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Uncertainty analysis for Probable Maximum Precipitation estimates

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SUMMARY

An analysis of uncertainty associated with Probable Maximum Precipitation (PMP) estimates is presented. The focus of the study is firmly on PMP estimates derived through meteorological analyses and not on statistically derived PMPs. Theoretical PMP cannot be computed directly and operational PMP estimates are developed through a stepwise procedure using a significant degree of subjective professional judgment. This paper presents a methodology for portraying the uncertain nature of PMP estimation by analyzing individual steps within the PMP derivation procedure whereby for each parameter requiring judgment, a set of possible values is specified and accompanied by expected probabilities. The resulting range of possible PMP values can be compared with the previously derived operational single-value PMP, providing measures of the conservatism and variability of the original estimate. To our knowledge, this is the first uncertainty analysis conducted for a PMP derived through meteorological analyses. The methodology was tested on the La Joie Dam watershed in British Columbia. The results indicate that the commonly used single-value PMP estimate could be more than 40% higher when possible changes in various meteorological variables used to derive the PMP are considered. The findings of this study imply that PMP estimates should always be characterized as a range of values recognizing the significant uncertainties involved in PMP estimation. In fact, we do not know at this time whether precipitation is actually upper-bounded, and if precipitation is upper-bounded, how closely PMP estimates approach the theoretical limit.

1. Introduction

Probable Maximum Precipitation (PMP) is "Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a given time of year" as defined in U.S. National Weather Service Hydrometeorological Report No. 55A (1988). PMP is used for estimating the Probable Maximum Flood (PMF), a parameter used for the design and operation for dams and spillways. Most PMP estimating procedures are based on rather complex meteorological analysis, whereas some earlier attempts were based on statistical analysis.

In the early years of the evolution of PMP estimation, Hershfield (1961a) developed a statistical method for estimating PMP. His method was based on the frequency analysis of the historically recorded annual maximum rainfall data at the location of interest. More specifically, Hershfield defined the PMP at a site by summing the mean value of annual rainfall maxima and the standard deviation of annual rainfall maxima multiplied by a frequency factor of 15. Hershfield estimated this frequency factor of 15 as the maximum observed value among 95,000 station-years of annual maximum rainfall data from 2645 stations, about 90% of which were located in USA. Later on (1965), Hershfield suggested that the frequency factor should not have the constant value of 15, but it should vary with rainfall duration. He noticed that the value of 15 is too high for wet (heavy rainfall) watersheds and for rainfall durations shorter than 24 h. Consequently, Hershfield derived a chart showing the variation of the frequency factor between the values of 5 and 20 depending on the mean value of annual rainfall maxima and the rainfall duration. More recently, Rezacova et al. (2005) used statistical method to derive point-PMP estimates for durations of 1–5 days, and then converted those estimates to basin average PMP values. The point-to-area conversion factors were derived through the analysis of local radar precipitation data. While statistical methods for PMP estimation provide relatively quick and easy way to obtain estimates of the PMP, they are seldom used in final design these days and have been replaced by more complex methodologies involving meteorological analyses. Therefore, the focus of this paper is firmly on PMP estimates

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derived through meteorological analyses. Such types of PMP calculations involve use of observed precipitation from historical storms modified by applying moisture maximization, storm transposition and other considerations (U.S. WB, 1961; WMO, 1986; U.S. NWS, 1988, 1994, 1999; Commonwealth Bureau of Meteorology, 2003). Meteorological PMP estimation methods could be generally categorized as follows:

- "In situ" storm maximization where only storms that had occurred over the catchment were maximized.
- Storm transposition methodology where storms that had occurred near the watershed or in areas with similar climatology/topography, are transposed to the watershed and maximized. This approach increases the sample size of historical storms that could be used for PMP estimation.
- Generalized (regionalized) methodology which represent an extension of storm transposition approach since it analyzes all available storms over a large region and include adjustments for topographic effects on PMP estimates.
- Storm model approach (Collier and Hardaker, 1996) which uses various physical parameters (height of storm cell, surface dewpoint, inflow and outflow) to simulate extreme precipitation.

Due to its theoretical definition as the physical upper limit, the concepts of PMP and resultant PMF floods are often believed to provide absolute safety or zero risk of dam overtopping. This is not true since theoretical PMP cannot be computed directly and operational PMP estimates are developed through a stepwise procedure in which meteorologists, due to limited availability of historical data, have to apply a significant degree of subjective professional judgement. Therefore, operational PMP estimates are typically lower than the theoretical upper limit by some variable amount that depends on the available storm data, the chosen methodology and the analyst's approach to deriving the estimate. Consequently, the exceedance probability of PMPs and resultant PMFs is typically greater than zero and could be relatively high in some cases. For instance, the National Research Council (1994) suggests that the return period of the PMP in the USA varies between 10^5 and 10^9 years. Furthermore, Koutsoyiannis (1999) used the Generalized Extreme Value (GEV) distribution to estimate a return period of PMP values derived by the Hershfield's method and came up with the return period of less than 10^5 years. It is therefore our opinion that it is more appropriate to provide ranges of PMP values rather than a single estimate, since there are multiple factors and uncertainties which can influence PMP.

This paper identifies sources of uncertainty in estimating PMP and discusses development of a methodology for assessing uncertainties. This methodology is intended for development of uncertainty bounds for PMP estimates to provide practitioners with information leading to more informed decisions on the hydrologic adequacy of dams and dam safety. In addition, we present the findings of a site-specific application of the methodology for assessing uncertainties in PMP estimates.

The paper is structured in the following manner: Section 1 discusses uncertainty in PMP estimates and relevant implications for various dam safety risk assessments. It also provides a brief discussion on physical limitation of commonly used PMP derivation concepts (moisture maximization, storm transposition, and storm efficiency assumptions) as well as a broad list of variables influencing the final PMP estimate. Section 2 provides in-depth discussion of some of these variables, including moisture maximization, methods used for storm analysis, storm center characterization, watershed/reservoir characteristics, temporal characteristics of the PMP storm, input data used in the analysis, and climate change considerations. Section 3 discusses some other factors that should be considered during the PMP estimation process such as non-linearity of maximized precipitation, PMP physical upper limit, and safety factors or conservatism built in certain PMP estimation methods. The PMP derivation for the La Joie basin in Canada is described in Section 4. Section 5 presents the proposed methodology for assessing PMP uncertainties and identifies five sources of uncertainty (in-place moisture maximization, surface dewpoints, storm horizontal transposition, storm center location and storm efficiency) used in the calculation along with their respective likelihood functions reflecting their plausible ranges. The results of the PMP uncertainty analysis for La Joie basin and their comparison with the traditional single-value PMP estimate are also shown in Section 5. Section 6 follows up by describing the derivation of the La Joie basin PMF and effects different PMP inputs have on it, i.e. the traditional single-value PMP estimate versus the range of PMP estimates obtained through the uncertainty analysis. Finally, Section 7 summarizes the study and provides concluding remarks.

1.1. Uncertainty in PMP analysis

Generally, PMP is assumed to be the upper bound for extreme precipitation values for dam safety, flood assessment, and other hydrological analyses. PMP values are generally listed and presented as single values; in reality, considerable uncertainty exists in these estimates due to various factors. In the example provided by Downton et al. (2005), the site-specific PMP for the Cherry Creek Dam watershed in Colorado, USA was estimated by the U.S. National Weather Service (NWS) in 1995. The 24-h PMP value was estimated to be 53.6 mm. The United States Army Corps of Engineers (USACE) then used this PMP to derive the Cherry Dam PMF and concluded that the dam could safely control only 75% of the PMF. To evaluate the NWS PMP estimate, Colorado Water Conservation Board in 2000 selected a consultant, Applied Weather Associates (AWA) to carry out a new site-specific PMP study for the Cherry Creek Dam watershed. The PMP estimates derived by AWA were lower than the NWS estimates by about 25% and received criticism from NWS experts. According to Downton et al. (2005), AWA and NWS disagreed on several aspects of PMP estimation methodology including orographic and barrier effects in the basin and assumptions about the spatial distribution of extreme rainfall. Consequently, USACE was reluctant to update the PMF estimate based on AWA PMP which would likely result in lower PMF (assuming all other PMF inputs such as basin impermeability, forest cover and initial snowpack remain unchanged) and indicate that the dam could safely handle more than 75% (and possibly 100%) of the updated PMF. This example illustrates the problem that dam owners and stakeholders face when the PMP is provided as a single-value. Is the dam inadequate for passing the extreme flood and should be upgraded or is it fine and nothing should be done? The dilemma is especially important considering that costs of modifying existing dams to accommodate the PMF are estimated to be in billions of dollars (Graham, 2000).

It should also be remembered that the primary application of PMP estimates is for extreme flood analyses. The meteorological components and associated uncertainties have importance in the context of how they affect flood magnitudes. This consideration is further complicated by hydrological considerations of the watershed of interest and the storage and operational characteristics of the dam and reservoir project. For example, if reservoir storage is small relative to the flood volume, then flood peak discharge and therefore maximum precipitation intensities during the storm are the primary concerns. Conversely, if the reservoir has very large storage, then runoff volume and total storm precipitation are the primary concerns. Many dam and reservoir projects are sensitive to a combination of maximum intensities and total precipitation. These considerations are important because uncertainties