ENGINEERS & GEOSCIENTISTS BRITISH COLUMBIA

PRACTICE ADVISORY

DETERMINING DAM HYDROLOGIC LOADING

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This practice advisory has been issued for registrants of Engineers and Geoscientists BC (engineering/geoscience professionals) who provide services related to hydrologic loading (i.e., from a flood event) on dam reservoirs and impoundments. Specifically, this advisory focuses on the role and responsibilities professional registrants[1] who undertake hydrologic loading estimation work.

This advisory discusses:

- the regulatory framework for dam safety in British Columbia (BC) as it relates to hydrologic loading;
- evaluating sources of uncertainty when estimating flood magnitude, including future climate change effects;
- types of flood hazard studies and reasons for conducting a hydrologic loading estimation study, such as for the design of a new dam or the evaluation of the safety of an existing dam;
- sources of information and data for completing a dam hydrologic loading estimate;
- flood magnitude estimation methods;
- addressing flood estimate confidence and uncertainty; and
- application of Engineers and Geoscientists BC quality management standards to this type of work.

For the purposes of this advisory, dam hydrologic loading is defined as an external hydrologic hazard acting on a dam, caused by high-intensity, high-frequency, or long-duration precipitation events and/or rapid snowmelt events.

Failure of the water conveyance system caused by debris blockage or gate inoperability may also occur during a flood event, but is outside the scope of this advisory.

There is historical evidence of dams being breached at reservoir inflows at far less than the design flood; these failures occurred within the design envelope due to an unusual combination of rare or even common events that arose at the same time as a flood event. This type of safety failure mode

[1] A "professional registrant" is defined by the Engineers and Geoscientists BC Bylaws as a registrant (also referred to in this advisory as an "engineering/geoscience professional") who is registered in a certain category, for example, P.Eng., P.Geo., P.L.Eng., or P.L.Geo. (Engineers and Geoscientists BC 2022a).

analysis should be considered during initial dam design, and should also be addressed during legislated dam safety reviews (see the *Professional Practice Guidelines – Legislated Dam Safety Reviews in BC* [Engineers and Geoscientists BC 2016]).

The intent of this practice advisory is to provide information that professional registrants can use to develop defensible dam hydrologic loading studies. A defensible study is generally considered to be one that:

- provides a reliable magnitude of flood estimate that the professional registrant and technical or independent reviewers can have confidence in;
- presents an adequate analysis, commensurate with the failure consequence of the structure; and
- documents and discusses the uncertainty with the estimate, commensurate with the failure consequence of the structure.

Determining dam hydrologic loading is a highly complex scope of work typically undertaken by registrants with subject matter expertise; as referenced in the Code of Ethics principle 2, professional registrants undertaking this work must be professionally competent to undertake this work, including having the appropriate education and relevant experience, and participating in ongoing training.

Each dam has unique hazards acting on it, so professional registrants must also consult guidance documents that apply to their particular project. Applicable guidance is available from various sources, such as Engineers and Geoscientists BC, provincial regulatory authorities, industry organizations (such as the Canadian Dam Association), and international dam safety organizations.

REGULATORY FRAMEWORK

Professional registrants must be knowledgeable about the appropriate regulatory framework and apply dam safety guidelines that are suitable for the system under study.

In BC, freshwater dams and mining dams are designed and regulated based on the failure consequence of the structure.

- The BC Ministry of Forests, the regulatory authority for freshwater dams, has adopted the flood hazard targets published by the Canadian Dam Association (CDA 2013). Freshwater dams in BC are regulated through the *Water Sustainability Act* and the *Dam Safety Regulation*.
- The BC Ministry of Energy, Mines, and Low Carbon Innovation, the regulatory authority for mining dams, provides a minimum flood design criteria in their *Health, Safety and Reclamation Code for Mines in British Columbia* (BC Ministry of EMLCI 2021), and indicates that the engineer of record for the dam shall determine the appropriate flood criteria.

Applicable regulations and guidelines are used to assess the failure consequence of the dam and determine corresponding design criteria. These approaches to determining hydrologic loading are for initial consideration, and higher design criteria can be adopted, as deemed appropriate.

BACKGROUND

Large-magnitude flood events in BC are typically caused by a combination of factors, such as melting of a large snowpack, late freshet, rain-on-snow events, higher-than-normal spring temperatures, and/or long-duration rainfall events. A combination of processes within a watershed may result in much greater flow events than might be anticipated through model calibration with observed data. Alternatively, the occurrence of an extraordinary event in an adjacent watershed (such as a landslide) may cause diversion of water into the design watershed.

EVALUATING UNCERTAINTY IN FLOOD MAGNITUDE ESTIMATES

Estimation(s) of the magnitude of flood events will always contain considerable uncertainty for a number of reasons. For example, the following factors can contribute to uncertainty in flood magnitude estimates:

- availability and quality of relevant rainfall, streamflow, and temperature data;
- availability of watershed characterization information;
- suitability of different flood estimation methodologies and/or models;
- decisions made by the professional registrant conducting the study; and
- watersheds and climate that are continuously changing.

Usually, the general approach for estimating the magnitude of flood events is to use historical information to predict how systems will behave in the future (i.e., assumption of stationarity). One problem with this approach is that low-probability or extreme flood events occur infrequently, so the data on these types of events may be absent from, or poorly represented in, historical records.

Furthermore, assumptions regarding climate stationarity are not valid in a changing climate. Therefore, it is necessary to not only determine the best estimate of the magnitude of a flood event, but also to assess the uncertainty of the estimate.

The Climate Change Action Plan (Engineers and Geoscientists BC 2021a) indicates it is no longer appropriate to base engineering and geoscience practice solely on historical climate data and methods. With climate change, extreme precipitation is expected to become more intense due to the increase in atmospheric moisture. Other future projected impacts include changes to watershed ecology and land cover, and changes to local flood regimes, which may transition from being snow-dominated to being rain-dominated, due to increasing atmospheric temperatures.

Therefore, all types of climate data—historic, current, and projected future—should be considered, and risk-informed approaches or other well-supported methods should be used to address climate change impacts on analyses. It is recognized this is an evolving area of engineering analyses.

TYPES OF FLOOD HAZARD STUDIES

Flood hazard studies are usually completed for the design of a new dam or the evaluation of the safety of an existing dam.

- The design for a new dam is based on the largest possible hydrologic event (for example, a rain-on-snow event in the spring or a rainstorm event in the summer) for the associated dam classification; this type of study is generally referred to as the inflow design flood (IDF).
- A study completed for the purpose of a safety evaluation can be referred to as the safety evaluation flood (SEF) estimate.

The level of effort and the methodology selected to meet the requirements of the study should be commensurate with the failure consequence of the structure and the reason for completing the analyses. The different classifications of studies, each of which have specific applications in infrastructure design and decision making, are briefly discussed below.

INFLOW DESIGN FLOOD (IDF) STUDY

An IDF study consists of a methodical analysis of all the potential flood scenarios that could impact a reservoir or impoundment for selected return periods and/or the probable maximum flood (PMF). For some mining dams, the environmental design flood (EDF) is determined and refers to the hydrologic event volume that is to be stored within the facility.

In both cases, the reservoir watershed should be properly characterized, and sufficient information collected, to adequately construct a rainfall-runoff model that is a reasonable representation of the physical system, and/or to complete a regional flood frequency analysis.

The watershed area used for flood calculations should include any diversion areas that report to the reservoir, unless it can be shown that flows from the diversion can be successfully controlled during a flood event, and the structure limiting the flow to the reservoir watershed is designed to withstand the design flood for the specified event.

SAFETY EVALUATION FLOOD (SEF) STUDY

An SEF study consists of a critical evaluation of a previously completed IDF or EDF study. In some cases, this may require additional analyses; for example, if a lack of clear documentation or evidence is discovered during the review, suggesting that some assumptions and/or model coefficients that were used in the original design study may be incorrect or outdated. An SEF study may focus on the estimation of the magnitude of the peak flow and/or total volume of water entering the reservoir during a flood event.

If several years of data have been collected in the region since the dam was first constructed, it may be used to check the original design study assumptions and/or magnitude of the flood event. In some cases, precipitation and flood regional analysis studies may have been completed since the dam was first constructed, and the results of those studies should also be used to check the IDF and/or EDF estimates.

Some examples of when a detailed review of the existing hydrologic loading estimate may be required are:

- land surface characteristics have changed over a large portion of the watershed reporting to the structure, such as large areas of tree mortality or forest fire, or urban development, indicating that a flood event could result in observable increases to the magnitude of flow;
- an extreme flood or precipitation event has occurred in the same region as the design watershed;
- flood hydrology practices have improved since the original study was completed;
- further confidence in the IDF or EDF best estimate is required; or
- the uncertainty of the design flood event requires further assessment based on requirements from the regulatory authority, dam owner or other parties.

SOURCES OF INFORMATION AND DATA

Professional registrants should confirm they are using scientifically defensible methods from commonly referenced sources, such as academic research, recent studies, and published industry guidance. Professional registrants must be able to clearly explain the approach that they have taken and the rationale for it.

In BC, a substantial amount of hydrometeorological data and watershed characterization information required for a flood study has been collected and assessed. As well, numerous technical guidelines and publications published by various sources present several flood estimation methods; these are available for registrants completing a dam hydrologic loading study.

The following resources are published and maintained by Engineers and Geoscientists BC and should be considered points of reference for registrants:

- The Climate Change Information Portal is an online information source that provides access to climate change adaptation tools and resources (Engineers and Geoscientists BC 2022b). Professional registrants should regularly check the portal for new information.
- The *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* (Engineers and Geoscientists BC 2018) is a comprehensive review of the applicable provincial flood assessment guidelines.
  - These guidelines acknowledge that global climate change is affecting the hydrologic regime in BC and encourages engineering/geoscience professionals to include climate change considerations together with land surface changes in flood assessments, where appropriate.
  - Professional registrants must meet the intent of these guidelines when assessing the suitable level of effort required when completing a flood study for a dam, considering both the failure consequence of the structure and the purpose of the study.

PROFESSIONAL PRACTICE

FLOOD MAGNITUDE ESTIMATION METHODS

There are multiple methods for estimating the magnitude (peak flow and total volume) of flood events. However, in BC, there are currently no regulatory standards for rainfall-runoff modelling, regional flood frequency analysis, or uncertainty assessment.

Streamflow annual maximum series (AMS) measurements can be used for conducting single-station frequency analysis, and regional methods utilizing homogeneous regions can be used for estimating low-probability events by combining data from several different stations.

Similar methods are used to conduct precipitation frequency (PF) analysis on individual rainfall-gauge data sets, and regional analysis is used to pool the data and develop low-probability event estimates. A different approach is the probable maximum precipitation (PMP) estimate, which is a deterministic rainfall depth value based on observed storm-event data in a region. The results of the PF and PMP studies are used with a watershed rainfall-runoff model to estimate the magnitude of the flood events.

In watersheds where there is snow, temperature data is required to estimate snowmelt rates. Watershed antecedent condition information, rainfall data, and resulting streamflow data are utilized to calibrate rainfall-runoff models.

FLOOD ESTIMATE CONFIDENCE AND UNCERTAINTY

Confidence in the reasonableness of a flood-magnitude estimate is built through a series of checks using different methods or multiple lines of evidence. In general, increasing the level of effort and sophistication of analysis techniques will increase the confidence level of a flood-magnitude estimate. However, if the environmental data used to develop the estimate has questionable accuracy, or the data is spatially or temporally limited, the validity of the estimate using even a sophisticated methodology will be diminished. The professional registrant completing the study is responsible for assessing what methodology produces the best estimate, and which methodologies provide reasonable checks.

A single flow rate entering a reservoir during a flood event does not sufficiently characterize the flood hazard acting on a dam. Professional registrants should explore the various loading scenarios that apply to the reservoir, and explain the potential hydrologic loadings by using design hydrographs.

In addition, a qualitative discussion of the uncertainty of the data used in the study, a sensitivity analysis with clear presentation of all the potential flood scenarios, and a description of the uncertainty with the estimates should be included in the study report, as this provides important information to characterize the flood hazard acting on the structure. This information should be clearly communicated to the dam owner and regulatory authority to assist with the risk-informed decision-making process.

Specific considerations that affect the confidence and uncertainty of estimates are discussed below.

CLIMATE PARAMETER MEASUREMENTS

Rainfall and snow-depth data, as well as temperature, humidity, windspeed, and other environmental parameters, are typical point measurements that feed into estimating PF and PMP values. The meteorological stations that collect this data are commonly located in the more heavily populated areas across the province. In mountainous areas, the stations are typically located in the valleys, and much of the province does not have stations, so there can be large areas with sparse data collection.

These environmental parameters (some more than others) vary considerably spatially and with time. The frequency of parameter measurements also varies, depending on the type of climate station.

STREAMFLOW MEASUREMENTS

Hydrometric stations typically measure the water levels at a specific stream location. This water level is used to estimate the instantaneous flow rate past the station by using a stage-discharge relationship or rating curve, which is dependent on the cross-sectional area, slope, and roughness of the stream at the point of measurement.

Rating curves are built from multiple measurements of stream stage and discharge at a specific location and can be extrapolated to cover a larger range of conditions other than those observed. However, caution should be used when extrapolating rating curves to estimate flood flows. Large flood events can overtop stream channels, at which point the typical stage-discharge relationship is not applicable. Furthermore, flood events often create large amounts of sediment erosion and deposition within streams and often cause the stage-discharge rating curve to change at a hydrometric station during and after a flood. During unusual-magnitude flood events, it is not uncommon for the hydrometric station to be destroyed, requiring professional registrants to instead estimate the maximum instantaneous flow rate during that flood.

FREQUENCY ANALYSIS

AMS measurements for environmental parameters, such as rain or snow depth, streamflow, and air temperature, are typically used with a frequency distribution fit to the data to estimate the magnitude of events of specific return periods or probabilities.

Interpolation of the AMS data to estimate the magnitude of the event for selected return periods can be done with reasonable confidence. Using the AMS data to extrapolate the magnitude of the event for selected return periods that historically have not been observed requires the assumption that the frequency distribution curve will represent these extreme events. Frequency analysis criterion for AMS data includes randomness, independence, stationarity, and homogeneity (Watt et al. 1989). It should be noted, however, that environmental data often do not strictly meet these statistical tests, and professional registrants must decide whether the AMS data are suitable for making event magnitude estimates for the required return periods.

Regional frequency analysis is a method of reducing uncertainty and consists of the analysis of environmental observations collected at a number of measuring sites within a suitably defined homogenous region. Regional analysis provides a scientifically defensible method for estimating precipitation, streamflow, air temperature, and other quantiles necessary for determining the rare-to-extreme flood events required for dam design or safety assessment.

Professional registrants are expected to conduct a robust regional analysis that provides adequate documentation for the selected region. A flood analysis that is based on data from a few hydrometric stations or rainfall gauges that are geographically close to or within the watershed of interest will not, in most cases, provide a flood estimate with sufficient confidence for design of a dam. The Climate Change Information Portal provides information on comparable climate and flood regions within BC (Engineers and Geoscientists BC 2022b).

It should be noted that climate change disrupts the suitability of AMS data by affecting the statistical assumptions implicit in frequency analysis. That is, the stronger the climate change signal, the less likely the past will be a good representation of what will happen in the future. In BC, it is generally acknowledged that what were formerly considered “infrequent” magnitude events are in fact occurring more frequently, likely due to climate change. However, in general, there is considerable uncertainty and data gaps in assessing climate-driven observed changes in the magnitude and frequency of floods at a regional scale. This is due to the limited availability of records of floods at gauge stations, and due to masking effects of changes in land use and antecedent conditions.

PROBABLE MAXIMUM PRECIPITATION

There are several sources of uncertainty when developing PMP estimates for a specific design watershed. King and Micovic (2022) provide a definition for PMP and a discussion of these sources of uncertainty when they conducted a PMF study for a reservoir in BC using PMP estimates taken from the BC MetPortal (an online application hosted by the BC Ministry of Forests as part of the BC Extreme Flood Project, which provides regionally consistent baseline PMP estimates across BC).

Current literature on the topic of PMP and climate change does not provide a definitive procedure on how to assess if or how design values for extreme storm events such as the PMP should be modified.

Professional registrants should be knowledgeable on the subject and use defensible methodologies when accounting for any uncertainty, including climate change, when estimating the PMP for a reservoir.

HYDROLOGIC MODELLING

A hydrologic model is a representation of the watershed area for the purpose of estimating the flow rate and volume of water entering the reservoir, given specified rainfall and/or snowmelt forcings.

An uncalibrated rainfall-runoff model will result in low confidence of the magnitude of flood estimated, even with a detailed or sophisticated model. Confidence in the ability of the model to predict reasonable results is built by calibrating the model against the historical flood of record in the watershed, developing a relevant hydrometric station flood frequency analysis, and determining regional flood frequency relationships and regional peak flow envelopes.

Uncertainty due to hydrologic modelling can be assessed using sensitivity analysis by varying model parameters to assess the change in hydrologic response.

APPLICATION OF QUALITY MANAGEMENT STANDARDS

All engineering/geoscience professionals must have regard for the regulatory framework and enactments applicable to their work. Engineering/geoscience professionals are required to follow quality management standards defined in the Bylaws of Engineers and Geoscientists BC (2022a), including determining whether they are qualified by training and/or experience to undertake and accept responsibility for the work. Furthermore, engineering/geoscience professionals involved in any high-risk professional activity or work must have an independent review of the high-risk work carried out by another appropriately qualified engineering/geoscience professional before the work is submitted to those who will be relying on it.

Depending on the relevant knowledge of the professional registrant completing the flood study, the professional registrant and/or dam owner may determine it is necessary to collaborate with a specialist such as a meteorologist (or similar) to conduct part of the required study. In this case, the professional registrant should refer to the *Practice Advisory – Relying on the Work of a Specialist* (Engineers and Geoscientists 2021b).

Dam hydrologic estimation work is generally considered high risk. In high-risk circumstances, professional registrants must also meet the requirements for independent review of high-risk professional activities and work. For water reservoir dams, the BC Ministry of Forests recommends that dams with a "significant" or higher consequence classification undergo independent review, as the dam failure consequence is risk-informed itself. Professional registrants should substantiate their decision whether to carry out independent review with a documented risk assessment that follows the requirements of the *Guide to the Standard on Independent Review of High-Risk Professional Activities and Work* (Engineers and Geoscientists BC 2021c).

It is understood that considerable professional judgment is necessary when determining data requirements, determining appropriate methods of analyzing or modelling the system, managing conflicting data, and communicating the level of uncertainty commensurate with the failure consequence of the structure. Compensation for professional services is a matter between professional and client; however, services provided must meet the intent of applicable guidance and current industry practice. Professional judgment cannot be used as a substitute for insufficient budget or time.

SUMMARY

When determining the hydrologic loading hazard for a dam, professional registrants must ensure that sufficient study has been completed in an appropriate manner, using scientifically defensible methodologies of sufficient rigor considering the failure consequence of the dam, such that the owner and regulatory authority can use the information to make informed decisions.

In BC, there are currently no regulatory standards for rainfall-runoff modelling, regional flood frequency analysis, or uncertainty assessment. Similarly, there is no simple guidance that can be provided to incorporate the effects of numerous types of uncertainty with estimates. This emphasizes the importance of applying sound professional judgment in accordance with relevant published industry guidance and research. Professional registrants who undertake this work should assess if there is an apparent or substantiated trend in factors that contribute to producing flood events in the applicable region, and should use appropriate methods to determine the best estimate as well as assess the uncertainty of the estimate.

Professional registrants must be appropriately qualified by education, training, and experience, and able to apply relevant guidelines, published methods, and current industry practice to their work. It is important that professional registrants stay up to date on information that is posted on the Engineers and Geoscientists BC Climate Change Portal (2022b), as well as with relevant industry and research publications and guidelines. Practices that were generally accepted in the past may now be obsolete considering advances in extreme flood estimating methodologies and available information.

REFERENCES AND RELATED DOCUMENTS

LEGISLATION AND REGULATIONS

Dam Safety Regulation [B.C. Reg. 40/2016].

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VERSION HISTORY

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1.0	August 2, 2022	Initial version.