# Uncertainty in Hydrologic Modelling for PMF Estimation

## Introduction

Estimation of the Probable Maximum Flood (PMF) has become a core component of the hydrotechnical design of dam structures [1]. There is a range of definitions of what a PMF is [2], but in general it is calculated by running a hydrologic model with a maximized precipitation event (PMP) as the input. A range of computer models have been used for this purpose, with different levels of complexity.

Most models will attempt to extract losses (interception, surface storage, infiltration) from the input and build a runoff hydrograph using empirical curves or by routing the excess water. Even the simplest models generally involve many parameters to describe these processes. Some parameters are estimated from published values, and others are set based on past practice and calibration of the model to observed rainfall-runoff data-sets.

The PMP inputs are generally combined with wet initial conditions, often modeled as a large storm immediately preceding the PMP. This results in peak flow and runoff volume estimates for PMF that are generally many times larger than any historic observations that may be available for calibration or verification of the model. This extrapolation introduces many uncertainties into the modelling process.

Application of PMF modelling to certain dam sites in Alberta has yielded a significant range of estimates from various sources. Attempts to improve consistency in these estimates [2] have identified many of the potential problems, but have been unable to provide specific guidance to address these problems. Some of the key issues identified include the magnitude of inputs (PMP, snowmelt), combination of inputs (e.g. rain plus snow, rain before PMP), limited availability of hydrologic data, complexity of the models, and changes in physical processes between the calibration data and the extrapolated PMF scenario. The difficulty in evaluating the results of these models has also been noted, due to the large extrapolation from known conditions.

## Inputs

The estimation of the PMP involves some uncertainty. The most accurate maximization processes rely upon upper air data, which is only available at one location in Alberta. The maximization is applied to large historic storms, leading to questions of how transposable these storms may be. Also, the storms are expressed in terms of depth-area curves, with the actual shape (geographical distribution) of the original storm being lost. Separation of storms into convergence and orographic components is largely done based on statistics, with little physical guidance available for maximization in areas of variable topography. Questions have also been raised as to potential limits on orographic lifting beyond certain elevation limits.

Another issue with inputs to PMF models is for areas where snowmelt may be a factor. Snowmelt estimation involves both available snow-pack and an aggressive temperature sequence to produce the melting. Consistent techniques for maximization of snowmelt are not available. The impact of snowmelt due to rainfall adds additional uncertainty to snowmelt estimates.

Additional uncertainty, in the model inputs is the combination of events used to derive the PMF estimate. In order to ensure that the estimate is based upon wet initial moisture conditions, it is common to run a large storm over the basin at a certain time prior to the PMP. In some cases, this has been an estimated 1:100 year storm, or a known historical storm for the area. This approach introduces questions of combined probability, can be somewhat arbitrary, and requires the model to account for potential drying of the basin.

## Complex processes

The rainfall-runoff response involves many physical processes, many of which are quite complex and not fully understood. For large basins, factors such as interception, surface storage, and infiltration capacity can vary greatly across the basin. Likewise, the drainage network can vary greatly, comprised of many channels and lakes with variable hydraulic properties. These parameters can also change with time due to factors such as land use, development, and post-flood channel changes.

This complexity is highlighted by the variance in the rainfall-runoff response noted in the existing data-sets [3]. Analysis of the response for the largest runoff events in Alberta notes some general trends. However, examination of the response at any one gauge with multiple events shows significant scatter that cannot be readily explained. This observation also highlights the fact that a model cannot be calibrated to all available rainfall-runoff data-sets.

## Data Limitations

Natural basins exhibit great diversity in hydrologic properties. Therefore, even if the physical processes were fully understood, a great deal of data would be required to precisely model the physics of the rainfall-runoff response. Available DTM and GIS vector data-sets can assist in quantifying certain geometric aspects of basins, such as sub-basin delineation and slopes. However, these data-sets offer limited ability to assess surface storage, overland flow characteristics, and network capacity.

Subsurface parameters affecting infiltration capacity may also vary significantly over a basin. Geologic maps and boreholes can provide some general guidance on soil properties, but little data is available on infiltration rates. As such, infiltration parameters are generally selected based on published values for the model being used, with modifications based on calibrations.

Data-sets can also impose limitations on calibrations. Rainfall gauging network density limits the ability to fully assess historic storms for use in calibration. Significant interpolation is usually required, and the eye of the storm may be poorly represented.

The timing of the storm can also vary across the basin. The lack or limited operation of a runoff gauge at the design site will also affect the ability to calibrate the model.

## Extrapolation

Estimates of PMP for sites in Alberta are typically in the range of double the typical large storm [4]. With the wet initial moisture conditions and typical hydrologic models which apply most of the losses to the first part of the rainfall, the majority of the increased rainfall input is assumed to become runoff. This results in peak flow and runoff volume estimates for PMF that are in the 4 to 5 times largest historic events for high runoff potential basins, and even higher ratios for less productive basins.

This significant extrapolation beyond observed events introduces significant uncertainty into PMF modelling. Many of the physical processes involved in the conversion of rainfall to runoff may be quite different under these extreme conditions. Hydraulic response of the drainage network changes dramatically once bankfull conditions have been exceeded. Significant storage areas may become activated during the routing of flows. Infiltration losses will likely be less than typically observed during smaller storms, but the magnitude under these extreme conditions is unknown. There may also be limitations on the timing of the PMP in order to reach these large rainfall values.

Due to the extent of extrapolation and changes in physical processes, even a well calibrated model is of little value under these conditions. More complex models may provide better fits to existing data, but introduce more parameters with uncertain values when applied to PMF conditions. The large number of parameters combined with the range of uncertainty results in a great range of possible results.

## Verification

With a large range of possible parameters and results, and the significant extrapolation from known data-sets, it becomes very difficult of judge which set of results is most applicable for the site. Some empirical techniques have been suggested to assist in this judgment. Comparison of runoff coefficients and unit discharges with results from other sites has been suggested as a method of evaluating consistency with other accepted values. However, there is a great disparity in runoff response across the province, making it difficult to know which sites are applicable for comparison of runoff coefficients. The Creager diagram has been promoted as an area-independent measure of flood severity. However, a recent flood envelope curve study [7] has shown that the Creager curves do not fit with the observed data-sets for Alberta, and that the Creager coefficient cannot be considered area-independent.

## Application

An example of the wide range of results possible with PMF studies is the Dickson Dam on the Red Deer River. The results of a 1979 PMF study, used for design of the dam, and an updated estimate from 1999 are shown in Table 1. The two largest historical events are also shown for context. The updated PMF estimate resulted in only a 10% increase in rainfall, but a 120% increase in peak flow and a 40% increase in runoff depth. A snowmelt contribution of 25mm was included in the 1999 PMF. It therefore appears that the significant increase in PMF flow is based on updated model calibrations (mostly timing) and changes in the standard practice for PMF estimation (mostly aggressive antecedent moisture conditions). The calibration events used in the 1999 study were recorded in 1990 and 1999, both of which had runoff depths less than 10mm and peak flows less than 1000cms. A subsequent review [5] of the updated PMF estimate recommended a peak flow of about 10,000cms. This review concluded that floodplain routing effects were minimal, although the entire base of the valley (up to 30 times the width of the channel) was treated as a channel.

**Table 1 – Dickson Dam, Alberta**

| Event | Rainfall (mm) | Runoff (mm) | Peak Flow (cms) |
|---|---|---|---|
| 1979 PMF | 290 | 200 | 5300 |
| 1999 PMF | 320 | 280 | 11800 |
| 2005 Flood | 95 | 30 | 2200 |
| 1915 Flood |  | 40 | 2000 |

An example of the extrapolated conditions at PMF can also be seen in recent studies for the Travers Reservoir and Little Bow Lake [6] in south-east Alberta. The impact of a reported severe prairie storm near Vanguard, Saskatchewan in 2000 was considered 6. This severe storm was barely picked up by the Environment Canada gauges, but a bucket survey of the area suggested about 375mm of rainfall fell in about 8 hours near the eye of the storm. The 300mm isohyetal covered an area of 300km$^2$. Transposing and maximizing this storm (only 1.2 multiplication) showed it to be of similar magnitude to the local storm (6 hour duration) PMP and by extension the general storm (48 hour) PMP used in the study. However, the estimated runoff coefficients derived in the PMF study were in the 0.43 to 0.48 range, whereas the direct runoff coefficient for the Vanguard storm has been estimated to be about 0.2. It was speculated in the study that the much higher values used in the PMF analysis are justified by the aggressive antecedent moisture conditions. No runoff coefficients in excess of 0.1 have been recorded in this area of Alberta. The runoff hydrograph for the Vanguard event shows a long duration of relatively high flows after the peak, suggesting that floodplain storage was a significant factor during the runoff.

## Conclusion

Hydrologic modelling is required to generate estimates of PMF for the design of dams. However, the process involves great uncertainty due to factors such as arbitrary inputs, complex physical processes, limited data availability, and significant extrapolation from known conditions. A wide range of results can be produced and there is little justification for the selection of one result over another. Recent attempts to improve the consistency of results have done little to address the fundamental issues.

Analysis of runoff data in Alberta has shown that a design hydrotechnical event equivalent to the largest historical event can be developed with some confidence and consistency [8]. It is understandable that design parameters for high consequence dams exceed the highest historical levels. However, with the level of uncertainty in PMF estimates, the extent of conservatism is not readily known, and it is very difficult to achieve consistency over a system. Practical alternatives could be investigated for use in dam design that do provide some context and could be used in an economic analysis to optimize the design. One such alternative could be to design the service spillway and the auxiliary fuse-plug spillway each for a flow value a certain amount in excess of the largest historic event. This could be considered similar to a factor of safety, with the overall multiplier selected based on the consequence of the dam, and the distribution between the service and auxiliary spillways could be based on economic analysis. An approach such as this would provide a clear context for the design event and consistency across the system.

## References

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