF target and synchronizing the timing of flood peaks

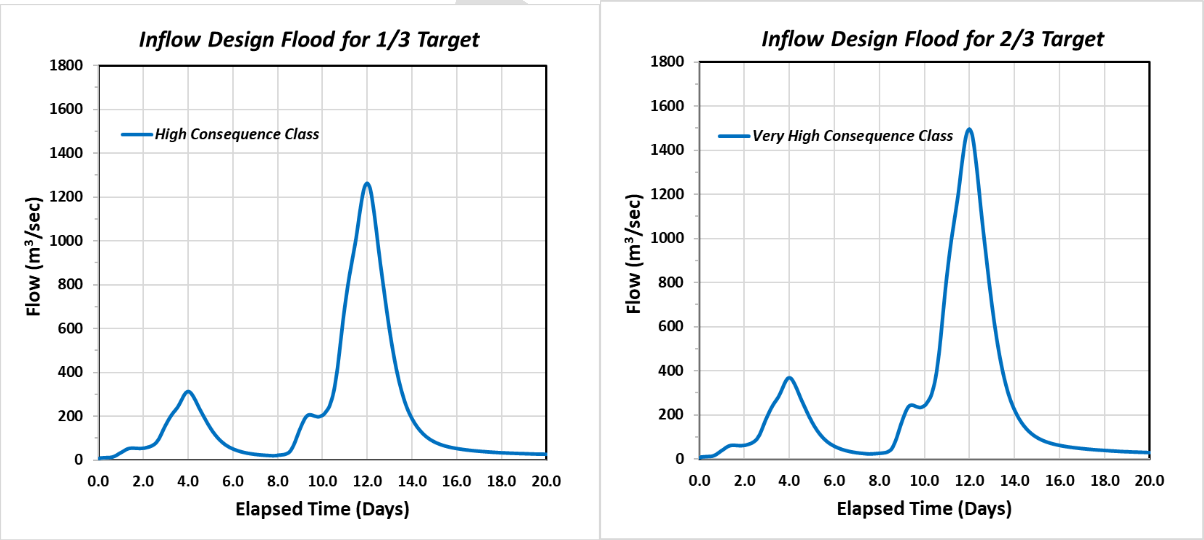


Figure 12. Final scaled flood hydrographs for 1/3 and 2/3 IDF targets

8 Probable Maximum Flood (High, Very High, and Extreme Failure Consequence)

Purpose

The goal in developing the PMF is to produce an extreme flood that could plausibly be produced by a watershed, given the occurrence of the PMP. In general, a PMF is typically in the range of 2 to 10 times rarer than the PMP because of the conservatisms used in computing the PMF. Excessive compounding of conservatisms can produce PMFs that are two orders of magnitude rarer than the PMP, particularly for arid and semi-arid climates. The PMF may be caused by rainfall, by snowmelt, or a combination of the two. Multiple factors affect the PMF:

1. The precipitation volume and timing
2. The temperature before and during the PMF
3. The initial conditions of the watershed (snow, soil moisture, and reservoir)
4. The watershed response

Because of differences in storm characteristics and the influence of snowmelt characteristics between watersheds, three different potential PMF events need to be considered:

1. A PMP event following a 100-year storm that sets wet antecedent watershed conditions
2. A PMP event following an extreme temperature sequence to generate snowmelt runoff and to set wet antecedent watershed conditions
3. A probable maximum snowmelt flood generated by sustained warm temperatures on a probable maximum snow accumulation (PMSA) followed by a 100-year storm

The first two scenarios are typical considerations for smaller watersheds and the third scenario is a consideration for very large watersheds and for some unusual climatic/watershed situations.

Available options

Two different alternatives are presented to assess the PMF for a dam.

1. Conduct a comprehensive analysis of each of the three potential PMF events, as depicted in Figure 13. King and Micovic (2022) describe how the inputs associated with each of these events were be developed for a dam in BC and is recommended as a basis for completing a comprehensive PMF analysis. This approach is summarized in Section 8.1.
2. The development of the various initial conditions and time series components associated with a comprehensive PMF analysis can be labor-intensive. The primary aim of a comprehensive analysis is to apply a PMP event to sufficiently saturated/high snowpack conditions. If conservative assumptions are employed, a simplified PMF analysis may be conducted, as depicted in Figure 14 and described in Section 8.3. Under this approach, a sufficiently large snowpack is employed such that snow remains at the conclusion of the simulation (referred to as an *abundant snowpack* below), soil moisture states are assumed to be saturated, and initial reservoir levels are assumed to be full.

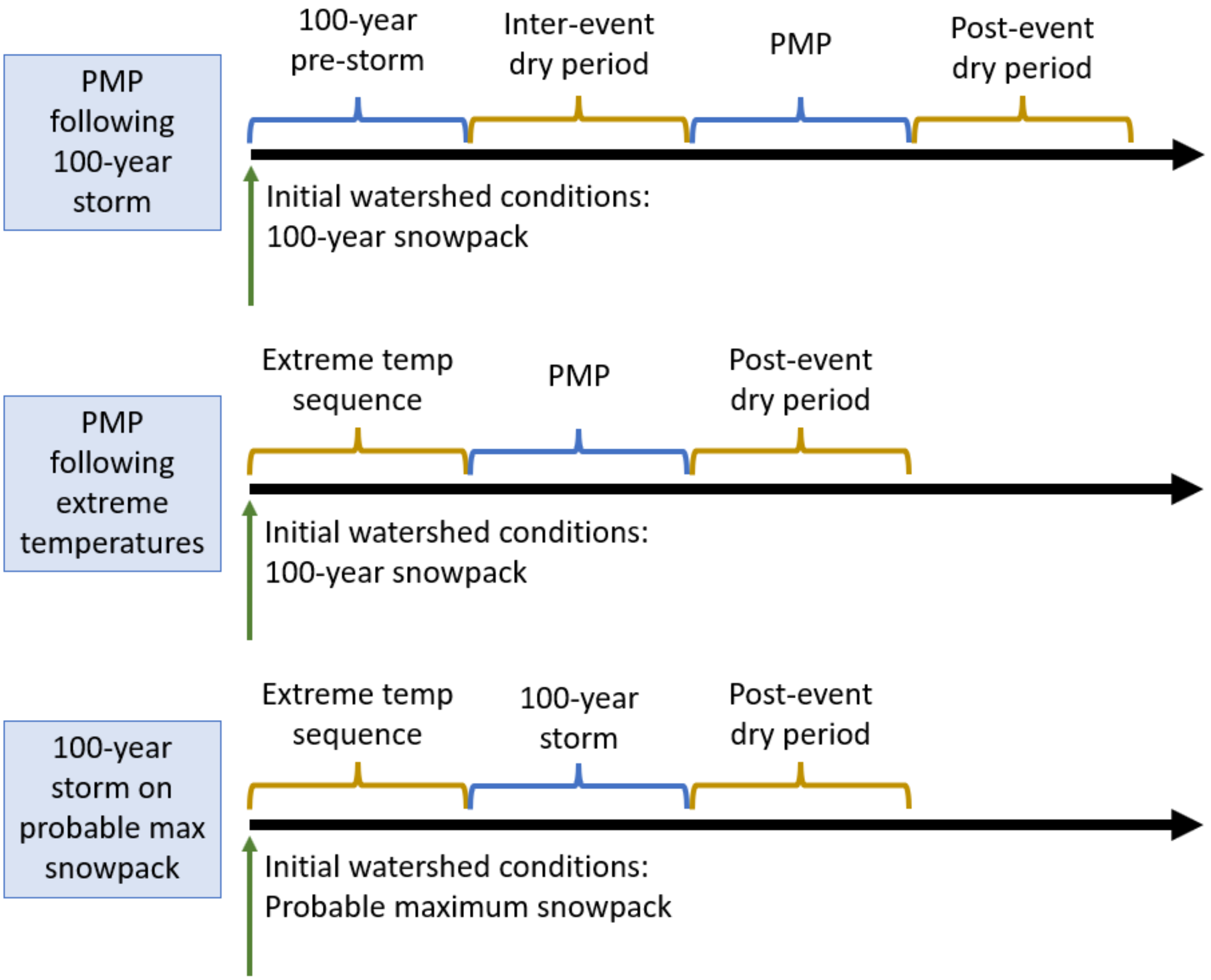


Figure 13. Summary of storm sequencing for each of the three scenarios to consider for a comprehensive PMF analysis

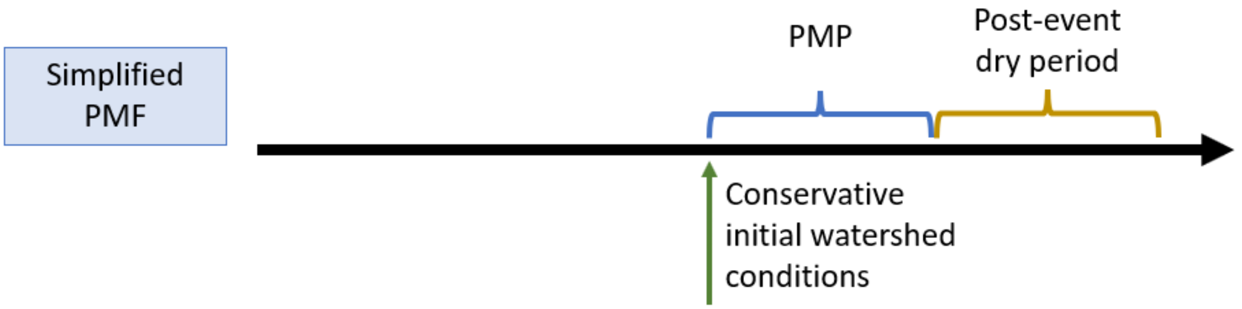


Figure 14. Summary of storm sequencing for a simplified PMF analysis

Recommended minimum hydrologic analyses

The simplified analysis presented in Section 8.3 should provide relatively conservative assumptions for basic watersheds; if the full approach outlined in Section 8.1 is followed, this may result in less conservative results. In both approaches, the sensitivity of key factors needs to be evaluated. This includes:

1. PMP volume
2. Storm spatial and temporal patterns
3. Air temperature time series and temperature lapse rate
4. Hydrologic modeling approach

Experience

The goal in developing a PMF hydrograph is to produce a sufficiently conservative estimate of the flood that could be produced by the occurrence of PMP for use in assessing spillway adequacy or design of a new/rehabilitated spillway(s). The PMF hydrograph developed should be consistent with the definition of the PMF which is "a flood than can be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a region" (emphasis added; FERC, 2015).

The analysis should evaluate each of the potential PMP events identified in MetPortal (i.e., for different durations) to identify the controlling storm for a watershed. The intent of including an antecedent precipitation event/high temperature sequence prior to the PMP storm event is to assure wet antecedent watershed conditions to enhance runoff generation and to produce a high initial reservoir level for beginning reservoir routing when the PMP event occurs. Finally, the intent of considering modifications to hydrologic model parameters is to reflect the likelihood of faster runoff responses during extreme precipitation events. That said, without careful consideration, the combination of conservatisms in initial conditions and watershed modeling parameters can result in excessive compounding of conservatisms, and unrealistically enlarging the PMF flood hydrograph. The analyst should evaluate the impacts of various inputs to understand the influence/sensitivity on flood outputs to produce a flood hydrograph that is adequately conservative ("reasonably possible") without excessive compounding of conservatisms.

8.1 PMP Time Series Development

Purpose

For both the comprehensive and simplified PMF analyses, precipitation and temperature time series need to be developed for the event. These data are available from the BC MetPortal site, as described in Section 3. The following discusses details of the PMP time series development using data from the BC MetPortal.

Details: Computation of PMP time series

Storm data selection

The first step in using data from the BC MetPortal is identifying grid points that should be considered given the watershed of interest. The PMP and secondary PMP storms will yield the largest PMP depths for that grid point. However, if the watershed of interest falls between grid points or covers multiple grid points, data from multiple grid points should be assessed to identify the event that produces the PMF (note that due to differences in underlying topography and orographic effects, the PMP storms should not be simply shifted in space).

Furthermore, storm patterns generated using the same original historical storm transposed to different grid points will differ in spatial characteristics because of the methodology employed to transpose the storms by the BC MetPortal. BC MetPortal also provides PMP estimates for different durations (24, 48, 72, and 96 hours). The controlling and secondary storms should be reviewed for each duration to identify any unique storms that should be evaluated as the PMF for a location.

Because of differences in storm volume and storm pattern, it is unknown a priori which inputs will result in the PMF. Thus, the preliminary analysis should consider the full suite of PMP inputs for each nearby grid point location.

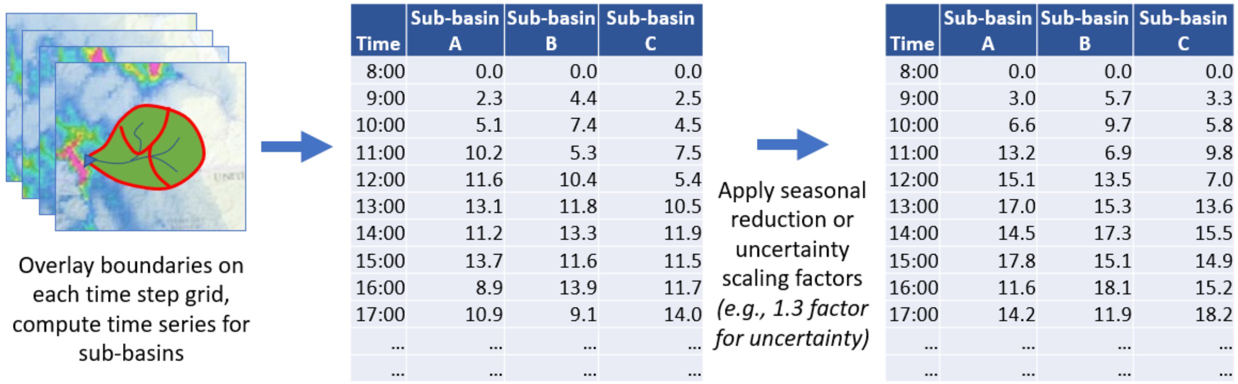
100-year dewpoint time series

The 1000-mb temperature and lapse rate time series provided with the PMP represent the temperatures/lapse rates that occurred during the historical storms. For PMP modeling, the temperatures should be increased to maximize the resulting snowmelt that occurs during the PMP event. Temperatures should be increased such that the highest temperatures during the event are equal to the 100-year dewpoint temperature during the month of interest. 100-year monthly maximum 12-hour dewpoint temperature maps are available in Appendix J of the BC MetPortal PMP Technical Report (DTN and MGS Engineering, 2020b).

PMP time series creation

BC MetPortal outputs time series of gridded precipitation datasets for each controlling/secondary storm along with time series of 1000-mb temperatures and air temperature lapse rates during the storm. These datasets may be used to create precipitation and temperature time series corresponding to sub-basins in a hydrologic model (see King and Micovic [2022] for details). For a given PMP storm, this involves:

1. Develop **precipitation time series** for the controlling (or secondary) storm (Figure 15):
    a. Overlay sub-basin/elevation zone boundaries over the PMP storm pattern grids to calculate precipitation time series for each sub-basin/elevation zone and the watershed-average precipitation time series
    b. Loop through the precipitation grids for each time step and intersect with basin boundaries to compute precipitation time series for each sub-basin/elevation zone.
    c. The above will result in the baseline PMP time series for a location. For shoulder seasons, scaling factors may be employed as reported in the BC MetPortal to lower the precipitation volume. If the 5th/median/95th percentile PMP will be evaluated, multiply the resulting time series by the reported scaling factor for the percentile of interest.
2. Determine corresponding **temperature time series** during storms (Figure 16):
    a. Begin with the 1000-mb temperature and freezing level time series associated with the storm
    b. For PMP storms, shift the 1000-mb temperature time series such that the 12-hour maximum temperature during the storm equals the 100-year, 12-hour maximum dewpoint temperature to maximize the potential snowmelt that may occur during the event (step 1 in the example in Figure 16).
    c. Use the freezing level to compute the corresponding lapse rate for every hour (assume 1000-mb temperature is at sea level) (step 2 in the example in Figure 16)
    d. Apply either a relatively flat fixed lapse rate (as low as -0.37ºC / 100 meters [-2ºF / 1000 ft]) or the time-varying lapse rate computed for the storm to shift the 1000-mb temperatures from sea level to the elevation of each sub-basin/elevation zone in the watershed (step 3 in the example in Figure 16).



Time	Sub-basin A	Sub-basin B	Sub-basin C
8:00	0.0	0.0	0.0
9:00	2.3	4.4	2.5
10:00	5.1	7.4	4.5
11:00	10.2	5.3	7.5
12:00	11.6	10.4	5.4
13:00	13.1	11.8	10.5
14:00	11.2	13.3	11.9
15:00	13.7	11.6	11.5
16:00	8.9	13.9	11.7
17:00	10.9	9.1	14.0
...	...	...	...
...	...	...	...

Time	Sub-basin A	Sub-basin B	Sub-basin C
8:00	0.0	0.0	0.0
9:00	3.0	5.7	3.3
10:00	6.6	9.7	5.8
11:00	13.2	6.9	9.8
12:00	15.1	13.5	7.0
13:00	17.0	15.3	13.6
14:00	14.5	17.3	15.5
15:00	17.8	15.1	14.9
16:00	11.6	18.1	15.2
17:00	14.2	11.9	18.2
...	...	...	...
...	...	...	...

Figure 15. Example PMP precipitation time series development.

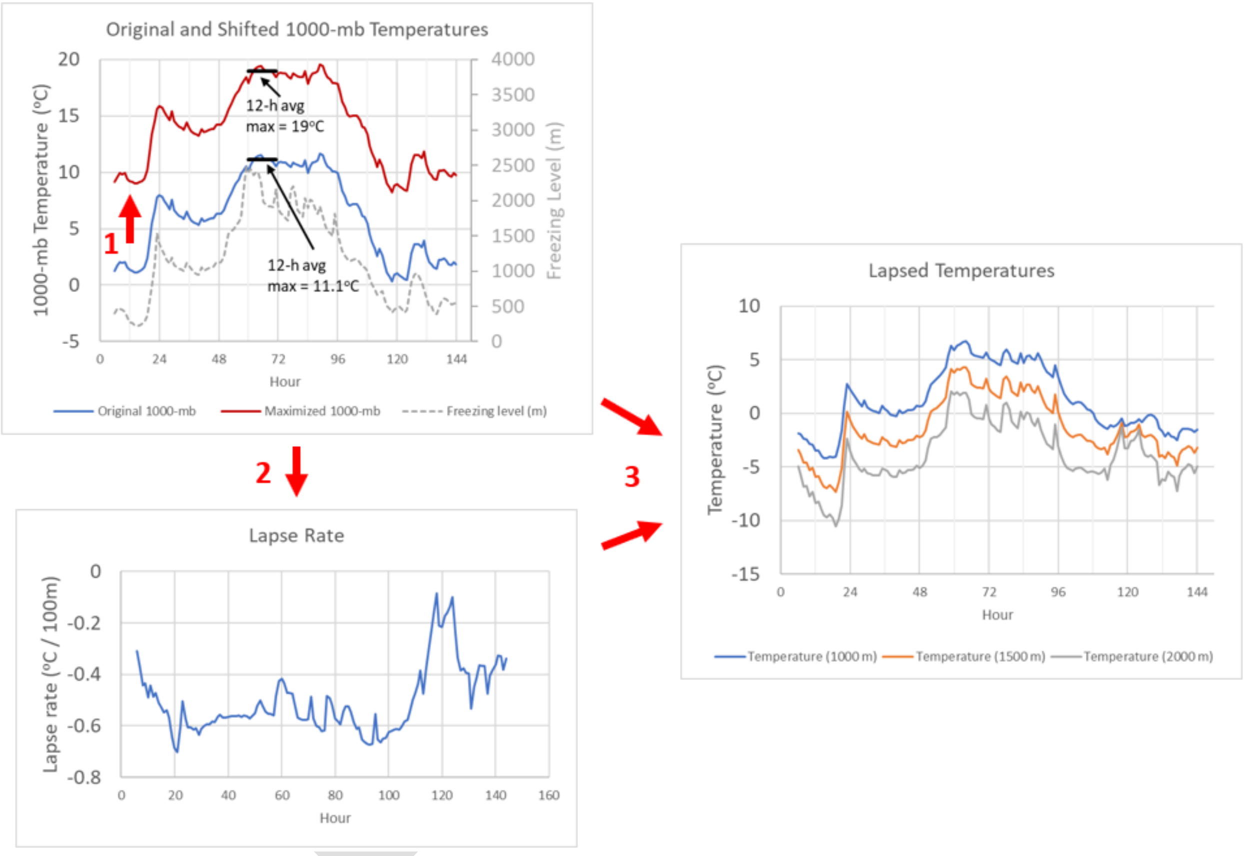


Figure 16. Example PMP temperature time series development. The 12-h 1000 mb maximum dewpoint temperature = 19°C.

<u>*Experience*</u>

- Because the PMP event volume and timing are the primary drivers affecting the PMF, the PMP storms and secondary storms identified for each duration at a location should be evaluated to determine the controlling PMF event. This may be done qualitatively or by executing the hydrologic models to evaluate runoff response.
- As noted in Section 5.1, the freezing level time series should be checked to confirm that precipitation is falling as rain throughout the majority of the storm event. Many of the temporal

patterns are associated with cold-front passage near the end of the storm which can result in snowfall at higher elevations in mountainous terrain. The watershed model results should be checked to confirm the freezing level is sufficiently high to produce rainfall throughout the majority of the storm event. The freezing level may be scaled higher to produce rainfall and not snowfall. Where appropriate, meteorologists should be consulted to obtain advice on adjustments to observed air temperature and freezing level height time series.

8.2 Comprehensive PMF Analysis

Purpose

A comprehensive analysis involves considerably more data analysis and data input preparation to allow evaluation of the different possible scenarios for watershed antecedent conditions and watershed model parameters for computing candidate PMF flood hydrographs. In addition, watershed modeling for selection of the PMF should include reservoir routing in order to properly assess the maximum reservoir level and resultant spillway discharge produced by the various candidate PMF flood hydrographs, though common practice is to determine a PMF inflow hydrograph without consideration of reservoir routing and only perform reservoir routing for the selected PMF event.

The simplified analysis presents conservative assumptions, yet this can lead to over-estimation of the PMF, particularly for larger watersheds This guidance document recommends following procedures outlined in King and Micovic, 2022 for conducting a comprehensive PMF analysis. Note that King and Micovic, 2022 do not discuss the application of a 100-year storm on a PMSA. This scenario typically does not control for the small watershed sizes that are the focus of this guidance. This condition should be evaluated for larger watersheds.

A comprehensive PMF analysis involves various time series analyses and distribution fitting exercises. Various statistical software packages are available to perform distribution fitting (e.g., RMC-BestFit; USACE, 2020).

Table 6 summarizes the primary components that need to be evaluated as a part of a comprehensive analysis.

Table 6. Summary of time series development required for each of the potential PMF combinations for a comprehensive analysis

PMP following 100-year storm	
Antecedent conditions	▪ **Snowpack**: Separate monthly distribution fitting analyses of snow data for stations spanning elevation of the watershed to determine 100-year snowpack ▪ **Soil moisture**: Typical soil moisture levels for the month of interest; the antecedent event is assumed to fill soil moisture zones. ▪ **Reservoir level**: Typical normal reservoir level for the month of interest for start of flood simulations (before 100-year storm)
100-year pre-storm	▪ Access 100-year data from BC MetStorm ▪ Identify median storm pattern ▪ **Precipitation**: scale storm pattern to 100-year depth ▪ **Temperature**: apply air temperature lapse rate to corresponding temperature pattern; maintain temperature of original storm without shifting
Inter-event and post-event dry periods	▪ No precipitation

	▪ **Temperature**: determine mean monthly temperature from station data. Apply typical diurnal pattern to create temperature sequence.
PMP	▪ Access PMP data from BC MetStorm ▪ **Precipitation**: scale storm pattern to PMP depths. For shoulder months, apply PMP reduction factor to reflect lower PMP volumes. ▪ **Temperature**: Distribution fitting analysis of temperature data to determine 100-year dewpoint temperatures for different months. Shift temperature pattern so the maximum 24-hour temperature equals the 100-year dewpoint temperature for the appropriate month. Apply air temperature lapse rate to resulting temperature pattern.
Analysis windows	Different combinations of initial conditions, 100-year pre-storm, and PMP patterns/depths will result in different runoff responses. The starting snowpack and PMP depth will vary by month. The different statistical analyses and simulation runs need to be repeated for each month to identify the PMF.
PMP following extreme temperature sequence	
Antecedent conditions	Same antecedent conditions developed for the PMP following a 100-year storm
Extreme temperature sequence	▪ No precipitation ▪ **Temperature**: Complete a distribution fitting analysis of temperature for 6 durations to determine the 100-year temperature for a given month. Construct temperature sequences using the results and typical diurnal patterns.
PMP	Same time series developed for the PMP following a 100-year storm
Post-event dry period	Same time series developed for the PMP following a 100-year storm
Analysis windows	Different combinations of initial conditions, extreme temperature sequences, and PMP patterns/depths will result in different runoff responses. The starting snowpack, temperature sequence, and PMP depth will vary by month. The statistical analyses and simulation runs need to be repeated for each month to identify the PMF.
100-year storm following a probable maximum snow accumulation	
Antecedent conditions	The probable maximum snow accumulation (PMSA) may be estimated following approaches described in Klein et al., 2016 and elsewhere. The impact of the PMSA may be approximated by assuming an abundant snowpack exists such that snow remains in the watershed following simulation of the PMF.
Extreme temperature sequence	Same temperature sequence as developed for the PMP following an extreme storm sequence

100-year storm	Same 100-year storm time series developed for the PMP following a 100-year storm
Post-event dry period	Same time series developed for the other scenarios
Analysis windows	The PMSA can vary by month. Similar to the other analyses, different combinations of antecedent snowpack, extreme temperature sequence, and 100-year storms will result in different runoff responses, requiring simulation of each scenario.

Experience

- **Comprehensive versus simple analysis**: The comprehensive analysis requires substantial time series analysis and distribution fitting, including evaluating conditions for multiple months. The simplified PMF analysis provides a more conservative approach to evaluate the PMF without performing many of these steps.
- **100-year temporal pattern:** In selecting a 100-year storm, the analyst may choose between different temporal patterns. The goal of the antecedent storm is to saturate the soils, but it is not necessary to select the most critical antecedent event. A median temporal pattern (e.g., the center-loaded pattern) may be selected for the antecedent event. The temperatures of the original 100-year event may be employed (with an appropriate air temperature lapse rate applied) and do not need to be shifted to higher temperatures.
- **Snowmelt prior to the PMP**: The snow states should be evaluated following the antecedent storm or antecedent high temperature period. In some cases, the antecedent event could melt out a substantial portion of the snowpack, effectively reducing the influence of snowmelt during the PMP event itself. In this case, the antecedent event (or high temperature sequence) should be modified to sufficiently ripen the snowpack and initiate melt without reducing the influence of snowmelt during the PMP event itself.
- **Historical data used in distribution fitting**: Snow observations will vary in how representative they are of a location to varying degrees and can be highly site dependent. When evaluating the 100-year SWE, if possible it would be good to consider multiple stations and consider typical snow patterns at the site versus the watershed of interest. If a continuous snow model is employed such as the UBC snow model for a long period of record, simulated SWE may be employed to develop the 100-year SWE.

Details

Sources of data include the following:

- Historical Rainfall Data from Environment Canada
  https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

- Archive Manual Snow Survey Data BC Government
  https://catalogue.data.gov.bc.ca/dataset/archive-manual-snow-survey-data

- Snow Survey Stations Interactive Map
  https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=c15768bf73494f5da04b1aac6793bd2e

- Observations of Weather and Climate Variables
  https://www.pacificclimate.org/data/bc-station-data

- Mean Monthly Temperatures (developed in 2002 for the 1961-1990 period) https://prism.oregonstate.edu/projects/canw.php

8.2.1 Sensitivity Analysis and Evaluation

Purpose

There are many factors that result in uncertainty in the PMF. As discussed in Section 5.3, sensitivity analyses provide a means of assessing the importance of different values of hydrometeorological inputs and watershed model parameters and the resulting impact on PMF estimates.

As described in Section 3 and presented in Chapter 11 of the PMP Technical Report (DTN and MGS Engineering, 2020b), the PMP analysis performed for BC included an assessment of uncertainties in the PMP. The analysis concluded that when uncertainties in key inputs used to derive the PMP are considered, the potential range in the resulting PMP is very large, with a median value substantially higher (1.2 to 1.3 times larger) than the base PMP developed for the project and presented in MetPortal, (see Table 5). Traditional PMP/PMF methodology has not considered these uncertainties, and the CDA guidelines do not address uncertainty in the PMP. Based on the recent findings of the BC Extreme Flood Project, however, the uncertainty in PMP is substantial and shifts PMP estimates upwards. These uncertainties should be considered as a part of a PMF sensitivity analysis to provide dam owners and regulators with information to properly understand the impact of uncertainty in PMP on the resulting PMF.

The major factors that typically affect uncertainty in the PMF include:

- **Uncertainty in PMP magnitude**: Table 5 presents 5th, median, and 95th percentile scaling factors for each of the climate macro regions in BC that can be used to characterize uncertainty in PMP magnitude.
- **Uncertainty in watershed modeling**: The timing of the watershed flood response to extreme storm events will differ from what occurs during more typical events. The timing of the flood response and resultant peak flow changes due to an increase of quickflow relative to interflow for extreme events and due to typically higher streamflow velocities for channel routing during extreme floods. Key hydrologic parameters controlling snowmelt and fast runoff response (soil moisture parameters as well as basin/channel routing parameters) should be varied to understand the sensitivity to the increased runoff magnitudes
- **Uncertainty in initial watershed conditions**: Typically, the combination of the antecedent event or the antecedent high temperature period will overwhelm any assumed initial watershed conditions that exist prior to the start of flood simulations. The antecedent events will typically result in very wet soil moisture conditions prior to the PMP and high initial reservoir levels for reservoir routing of the flood hydrograph generated by PMP. The 100-year snowpack condition is intended to result in snowmelt generation throughout the antecedent storm and PMP events. If these conditions are achieved, it is anticipated the initial watershed conditions prior to the antecedent events will have minor impacts on the flood results. However, the initial conditions should be varied to confirm this is the case.
- **Climate change**: Although this Guidance document does not provide specific recommendations for assessing climate change impacts, the analyst should be aware of the potential impacts of climate change on extreme events. Section 1.3 includes a few references for additional information on previous approaches employed.

Experience

The uncertainty in the estimate of the PMP is the primary source of uncertainty affecting the PMF. As shown in Table 5, the *median* scaling factors reflecting uncertainty in the PMP multiply the conventional PMP values presented in the BC MetPortal by a factor of 1.2 to 1.3. Traditionally, PMF analyses have not considered uncertainty in the underlying PMP. However, the high degree of uncertainty in PMP should be recognized, particularly in situations where the sufficiency of spillway capacity is in question. At this time, the Ministry of Forests has no specific guidance on how to address uncertainty of flood estimates with respect to design or operation of a dam. The Ministry of Forests requires that the Canadian Dam Association guidelines are followed and that other guidelines from international dam safety organizations or other regulatory agencies are utilized as required. A defensible study is generally considered by the Ministry of Forests to be one that the hydrologist who completed the study, and reviewers, have confidence in the magnitude of the PMF flood estimate and an adequate analysis and/or discussion of the uncertainty with the estimate has been documented, commensurate with the failure consequence of the structure. The implications of uncertainty in the PMF resulting from uncertainty in the factors identified above will provide valuable information to dam owners and regulators for discussions of spillway adequacy.

Ultimately, if spillway modifications are under consideration, a PFHA and RIDM approach are well-suited to better understand the probabilities of floods of different magnitudes and associated flood risks (Section 9). These approaches also provide a framework for assessing the aleatoric and epistemic uncertainties inherent in hydrologic analyses.

Recommended Minimum hydrologic analyses

As discussed in Section 8.1, the preliminary analysis should consider each of the PMP storm and secondary storm patterns identified for different durations (24, 48, 72, and 96-hours) to identify the controlling storm that results in the PMF.

It is recommended that uncertainty in the PMP estimate be considered as part of the sensitivity analyses for the PMF. This can be accomplished by including a range of PMP estimates as indicated by the 5th, median, and 95th percentile scaling factors for the baseline PMP. Inclusion of uncertainty in the PMP estimate would be in addition to the usual considerations for uncertainty/sensitivity to the watershed model parameters and initial watershed conditions. This approach will provide a more comprehensive assessment of the sensitivity of the candidate PMF to the various hydrometeorological inputs and watershed model parameters.

Details

For reference, the following scenarios for inflow uncertainty were evaluated by King & Micovic (2022):

1. **Baseline watershed model**: The initial calibrated hydrologic model with the PMP output from BC MetPortal. The baseline analysis considered many potential PMP storm patterns along with different combinations of antecedent storms and extreme temperature sequences to identify the controlling PMF event.
2. **Variations in PMP inputs**: Using the baseline watershed model, key inputs were varied for multiple scenarios:
    a. Apply the 95th percentile PMP uncertainty scalar
    b. Apply the median PMP uncertainty scalar
    c. Increase temperatures to reflect potential climate change (no change to PMP)
    d. Apply the 95th percentile PMP uncertainty scalar and increase temperatures to reflect potential climate change
3. **Variations in PMP inputs and the baseline watershed model**: Key watershed model parameters (snowmelt and fast runoff parameters) were varied and each of the scenarios outlined in #2 were executed to understand the influence of the watershed model on results.

Finally, King and Micovic (2022) also evaluated the impact of losing outlet capacity by executing scenarios with reduced outlet capacity for all or a portion of the simulation for both the baseline PMF and the highest uncertainty PMF scenarios.

8.3 Simplified PMF Analysis

Purpose

The development of the various initial conditions and time series components associated with a comprehensive PMF analysis can be labor-intensive. The simplified PMF analysis intends to bypass much of this development effort by employing conservative assumptions for initial conditions, intended to effectively replicate the impact of a large antecedent storm or high temperature period prior to a PMP event on the resulting PMF.

Available options and details for a simplified PMF analysis

Figure 14 presents the sequence of components for a simplified PMF analysis. These include:

1. Definition of conservative initial conditions
2. PMP event
3. Post-event dry period

Precipitation and temperature during the PMP

The precipitation and temperature time series associated with the PMP event should be developed addressing the same considerations as a comprehensive PMF analysis, as outlined in Section 8.1.

Definition of initial conditions

The following initial conditions should be employed for the simplified PMF:

1. An **abundant snowpack** sufficiently large such that snow remains in the watershed at the end of the simulation
2. A **ripe snowpack** such that snowmelt will begin as soon as rainfall and/or air temperatures above freezing initiate melt at the start of the simulation
3. **Saturated soil moisture conditions** for all sub-basins
4. **Mean mid-month initial streamflows** to avoid any delay between the start of the simulation and the routing of flow over the watershed
5. **Reservoir levels at the maximum normal pool** and spilling the initial streamflow defined by #4

Furthermore, the watershed parameters should be selected to reflect conservative assumptions related to runoff timing.

Basins with intermittent snowpack

In basins with intermittent snowpack (in contrast to basins with clearly defined snow accumulation and melt seasons associated with a significant seasonal snowpack), the assumption of an abundant snowpack that persists through the PMP may be overly conservative. In situations with intermittent snow accumulation, the analyst may develop a 1:20-year SWE value based on frequency analysis, recognizing that there is a good chance of no or limited snow at the time the storm occurs. Because of other conservatisms employed for the simplified PMF (e.g., saturated initial soil conditions), this assumption should still yield a conservative estimate of the PMF.

In these cases, it is likely there are few data available to characterize SWE due to the lower priority placed on snowpack data collection. The analyst may need to rely on snow-on-ground data collected at stations and convert these to SWE to develop the 1:20-year SWE estimate for the analysis.

Possible need to evaluate two scenarios

In some situations, the maximum snow accumulation may occur in a shoulder season when the PMP seasonal scaling factor is less than 100% (e.g., if the highest snow accumulation occurred in May in the Hybrid macro climate region; see Figure 2 and Table 4). In these cases, the simplified PMF analysis should consider two scenarios:

1. [*Seasonal PMP scaling factor*] * PMP with an abundant snowpack (i.e., PMP seasonality scaling factor < 1.0 with a sufficiently large snowpack that remains following the PMP event)
2. 100% PMP with no (or minimal) snow on the ground

The analysis of both scenarios will allow for a comparison between the influence of snowmelt-augmented partial PMP and a full PMP on bare ground. In both cases, fully saturated soil moisture conditions should be employed.

Table 7. Summary of simplifications associated with a simplified PMF analysis

Simplified PMF Analysis	
Antecedent conditions	▪ **Snowpack**: Define the starting snowpack depth such that snow remains in the watershed following simulation of the PMF. Set other snow states to a ripe condition such that snowmelt begins immediately. ▪ **Soil moisture**: Set soil moisture states to fully saturated conditions. ▪ **Reservoir level**: Set reservoir levels to full.
Post-event dry period	▪ No precipitation ▪ **Temperature**: determine mean monthly temperature from station data. Apply typical diurnal pattern to create temperature sequence.
PMP	▪ Access PMP data from BC MetStorm ▪ **Precipitation**: scale storm pattern to PMP depths. For shoulder months, apply PMP reduction factor to reflect lower PMP volumes. ▪ **Temperature**: Distribution fitting analysis of temperature data to determine 100-year dewpoint temperatures for different months. Shift temperature pattern so the maximum 24-hour temperature equals the 100-year dewpoint temperature for the appropriate month. Apply lapse rate to resulting temperature pattern.
Analysis windows	The historical snow accumulation should be assessed for a nearby snow gage to determine the latest month with snow accumulation. If the PMP scaling factor is less than 1.0 for this month, two scenarios should be assessed: ▪ Infinite snowpack with [scaling factor for latest month] * PMP ▪ No snowpack with full PMP

Experience

The simplified PMF analysis employs conservative initial conditions. In many cases, these simplified assumptions would result in a very similar PMF to the comprehensive PMF (e.g., for small watersheds and reservoirs with relatively small storage capacity or minimal ability to modify operations during events).

The driving uncertainty in the PMF is caused by uncertainty in the PMP. The impact of employing simplified assumptions related to initial conditions will typically have a minor impact on results compared to the impacts of considering the uncertainty in the PMP, particularly for watersheds smaller than 100 km^2.

8.3.1 Sensitivity Analysis and Evaluation

Purpose

As noted earlier, traditionally, PMF analyses have not considered uncertainty in the underlying PMP, yet uncertainties in the PMP are large. As with a full analysis, it is recommended that uncertainty in the PMP estimate be considered as part of the sensitivity analyses for the PMF. This can be accomplished by including a range of PMP estimates as indicated by the 5th, median, and 95th percentile scaling factors for the baseline PMP. Inclusion of uncertainty in the PMP estimate would be in addition to the usual considerations for uncertainty/sensitivity to the watershed model parameters and initial watershed conditions. Thus, as with a full analysis, the simplified PMF analysis should consider uncertainties in the following:

- Evaluate each of the potential controlling PMP events for different durations available from MetPortal
- Evaluate the baseline PMP available from MetPortal as well as applying the 5th, median, and 95th percentile scaling factors
- Evaluate modifications to the hydrologic model parameters to increase runoff timing compared to historical events

This approach will provide a more comprehensive assessment of the sensitivity of the candidate PMF to the various hydrometeorological inputs and watershed model parameters.

9 Probabilistic Flood Hazard Analysis (PFHA) for Risk-Informed Decision-Making (RIDM)

Purpose

The term Probabilistic Flood Hazard Analysis (PFHA) is a generic term intended to cover a variety of probabilistic approaches for developing probabilistic flood information for various flood-related purposes. This section is restricting the term PFHA to those cases where the probabilistic information is to be used for assessing risk leading to Risk-Informed Decision-Making (RIDM). This level of detailed analysis is usually employed when very large capital expenses are anticipated for dams with very high and extreme consequences of failure.

Stochastic flood modeling is the preferred approach for many water resource agencies for conducting a PFHA when major capital expenses are anticipated at dams with very high and extreme consequences of failure. Stochastic flood modeling provides a comprehensive analysis of the likelihood of various combinations of hydrometeorological inputs to provide a realistic assessment of the hydrologic loadings posed by very rare and extreme floods. The probabilistic flood information is expressed as probability-plots that are termed Hydrologic Hazard Curves (HHCs). HHCs can be developed for any flood characteristic that can be obtained from watershed modeling such as: reservoir peak inflow; reservoir inflow volume; maximum reservoir level (Figure 17); depth and duration of flooding above a user-specified elevation such as a dam crest or earthen core; maximum reservoir discharge; magnitude and duration of discharge from a spillway; etc. The HHCs are necessary inputs for conducting risk analysis and for assessing the likelihood and consequences for various potential failure modes for existing dams and for using PFHA within a design mode for new dams.

Stochastic flood modeling can be paired with uncertainty analysis that allows both a mean-frequency curve and uncertainty bounds to be computed for the HHCs.

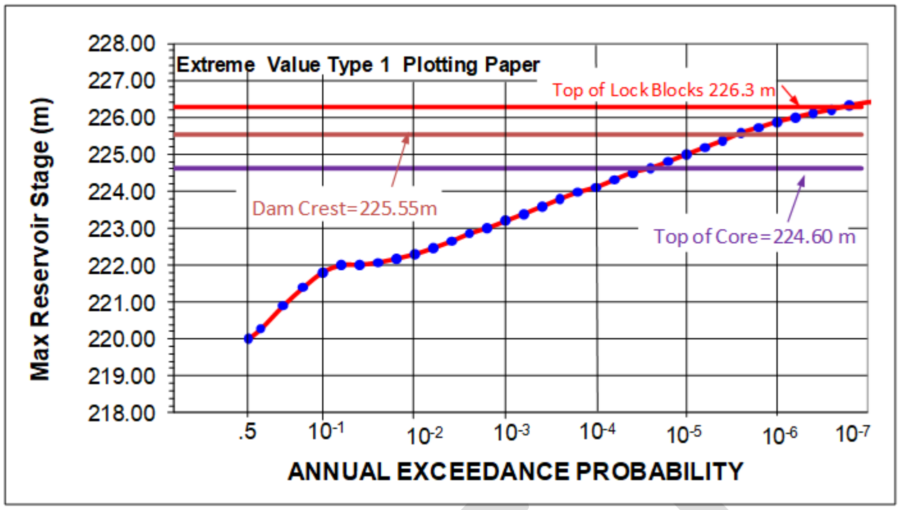
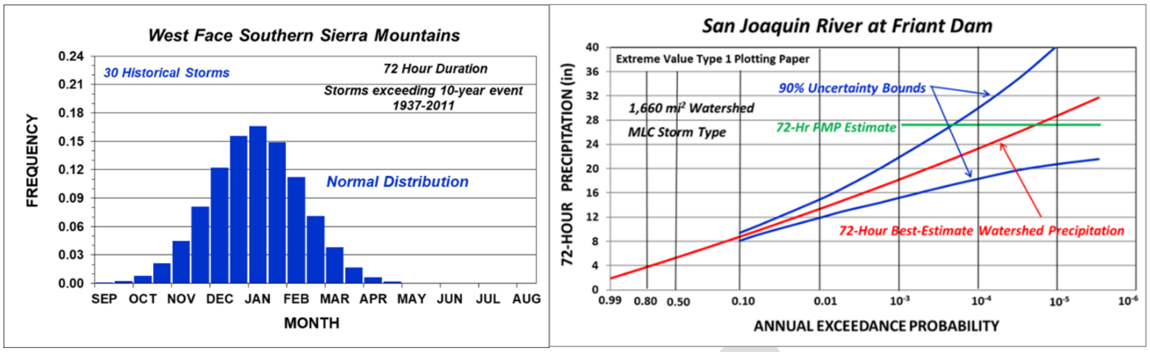


Figure 17. Example of hydrologic hazard curve for maximum reservoir stage

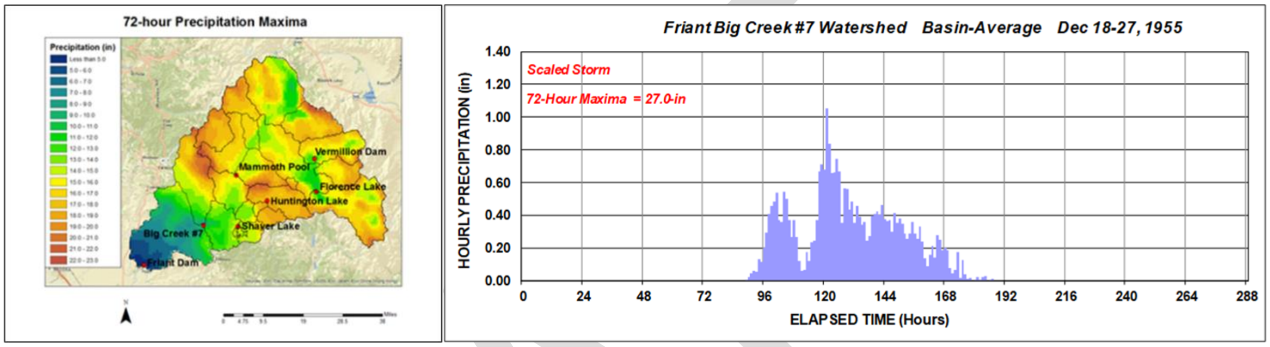
Basic Concepts for Detailed Stochastic Flood Modeling

The basic concept in stochastic flood modeling is to employ a conventional watershed model for flood computations and to treat the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the hydrometeorological input parameters to vary in accordance with that observed in nature while preserving the natural dependencies that exist between some climatic and hydrologic parameters. Multi-thousand computer simulations are conducted where each simulation contains a set of hydrometeorological inputs that are selected based on historical data for each input while preserving any dependencies that exist between hydrometeorological variables. The simulated floods constitute elements of an annual maxima flood series and the resultant hydrologic hazard curves (Figure 17) reflect the likelihood of occurrence of the various combinations of hydrometeorological factors that affect flood magnitude. Figure 18 depicts the various hydrometeorological inputs to a watershed model that are used in stochastic flood modeling for developing HHCs. The graphics in Figure 18 were obtained from a project for the USBR in southern California where a sample set of 18 spatial and temporal storm templates were used in developing HHCs.



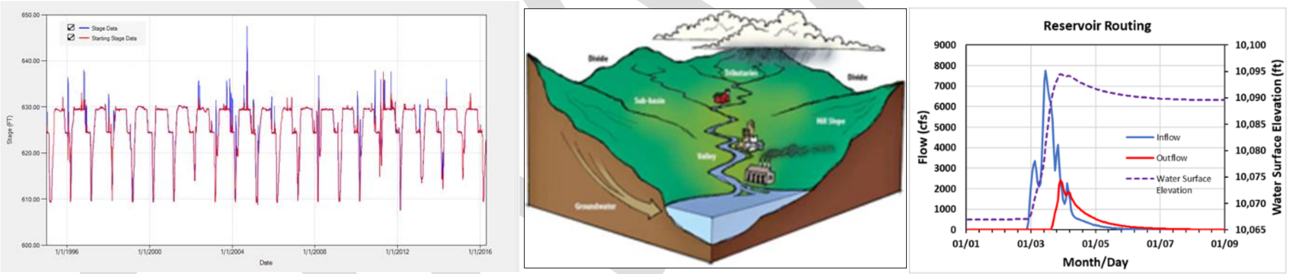
Season of Storm Occurrence

Precipitation Frequency



Storm Spatial Coverage

Storm Temporal Distribution



Initial Reservoir Level, Snowpack, Soil Moisture

Watershed Model

Reservoir Routing

Figure 18. Depiction of storm-related and other hydrometeorological inputs to the watershed model for stochastic modeling of floods

The detailed stochastic flood modeling approach requires assembly of historical data for the various meteorological and hydrometeorological variables listed in Section 5.1. Those data may either be for the specific project or obtained from a hydrologically similar watershed. The data may be resampled directly in the stochastic flood simulations, or probabilistic analyses can be conducted wherein a probability distribution is fitted to the historical data and hydrometeorological inputs are sampled from the fitted distribution.

Available options for stochastic flood modeling

The very large number of flood simulations required for stochastic flood simulations requires either dedicated software specifically for that purpose or for the chosen watershed model to be run in a batch mode. The following is a list of software programs where the watershed model(s) operate in a stochastic mode specifically for generating Hydrologic Hazard Curves.

- Stochastic Event Flood Model (SEFM)
- HEC-WAT with FRA compute option

- Australian RORB model
- EDF SCHADEX method

Details of the stochastic flood modeling approach

The detailed stochastic approach is data intensive and users are directed to read the user manual and reports from completed projects to obtain a working understanding for conducting the stochastic flood modeling. Users of this method are also directed to ICOLD Bulletin 187 Flood Evaluation, Hazard Determination and Risk Management Chapter 3 – Stochastic Approach to Flood Hazard Determination (Micovic, 2019).

10 Summary

This document provides a level of effort expected by the Ministry of Forests regulators regarding flood studies that are completed for freshwater reservoirs in BC. The Ministry of Forests currently does not have regulatory standards for rainfall-runoff modelling or uncertainty assessment. There is no simple guidance that can be provided to incorporate the effects of numerous types of uncertainty with estimated IDF values. To determine the design flood event for a dam, scientifically-defensible methodologies, of sufficient rigor considering the failure consequence of the dam, should be used. The dam owner and regulator should be able to use the information to make informed decisions.

A defensible study is generally considered by regulators to be one that the registrant who completed the study, and reviewers, have confidence in the magnitude of flood best estimate and an adequate analysis and/or discussion of the uncertainty with the estimate has been documented, commensurate with the failure consequence of the structure. As each dam has unique hazards acting on it, hydrologists should use the applicable guidance documents that are available, as required, from the Canadian Dam Association and various other dam safety organizations and/or dam safety jurisdictions.

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