Journal of Hydrology 521 (2015) 360–373

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Uncertainty analysis for Probable Maximum Precipitation estimates

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ARTICLE INFO

Article history:
Received 31 December 2013
Received in revised form 20 May 2014
Accepted 12 December 2014
Available online 20 December 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Sheng Yue, Associate Editor

Keywords:
Uncertainty
PMP
Meteorological analysis
PMF
Watershed model

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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http://dx.doi.org/10.1016/j.jhydrol.2014.12.033

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 associated with maximum precipitation intensities are different than uncertainties associated with total precipitation.

As mentioned in the previous section, meteorological analyses for PMP estimation typically involve procedures for in-place moisture maximization and transposition of the storm from where it occurred to a location(s) of interest. In-place moisture maximization is intended to account for the maximum atmospheric moisture that could have occurred for a given time of year relative to the atmospheric moisture that was present for storm development. This is a linear scalar based on ratios of maximum to observed precipitable water. Storm transposition encompasses a number of procedures that are intended to account for the change in precipitation magnitude due to transposition of the storm mechanisms from the location where the storm occurred to another location(s) of interest. These procedures can become quite complicated in mountainous areas where orographic precipitation is a major component of the total precipitation amount.

In addition, a key assumption in PMP estimation is that maximum storm efficiency has occurred in the controlling storm(s) that governs PMP magnitude. Storm efficiency cannot be measured directly and so this assumption cannot be verified. It seems reasonable that this assumption is more nearly true for large geographic regions with long precipitation records that have experienced a large number of very extreme storms. This assumption becomes less realistic as the study region becomes smaller, there are shorter record lengths and the frequency of storms becomes less (such as arid, sub-arid and sub-humid climates).

Variables which influence PMP values include:

a. The overall weather conditions producing the precipitation for general storms and local storms.
b. Available atmospheric moisture for given location and time of year.
c. Variation of atmospheric moisture during the period of storm activity.
d. Method for in-place moisture maximization.
e. Estimation of storm center and precipitation magnitude at storm center.
f. Storm efficiency in the controlling storm relative to maximum storm efficiency.
g. Horizontal transposition.
h. Path of the storm through the location(s) of interest.
i. Location of the transposed storm over the watershed of interest.
j. Freezing level over the basin.
k. Modeling method (e.g., Storm Separation Method, Isopercental, others).
l. Methods employed in developing the temporal distribution of PMP.
m. Methods employed in developing the spatial distribution of PMP.

Brief discussions of some of these variables appear in the following sections.

2. Discussion of PMP variables

2.1. Moisture maximization

In the U.S. National Weather Service "HMR" documents, such as HMR-57 (1994) and HMR-59 (1999), the 12-h persisting dewpoint is used to characterize available atmospheric moisture. This value represents the highest dewpoint equaled or exceeded throughout a 12-h period. Observed values for individual storms are compared with long-term maximum observed values to obtain in-place moisture maximization, using the assumption that the atmosphere aloft is saturated. Part of this computation process is converting dewpoint to precipitable water (total integrated water vapor in the vertical column) assuming moist adiabatic lapse rate and 100% relative humidity. Generally, surface data (e.g., airport) are used. In some cases, sea surface temperature analyses augment or replace onshore values (this is especially true in HMR-57). In other cases, upper-air data (generally from balloon soundings) are employed.

Some studies (e.g., EPRI, 1993) have suggested using average dewpoints rather than 12-h persisting values for representing storm moisture. HMR-59 (U.S. NWS, 1999) acknowledged that persisting dewpoints lead to lower precipitable water values than average dewpoints, but this results in greater conservatism for the PMP values computed.

In some cases, upper-air data (meteorological balloons go as high as above 15 km but we are interested in only about the lowest 3 km) are used instead of surface data for obtaining representative dewpoints. Upper-air data have the advantage of accurate moisture measurements throughout the air column but represent only a single point in space (and thus may miss the storm center) and are taken only once every 12 h (and may not be representative of the timing of the heaviest rain). The low frequency of upper-air measurements is mainly due to practical reasons of balloon soundings being difficult, labor intensive and expensive. To our knowledge, no systematic comparison of in-place moisture maximization techniques has been done.

Persisting dewpoints and snapshot upper-air soundings may provide poor measures since atmospheric moisture changes during the period of storm activity both with time and along the vertical profile. The ideal moisture availability parameter for PMP studies would be "moisture flux" for the entire vertical column of air. Moisture flux is a measure of the volumetric rate of transport of moisture with time, typically expressed as $[\mathrm{MT}^{-1}]$. At this time, it is not possible to compute moisture flux accurately; the best that can be done is to interpolate between upper-air soundings. Perhaps in the future, accurate high-resolution values of moisture flux will be available from remote sensing platforms.

2.2. Methods used for analysis of storms

The National Weather Service's "Storm Separation Method" (SSM) is commonly used for analysis of storms in complex terrain. According to HMR-57:

> "The storm separation method (SSM) is an outgrowth of practices that were initiated in the late 1950s for PMP studies in orographic regions". HMR 36 (U.S. WB, 1961) is one of the earliest reports to discuss PMP development in terms of orographic and convergence precipitation components. Convergence precipitation in this context is the product of atmospheric mechanisms acting independently from terrain influences. Conversely, orographic precipitation is defined as the precipitation that results directly from terrain influences. It is recognized that the atmosphere is not totally free from terrain feedback (the absolute level and variability of precipitation depths in some storms can only be accounted for by the variability of the terrain); but cases can be found where the terrain feedback is either too small or insufficiently varied to explain the storm precipitation patterns and in these cases, the precipitation is classified as pure convergence or non-orographic precipitation."

The biggest difficulty in using SSM is the assumption that the convergence and orographic rainfall amounts can be explicitly determined. Is it possible to truly estimate precipitation amounts in complex terrain which would have occurred in the absence of said terrain? It is a very difficult (possibly insoluble) task.

In contrast, a technique known as “isopercental analysis” (Shaw et al., 2011), which relies heavily on Geographic Information Systems (GIS) analysis, is in increasingly widespread use. This approach hinges on the availability of prior regional precipitation analyses for development of base maps (specifically, gridded datasets of mean annual maxima, 10-year or 100-year precipitation for selected durations). It avoids some of the arbitrary nature of SSM (particularly the assessment of convergence and orographic components of a storm). The process is as follows:

a. Identify major storms from the historical record. They may be large, multi-day “general storms” or smaller, shorter-period “local storms” depending on the climatic aspects of a location and the size of the watershed.
b. Create isohyetal coverages (spatial distribution of precipitation). This is accomplished by comparing observed values for each station and storm with the gridded base map value for that location. A gridded dataset is created using interpolation of computed isopercental values representing percentage of base map precipitation.
c. Maximize moisture using historical extremes. This is a linear operation; the entire grid is multiplied by the maximization ratio.
d. Transpose the maximized storm to the watershed. The “percentage” values from step *b* are moved to the watershed, often to the centroid of the basin (see discussion in Section 2.3).
e. Calculate transposed storm values. The percentage values from step d are multiplied by the base map grid for the watershed of interest to obtain a transposed grid, representing the best estimate of precipitation if a maximized storm were transposed to the watershed.
f. Determine depth–area (DA) values for the maximized, transposed storm. This is done explicitly using all grids within the basin.

Isopercental analysis is a way of characterizing the rarity of a storm compared with historical extreme values for those same areas. Use of the isopercental approach removes the arbitrariness of the SSM process.

2.3. Storm center

Another source of uncertainty in PMP values occurs due to the different ways of characterizing the storm center at the location of storm occurrence. For example, some analyses use the maximum observed precipitation value or use radar data where they are available for locating the storm center. Other methods are frequency-based (i.e., percent of 100-year value) to infer the location of the storm center (Shaw et al., 2011).

Uncertainty also occurs in transposing an observed storm to a location of interest. One approach which is often used in PMP analyses to address this issue lies in systematically changing the location of the storm center during the storm transposition process. This is described in step *d* in Section 2.2.

If such a systematic analysis is performed, one can assume that the maximized “transposed storm location” has been established.

2.4. Basin and reservoir characteristics

Depending on the size, topography, and other features of a basin, short-duration local storms – 6 h or less (Commonwealth Bureau of Meteorology, 2003), or long-duration general storms (U.S. NWS, 1994, 1999) may be of most concern. Flood peak discharges for smaller basins tend to be affected primarily by high precipitation intensities during short-duration storm events, while flood peak discharges for larger basins are affected by precipitation for longer durations and are contained within multi-day floods. Generally, the total volume of floodwater affects the reservoir elevation more significantly than the peak flow for very large storage reservoirs. Thus, the temporal and durational aspects of PMP of importance to a given project are dependent upon the size of the basin and storage capacity and operational procedures of the reservoir.

2.5. Multi-day and temporal characteristics

The methods for specifying variables for multi-day events have not been specified in HMR documents. For example, moisture maximization ratios are specified as a single value for an entire storm; in reality, moisture varies considerably over time. Ideally, a new ratio should be specified for each day (or partial day) for the entire event. The HMR documents use the maximum ratio for the storm period, so the published ratios should be considered an upper bound. Yet more realistic approaches would seem to be justified as better characterization of a storm.

Historically, most analyses of PMP begin with 24-h calculations due to the greater availability of precipitation data for that duration. Conversion of 24-h PMP to both shorter and longer durations has been done in a variety of ways: (1) using historical storms and their temporal characteristics for a given region (WMO, 1986); (2) using a particular “controlling” storm (WMO, 1986); or (3) using point 24-h PMP maps with prescribed methodology for conversion to 72-h PMP (e.g., in HMR analyses). Thus, the consequences of different methodologies for transitioning from 24-h PMP to 6-h, 12-h, 72-h or 96-h PMP are not fully known. Here again, the adequacy of the available record of historical storms and the analyst’s choice of methods determines the depth–area–duration characteristics of PMP.

One additional aspect of daily and multi-day calculations involves a reality of weather/climate measurement, i.e. many stations report once per day. Daily (fixed observation time) and maximum 24-h precipitation are often significantly different, even for the same location. Hershfield (1961b) suggested a correction factor of 1.13 (that is, daily values are multiplied by 1.13 to obtain a 24-h estimate). This is only an approximate, average value, but it remains in widespread use. In reality, the correction factor can be as high as 2.

2.6. Input data

Early storms in the record (e.g., the January 1935 storm in northern Washington and southern British Columbia) had nothing more than surface observations. Since the 1940s we have had upper-air data from balloon launches. Since the 1960s satellite data have been available. And since the early 1990s we have had Doppler radar data. Some PMP researchers have suggested that storms in the last 20 years give us sufficient information to evaluate PMP, and that we can do so more effectively due to modern data sets (especially radar, which gives us detailed storm spatial distribution information). We concur with the HMR approach: use all significant storms from the historical record. Yet the difficulty of comparing the information provided from, say, a 1935 storm to a 2006 event is significant.

An additional aspect of this question lies in the length of available data for analyses. For example, the precipitation–frequency atlas NOAA Atlas 2 (Miller et al., 1973) is still in use in several states in the western U.S. (Colorado, Idaho, Montana, Oregon and Washington), despite its age. NOAA Atlas 2 is based in large part on mean annual precipitation analyses created in the early 1960s, which was in turn based on data up to 1960. The ensuing 50 years have seen many significant storms, whose inclusion would certainly alter Atlas 2's results and alter the findings where this atlas is used as a base map.

Finally, the analysis of the various input data sets has changed significantly over time. The advent of GIS has revolutionized many aspects of data analysis. Other exciting developments of data analysis and characterization include the PRISM system (Daly et al., 1994), which takes point measurements of precipitation (and other parameters) and creates GIS-compatible data layers which faithfully represent the orographic processes so important in places like the western United States and Canada.

To summarize, if the controlling storms occurred in the distant past, then data availability and analysis methods may impart uncertainties to the estimation of PMP.

2.7. Climate change

If there are systematic long-term changes in climate, the variables likely to change include moisture maxima, storm efficiencies, precipitation intensities, wind speeds and freezing levels. A recent study (Kunkel et al., 2013) used simulations from seven climate models to examine potential climate change effects on PMP. Their simulations indicated a significant future increase in mean and maximum water vapor concentrations (i.e. precipitable water). According to their research, future increase in greenhouse gases will most likely be manifested in an increase in ocean heat content, which will then lead to an increase in atmospheric water vapor concentrations. Their models predicted approximately 20–30% increase in maximum water vapor concentrations, which is one of the main inputs to PMP estimation. Model-simulated changes in the maximum values of vertical motion and horizontal wind speed were too small to offset the water vapor increase. Therefore, Kunkel et al. (2013) concluded that PMP values will increase in the future due to higher levels of atmospheric moisture content and consequent higher levels of moisture transport into storms.

To date, the issue of climate change has not been addressed in PMP estimation methodologies. But if, for example, a 100-year storm (annual exceedance probability 0.01) becomes a 25-year storm (annual exceedance probability 0.04), would this affect the entire frequency distribution including its upper tail where extreme events are? And do we even have sufficient data to determine the effect? Any study findings will likely remain controversial for the foreseeable future.

3. Other considerations

3.1. Non-linearity of maximized precipitation

The most significant calculation in PMP is the moisture maximization step. Traditional approaches, such as those favoured by NWS and WMO, assume a linear relationship between atmospheric moisture and rainfall. However, some research findings suggest otherwise. The "accepted" approach of moisture maximization is to increase observed storm rainfall to correspond to the maximum possible moisture availability. It is assumed that the maximized precipitation is proportional to the atmospheric moisture availability and varies linearly. Thus, observed rainfall amounts are scaled by the ratio of the historical maximum moisture to the observed moisture condition during an event (the "precipitable water" ratio). This idea comes from an approximate solution of the basic continuity equation of water vapor for an atmospheric control volume, which shows that precipitation is proportional to precipitable water and wind convergence. The PMP assumption results from assuming constant wind convergence while increasing the atmospheric moisture availability.

Chen and Bradley (2003) described the results of an analysis using the MM5 mesoscale model to "evaluate the effects of the initial atmospheric moisture availability on storm dynamics and rainfall accumulation for the Northeastern Illinois storm of July 17–18, 1996". The atmospheric moisture availability was adjusted over a wide range but "within the upper limits of the maximum observed precipitable water using three different moisture adjustment methods". It was found that the relationship of precipitation to precipitable water depends on spatial scale. For large spatial scales, precipitation was shown to scale linearly with precipitable water, but with a slope larger than that assumed in PMP analysis. Increasing atmospheric moisture availability caused increases in large-scale wind convergence, which led to greater average precipitation over the region. Hence, the assumption of constant wind convergence is not valid. The maximized precipitation depends on both the precipitable water ratio and the wind convergence ratio. For small spatial scales, the relationships of precipitation to precipitable water are nonlinear and vary with atmospheric moisture adjustment methods.

The Chen–Bradley findings suggest much higher maximization than that obtained from methods currently in common use, most of which assume a linear relationship between atmospheric moisture (precipitable water) and extreme precipitation.

3.2. PMP physical upper limit

To this point, PMP has been assumed to be a physical upper limit as stated in the theoretical definition. In reality, there is no conclusive evidence to either support or refute the commonly adopted belief that there is a physical upper bound. PMP is designed to represent an exceedingly rare event; in terms of frequency PMP values have estimated Annual Exceedance Probabilities (AEPs) that range from 10^{-4} to perhaps 10^{-10} (Schaefer, 1994; Schaefer and Barker, 2005). Many analyses take existing data and extrapolate them, or create "envelope" curves to establish upper limits. But are there upper limits to PMP storms? There are three possible answers to the question of a physical upper limit for precipitation for a given location, duration and season:

1. Yes, there is a physical upper limit to precipitation.
2. No, there is no physical upper limit but the rate of change of the precipitation–frequency relationship at the upper end of the frequency curve is sufficiently flat that a practical limit can be adopted for engineering applications.
3. No, there is no physical upper limit – the rate of change of the precipitation–frequency relationship at the upper end of the curve implies the possibility of greater precipitation with decreasing likelihood.

The above discussion applies to all PMP variables listed previously. If any of the factors involved in computing PMP is not upper-bounded, then PMP itself is not upper-bounded.

For example, Papalexiou and Koutsoyiannis (2006) examined various approaches to computing moisture maximization. Assuming that moisture maximization is based on the ratio of maximum historical dew point to observed dew point, they examined several statistical methods for estimating extreme moisture conditions. The sample of the 120 maximized rainfall depths (the highest depth is considered to be the PMP estimate) was analyzed in the same probabilistic manner as the maximum monthly and annual rainfall depths were analyzed. The fitted distributions (GEV) to these three sets of data suggested the absence of the upper bound, so it is likely that if a longer rainfall record were available, the estimate of the PMP would be higher. Papalexiou and Koutsoyiannis also calculated PMP values using the monthly maximum daily dew point for a wide range of return periods, recognizing that the WMO suggestion to use a 100 year return period is arbitrary and this return period could be assumed greater. The PMP estimates were higher when higher return periods of the monthly maximum daily dew point were used. Finally, they fitted the GEV probabilistic model on the historical data and concluded that the PMP estimate has a return period of less than 500 year for the studied region of Athens, Greece.

Recent extreme events, including several large Pacific Northwest rain events and 2012s superstorm “Sandy”, have suggested that “unprecedented” weather events can and do occur. Removing arbitrary limits to moisture maximization does not seem unreasonable.

3.3. Safety margin

Earlier PMP analyses (such as the HMR reports) had conservatism built in. Granted, it is not always clear exactly where and how this took place (it is difficult to replicate many of the HMR results since in many cases HMR authors list results but do not explain how those results were derived), but it is clear that the National Weather Service (NWS) recognized the importance of conservatism in their published results. Clearly PMP and PMF are of utmost importance due to the potential consequences of a dam failure. Clearly also it was the intent of the NWS to publish PMP estimates which were on the high side to establish a margin of safety. Thus conservative assumptions such as 12-h persisting dewpoint and enveloping procedures were used by the NWS.

NWS’ HMR documents represent regional analyses of PMP. NWS also allows “site-specific” PMP analyses to be made for a particular location. It is the experience of the authors that site-specific analyses nearly always produce lower PMP values, often by 20% or more. The main reason for this has to do with the selection of the study region. The criteria for defining the geographical area where storms are transposable to a specific watershed are more restrictive in a site-specific study. This generally results in the transposable region for a site-specific PMP analyses being smaller than the geographical area used in a generalized PMP study conducted for a large area of the United States. The largest storm in a small region is generally smaller than the largest storm in a large region. This tends to result in a smaller sample-set of storms from which to select the controlling storm(s), which typically produces smaller PMP estimates. The site-specific analyses may be giving more accurate PMP estimates, based on current techniques and available data sets, but we wonder: should there be a factor of safety applied to guard against underestimating the *maximum* storm?

4. Determination of “traditional” single-value PMP estimate for the La Joie basin

The La Joie Dam basin is located on the Bridge River, approximately 200 km northeast of Vancouver, BC, Canada (Fig. 1). La Joie Dam impounds Downton Lake, which has a surface area of 24 km^2 at the maximum normal level of El. 749.8 m. The minimum operating level for the reservoir is El. 701 m. The drainage area upstream of La Joie Dam is 998 km^2. The La Joie Dam basin is situated in the rain shadow of the southern coastal mountains. The Bridge Glacier occupies 140 km^2 of the La Joie watershed. The Bridge River flows eastward from the glacier towards more low lying terrain. Elevations within the basin range from 650 to 2900 m, and the average elevation for the La Joie basin is approximately 1900 m. The La Joie Dam watershed is characterized by

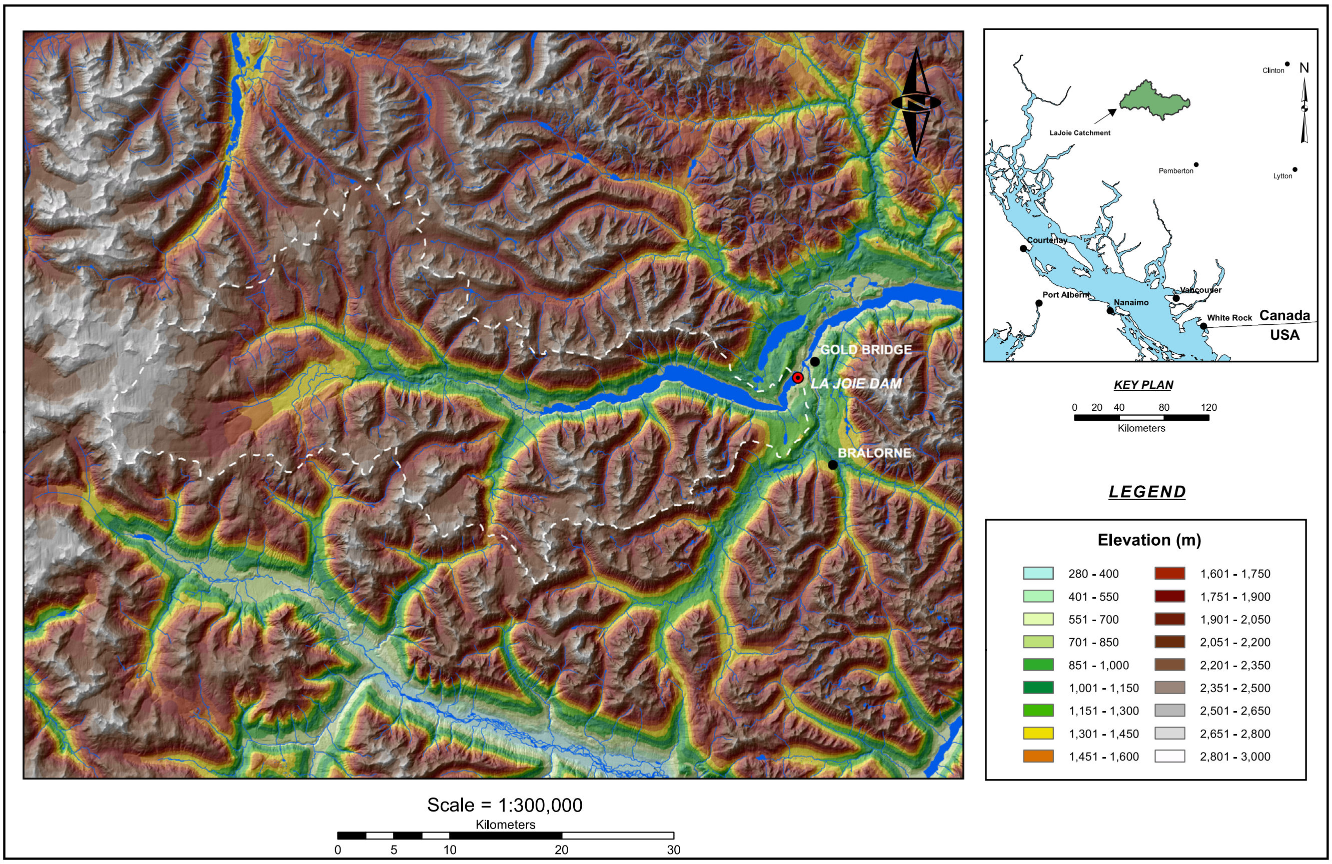

Fig. 1. La Joie basin location.

Table 1
Historical storms selected for La Joie PMP analysis.

Cool season storms	Longitude	Latitude
January, 1935	−120.50	49.43
January, 1974	−115.80	48.72
February, 1949	−120.70	48.72
October, 1945	−123.70	48.52
October, 1963	−124.00	48.50
November, 1955	−123.43	48.08
December, 1937	−123.65	49.12
December, 1956	−123.40	48.50

steep valley side slopes and short tributary streams which flow into Bridge River almost at right angles.

The basin lies in the Cordilleran climatic region and is affected by both continental and modified maritime conditions. The general climatic conditions produce large snowpacks in the winter, warming conditions in April to June, and often heavy short duration rainfall in June and July. The presence of the Bridge Glacier and several smaller glaciers along the southern mountain ridges indicate heavy winter precipitation and cool temperatures.

In terms of seasonality, the PMP-type storm could occur over the La Joie Dam basin only during the 'cool season', i.e. the October–February period. Therefore, the meteorological analysis for the La Joie PMP study comprised the major cool season storms shown in Table 1. Locations of the "storm centers" (assumed to be the locations of the highest percentage of 100-year precipitation for each storm) are shown in Fig. 2.

The site-specific La Joie PMP was estimated using the isopercental technique described earlier in Section 2.2. The analysis was carried out for three durations, namely 24, 48 and 72-h. The 24-h depth–area values for each storm are shown in Fig. 3. An envelope of maximum values was created for each duration, as shown in Fig. 4.

The La Joie PMP values for different duration and different size areas up to 1000 km^2 are shown in Table 2. Depth–area calculations were made using actual grid cell values for the transposed storms. For successive thresholds in increments of 2.5 mm, the number of cells exceeding each threshold value was calculated and converted to area. Note that the highest historically observed point-precipitation values in this region (i.e. east of the BC southern coastal mountains) are 199, 221 and 246 mm for 24, 48 and 72-h durations, respectively. These historical records were observed during the August 1991 storm at Hurley River meteorological station, located outside the La Joie basin but relatively close to it (15 km southwest from La Joie Dam).

The 6-h/24-h PMP ratio was derived from the analysis of historical hourly storm precipitation data for the all available stations located east of the Coastal Cascades range in southern British Columbia and northern Washington State. The 6-h/24-h PMP ratio of 48.5% was found to be applicable for the La Joie basin. The 48-h/24-h PMP ratio of 1.42 and the 72-h/24-h PMP ratio of 1.84 could be derived from Table 2 for a 1000 km^2 basin. Reservoir routing scenario testing indicated that the most critical option would be an "end-loaded" hyetograph scenario, which was the reason to place the maximum 24-h increment of 273 mm at the end of the

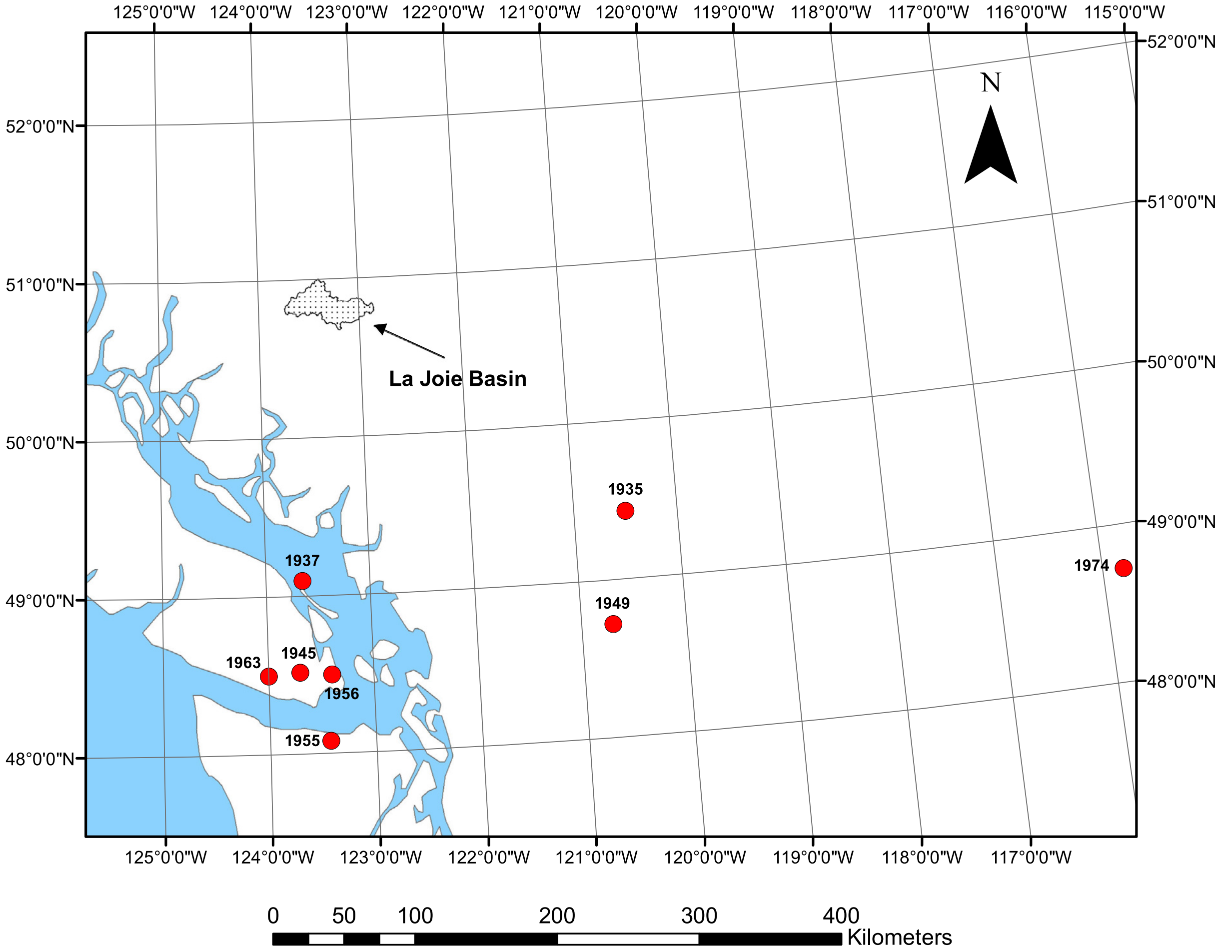

Fig. 2. Locations of historical storms used in La Joie PMP analysis (defined as the locations of the highest percentage of 100-year precipitation).

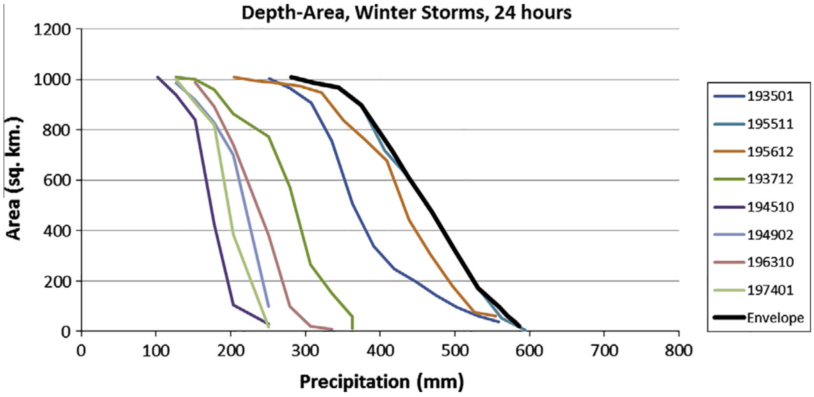

Fig. 3. Depth–area values for cool season storms, 24 h duration.

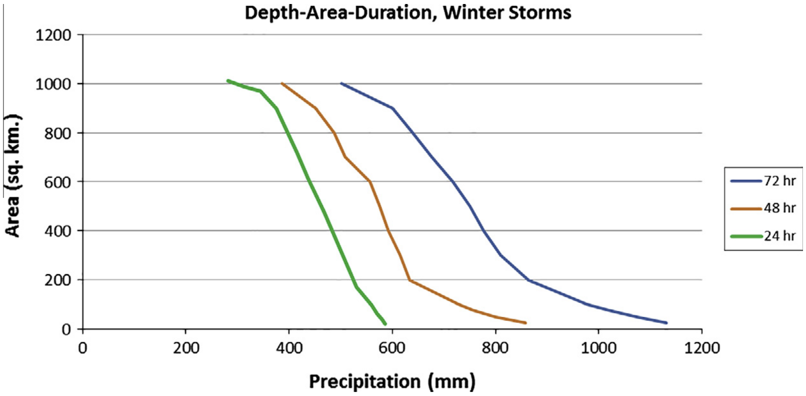

Fig. 4. Maximum depth–area values for cool season storms, 24–72 h durations.

Table 2
PMP precipitation (mm) for 24, 48 and 72-h durations.

Area (km^2)	24-h	48-h	72-h
25	542	858	1132
50	533	800	1074
75	525	757	1021
100	517	729	978
200	482	633	863
300	468	614	810
400	449	592	777
500	430	575	750
600	408	557	718
700	389	509	676
800	368	488	639
900	347	451	601
1000	273	387	501

72-h PMP storm. Thus, the temporal distribution (in 6-h increments) of the 72-h PMP for the La Joie basin which satisfied discussed ratios and incremental precipitation magnitudes is shown in Table 3.

Another important consideration in PMP estimates is the freezing level. Freezing level variations during the PMP storm can potentially affect the precipitation amount that will be immediately available for runoff. With the maximum elevation within the basin about 2900 m, freezing levels below this elevation will produce snow versus rainfall over the higher elevations of the basin. Also, with approximately 25% of the basin above 2400 m, freezing level variations below this elevation can significantly affect rainfall volumes. To examine this issue, the balloon soundings from Quillayute, Washington were used. Quillayute is the nearest station to La Joie basin that has both surface and upper-air data. It is located about 350 km southwest of the La Joie basin and thus upwind of the basin during the typical southwesterly flow regimes which characterize large rainfall events. The analysis of Quillayute observed precipitation and freezing level data for three typical large cool-season storms (November 1990, January 2005 and November 2006) showed that freezing levels during the storm stayed above 2900 m elevation for longer than 3 days (5 straight days in the January 2005 storm case). If similar freezing levels occurred in the La Joie Basin, one could reasonably assume that 100% of the precipitation fell as rain. This analysis suggests that a 72-h precipitation total could be considered to be exclusively liquid. Therefore, this study assumed that all PMP precipitation falling in the La Joie Basin is in the form of rain (i.e., that freezing levels are above the highest elevation of 2900 m).

Table 3
Temporal distribution of the 72-h PMP storm.

Hours	1–6	7–12	13–18	19–24	25–30	31–36	37–42	43–48	49–54	55–60	61–66	67–72
% of 24-h max. PMP	10	10	11	11	10	10	11	11	12	18	21.5	48.5

5. Proposed methodology for assessing PMP uncertainties

The methodology for assessing uncertainties in PMP estimates is as follows:

a. Identify sources of uncertainty (parameters) for a project-specific application.
b. Determine the range of plausible parameter values for each of the identified parameters used in computation of PMP.
c. Develop a probability distribution or otherwise characterize the likelihood of parameter values over the range of values for each parameter.
d. Use numerical integration methods to determine the distribution of possible PMP values and uncertainty bounds for the adopted PMP value.

In this paper we considered five main sources of uncertainty which are identifiable components of the PMP estimation process and whose uncertainties could be readily described as simple proportions of the original PMP estimate. The likelihood functions for depicting uncertainties were chosen consistent with the concept of an upper bound for precipitation and have fixed lower and upper limits. The shapes of the likelihood functions were based on judgment and experience with the uncertainty characteristics for each of the factors. As a result of the conservative nature of the procedures and policies for estimation of PMP, the majority of the likelihood functions are more restrictive in the direction of smaller PMP estimates and less restrictive to the possibility of larger PMP estimates. The process for creating the shape of the likelihood functions starts with setting the upper and lower bounds which determines the range for a given factor (e.g. +20% and −10% in Fig. 6a). The relative likelihoods of the smallest and largest values are then considered along with any central tendency for a given factor (e.g. relative likelihood of 1 for the +20% and −10% bounds, and a relative likelihood of 2 for the central tendency of a 5% increase in the PMP value in Fig. 6a). An equally-likely likelihood function is used when there are no discernible differences across the range for a given factor (e.g. Fig. 6c and d). Empirical cumulative distribution functions (CDFs) were created by first integrating the area under the likelihood functions and then rescaling to an area of unity. Latin-hypercube sampling was then conducted using the empirical CDF for each source of uncertainty. The procedures to account for uncertainties follow the conventional approach for PMP estimation:

$$\mathrm{PMP24} = \mathrm{P24C} * \mathrm{FMM} * \mathrm{FMHT} * \mathrm{FSC} * \mathrm{FSE} \quad (1)$$

where PMP24 is the 24-h PMP value (mm) derived through meteorological analyses; P24C is the 24-h precipitation for the controlling storm at the location where recorded (mm); FMM is the factor for in-place moisture maximization and setting of the maximum in-place surface (ground) dewpoint; FMHT is the horizontal transposition factor which accounts for the change in maximum atmospheric moisture from the location where the controlling storm was observed to the centroid of the basin of interest; FSC is the factor for centering of the storm within the basin to produce the maximum basin-average precipitation relative to the precipitation for the storm centered at the centroid of the basin; and FSE is the factor for storm efficiency to account for the situation that the efficiency of the controlling storm was likely something less than maximum efficiency.

To our knowledge, this is the first uncertainty analysis conducted for a PMP. While the goal is to develop uncertainty bounds for PMP specifically for the La Joie watershed, the computational procedures have been set up in a more generic manner to provide general insight into the behavior of the effect of uncertainties in PMP estimation. We proffer that the approach captures the basic characteristics of uncertainties in estimation of PMP based on current practices. It would be expected that other analysts would have differing views on the ranges of uncertainties and the shapes of the likelihood functions.

5.1. In-place moisture maximization

There are three techniques which have been used for moisture maximization:

a. 12-h persisting surface dewpoint,
b. sea surface temperature (SST),
c. upper-air soundings.

Preliminary findings suggest greater variation and uncertainty in surface dewpoint and upper-air sounding approaches, while SST data produce less uncertainty due to smaller ranges of values computed (SST variations are much smaller than those of the other two approaches).

Uncertainties from maximization using surface dewpoint are due largely to decoupling between the surface and upper-air. The assumption of adiabatic lapse rate and 100% relative humidity can be a very poor one. In the case of upper-air soundings, estimates may not be representative of actual conditions due to the large (12 h) time step between data points. To illustrate differences between surface dewpoint and upper-air sounding approaches the moisture maximization was carried out using observed data from the Quillayute, Washington, which is the nearest station to La Joie basin that has both surface and upper-air data. Storm path was estimated using HYSPLIT, the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. It provides an estimate of the path that air parcels followed as they moved toward a particular location (in this case, a storm center).

The wettest days at Quillayute since 1994 were selected. Data were obtained for the high-precipitation day plus two days before and two days afterward. Precipitable water (PW) was calculated for both upper-air soundings and surface dewpoint data. The latter were produced using the relationship between dewpoint and PW contained in HMR-57 (which assumes a saturated atmosphere and cooling at the moist adiabatic rate – approximately 5 °C per km).

For each sounding, the following variables were collected: Surface Pressure (mb); Surface Height (m); Surface Temperature (°C); Surface Dewpoint (°C); Surface Wind Direction; Surface Wind Speed (m/s); Surface PW (mm); Sounding PW (mm); Station Pressure (mb); Station Temperature (°C); Station Dewpoint (°C); Station Wind Speed (m/s); and Station PW (mm).

Table 4 shows a summary comparison. Results for two individual storms are also shown in Fig. 5. As expected, the "surface" PW values are larger, since upper-air soundings seldom reveal a completely saturated atmosphere. Note that the best way to determine precipitable water is from balloon soundings, but these are available only several times a day. Surface dewpoints can also be used for these calculations, and have the advantage of being available every hour, but are less accurate than soundings because it must be assumed that the atmosphere is saturated, which is often not the case. Thus, the trade-off is between accurate measurements a few times a day versus generally less accurate measurements every hour. It can be seen in Table 4 that, while precipitable water values calculated from surface dewpoints are generally higher that those estimated from upper-air soundings due to the saturated atmosphere assumption, their ratio is not uniform and varies from storm to storm. Occasionally, as in the case of the 200501b storm (see Table 4), the surface-based estimate of the precipitable water

Table 4
Comparison of precipitable water values calculated from surface dewpoints and upper-air soundings.

Storm (yyyymm)	Max SFC	Max SND	Avg SFC	Avg SND	Ratio Max	Ratio Avg
201001	24.7	22.1	20.1	17.2	1.12	1.17
200811	25.4	24.4	19.3	17.4	1.04	1.11
200501a	23.6	21.1	21.3	18.7	1.12	1.14
200501b	22.3	24.1	17.3	15.6	0.93	1.11
200311	18.9	17.4	13.5	11.5	1.09	1.18
200310	30.4	24.9	21.6	16.1	1.22	1.34
200211	25.9	22.4	19.9	15.7	1.16	1.26
200202	20.0	18.2	16.3	12.3	1.10	1.32
199912	23.3	20.3	16.2	11.4	1.15	1.43
199811	27.4	22.8	19.7	16.0	1.20	1.23
199508	28.7	24.7	25.7	21.0	1.16	1.22

Where:
Max SFC: Maximum PW from surface dewpoint (mm).
Max SND: Maximum PW from upper-air sounding (mm).
Avg SFC: 5-day average PW from surface dewpoint (mm).
Avg SND: 5-day average PW from upper-air sounding (mm).
Ratio Max: Ratio of Max SFC/Max SND.
Ratio Avg: Ratio of Avg SFC/Avg SND.

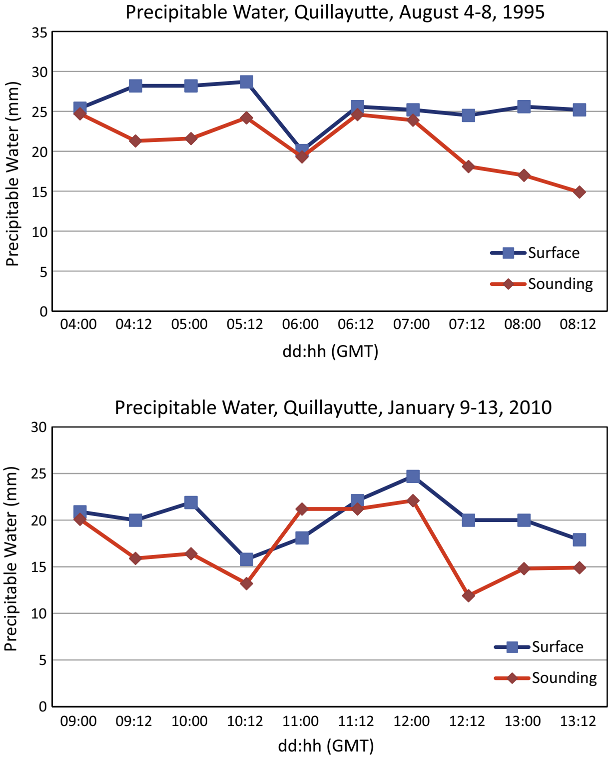

Fig. 5. Precipitable water from surface dewpoint and upper-air soundings.

is lower ("Ratio Max" of 0.93). This can occur if the observed surface dewpoint is not representative of the air mass due to local winds or other factors. But such cases are rare.

Therefore, we can identify two sources of uncertainty in the procedures for computing in-place moisture maximization associated with assumptions made for a saturated atmosphere. First, there is a tendency to underestimate in-place moisture maximization for conditions which commonly occur in the vertical moisture profile. Examination of vertical moisture profiles from radiosonde data for days of extreme precipitation in the Pacific Northwest shows that moisture inflow often occurs in several elevation bands whereas the assumption is made for a fully saturated atmosphere. This results in underestimation of PMP when a fully saturated atmosphere is assumed for PMP conditions. Conversely, there is a tendency for the sea-surface temperatures to be colder than the overriding inflow moisture at elevations near the sea surface. This tends to overestimate the in-place moisture maximization factor and overestimate PMP.

A likelihood function was created (Fig. 6a) which reflects a plausible range for the effect of uncertainties from estimation of the in-place moisture maximization factor in computation of 24-h PMP. The likelihood function was constructed with a central tendency for conditions to occur which are closer to the assumptions made for PMP computation.

5.2. Policy limitation of PMP surface dewpoint to 2-Sigma

Standard NWS policy in computation of PMP is to limit the maximum monthly surface dewpoint to two standard deviations above the mean (2-Sigma). The prior policy was to use maximum observed surface dewpoints. This had resulted in continual ratcheting up of PMP estimates because historical maximum dewpoints tend to increase with longer record lengths. The current policy of using 2-Sigma as a limiting value was an attempt to provide "stability" to the PMP estimates for analyses conducted in future years and avoid complaints from the engineering community of ever-increasing PMP estimates.

In the context of maximizing precipitation, it is possible to have surface dewpoints (and a level of atmospheric moisture) greater that 2-Sigma. Fig. 6b depicts a likelihood function for the case where surface dewpoint is at or above 2-Sigma. The likelihood function was developed based on the shape of the standardized Normal distribution in the range of 2-Sigma to 4-Sigma. The standard deviation for surface dewpoint in the fall and winter storm season is about 1.2 °C which equates to about a 10% increase in atmospheric moisture and a 10% increase in the PMP estimate.

5.3. Horizontal transposition

Horizontal transposition accounts for the change in maximum surface dewpoint in transposing the storm characteristics from the location where it occurred to the location of interest. This was taken to represent an uncertainty of about +5% (about 0.6 °C) for spatial mapping of maximum surface dewpoints. The likelihood function was taken to be equally-likely for uncertainties in horizontal transposition and is depicted in Fig. 6c.

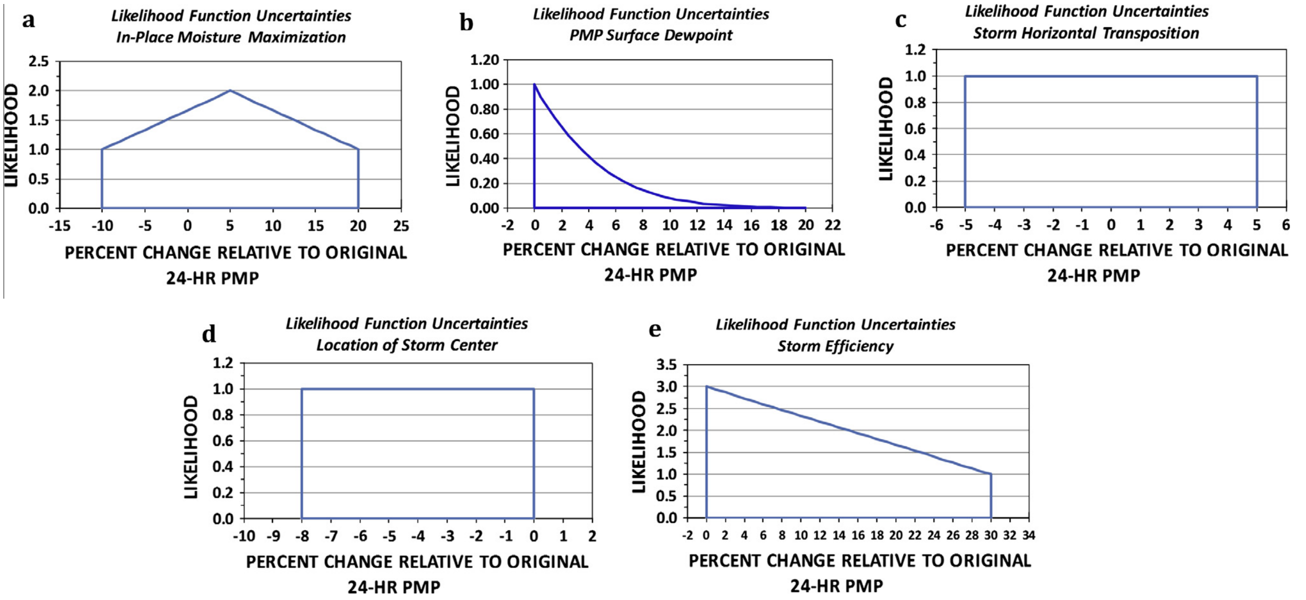

Fig. 6. Likelihood functions for the effect of uncertainties expressed relative to the original 24-h PMP estimate (a: in-place moisture maximization; b: maximum surface dewpoint; c: storm horizontal transposition; d: storm center location; e: storm efficiency).

5.4. Storm centering

In the original La Joie PMP study, a procedure was used for storm centering which examined alternative locations for centering the transposed storm on the La Joie watershed. The transposed storm center was successively placed on every grid cell in the basin and basin-average precipitation compared for each case. This was done to address the question, "How do basin-average PMP calculations change when the transposed storm center location is shifted?" The procedure consists of the following steps:

1. Begin with isohyetal precipitation coverage of a large storm (in this example, the January 1935 event).
2. Calculate the percent of 100-year precipitation for each grid cell (isopercental coverage).
3. Transpose isopercental grid to La Joie Basin, incrementally:
    i. Place "storm center" (cell with highest isopercental value) on one of the grid cells in the La Joie Basin.
    ii. Multiply transposed grid by 100-year 24-h grid to obtain precipitation grid.
    iii. Calculate basin average using all grid cells within the basin.

Fig. 7 shows the results of the analysis. Note the La Joie Basin outline as well as the analysis points (locations for storm center placement) and the geographic centroid of the basin. The grid in Fig. 7 was derived by plotting basin-average values resulting from

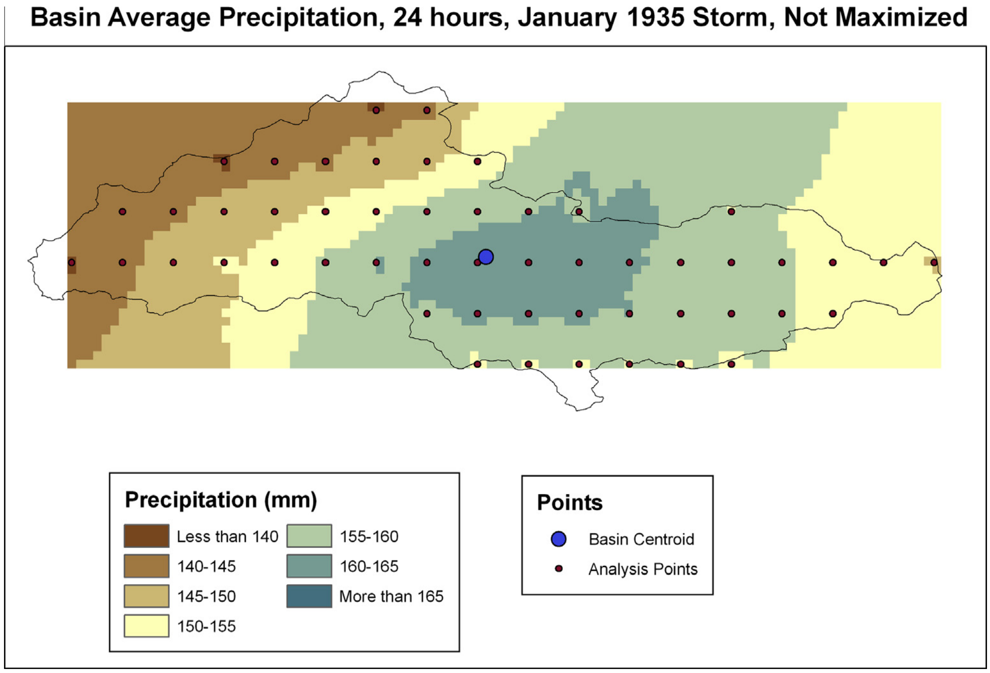

Fig. 7. La Joie basin-average precipitation for transposed January 1935 storm centered on each grid point.

storm centering at each grid point. The highest basin-average values occur for storm centers near the centroid. Note that the values shown are not maximized, merely transposed. They are thus significantly lower than PMP values, but they serve as relative indicators of spatial distribution.

The location which maximized 24-h basin-average precipitation was selected in the original La Joie PMP study. It is anticipated that other analysts might select alternative storm centering based on other considerations which would have yielded slightly lower basin-average precipitation amounts. A likelihood function (Fig. 6d) was created that reflects an equally-likely chance for the range of 24-h PMP based on alternative storm centers.

5.5. Storm efficiency

Standard policy in PMP estimation is to assume that a storm with maximum storm efficiency has occurred in the study region. This is the “controlling storm”, the historical storm that when transposed to the watershed of interest produces the largest moisture-maximized precipitation. This is an assumption made for convenience of analysis because there is no generally accepted measure of storm efficiency. While it is reasonable to assume that the controlling storm has relatively high storm efficiency, it is unreasonable to assume that, given a sufficiently long record length for a large study area, greater storm efficiency would not occur. The meteorological process of precipitation production has a very large number of parameters that affect the magnitude of precipitation. This is analogous to a slot-machine with a very large number of spinning wheels. It would likely take an incredibly large number of simulations to get a line of cherries on all of the wheels. Likewise, it would take a very large sample set of storms to experience a storm that approaches maximum efficiency. As discussed previously, if any of the individual processes/parameters that produce precipitation are unbounded, then the precipitation process is unbounded and there is not a physical upper limit.

The simplifying assumption that maximum storm efficiency has occurred in the controlling storm is injected into PMP estimation by policy. An example of the need to consider the possibility of greater storm efficiency occurred in the Cascade Mountains of western Washington where the January 1935 storm was the controlling storm for over half of a century. It was subsequently exceeded by the November 2006 storm, only to be exceeded again by the storm of December 2007 representing a 20–30% increase in 24-h precipitation relative to that for the January 1935 storm.

A simple example for increased storm efficiency can be made by considering one of the process parameters, the rate of storm movement. If movement of the controlling storm were to slow or stall for a period of time, then it is possible to produce greater precipitation at a specific location. This would be seen in the temporal pattern of the controlling storm where, for example, the rate of precipitation production for the maximum 6-h period would continue to be produced over a longer time period. This would increase the total precipitation for the 24-h PMP.

A likelihood function was created reflecting the consideration that maximum storm efficiency was not achieved in the controlling storm and greater storm efficiency could be obtained but with lower likelihood. Fig. 6e depicts a likelihood function with these characteristics.

5.6. Results of 24-h PMP uncertainty analysis

The uncertainty analysis was conducted using Monte Carlo simulation methods by considering the contribution from each of the five sources of uncertainty described above. Latin-hypercube sampling methods were used to assemble 2000 sample sets comprised of combinations of the five sources of uncertainty. Each source of uncertainty was considered independent of the other sources. The combined effect of the five uncertainty sources was considered to operate as described in Eq. (1), with each component being a linear multiple of the original 273 mm estimate of the 24-h PMP (the value for 1000 km^2 area in Table 2). The sensitivity of the PMP estimate to the various factors can be inferred from the range and magnitude of the likelihood functions shown in Fig. 6. This occurs because the likelihood functions are expressed as a percentage of the PMP estimate and estimation of PMP is a multiplicative process. A review of the likelihood functions in Fig. 6 shows the PMP estimate to be most sensitive to the factors for Storm Efficiency and In-place Moisture Maximization.

The resultant distribution of PMP estimates is depicted by the histogram in Fig. 8. Values of 24-h PMP for selected percentiles are listed in Table 5. It is seen in Table 5 that the mean value for 24-h PMP is 321 mm (118% of the original estimate) when uncertainties are considered. The value of the 24-h PMP estimate for the 10th percentile is close to the original PMP estimate of 273 mm and the value for the 90th percentile is 372 mm which is 136% of the original PMP estimate.

5.7. Uncertainties for 48-h and 72-h PMP estimates

Uncertainties are also present in the estimation of 48-h and 72-h PMP. Standard practice in PMP development is to use depth–area–duration data obtained from historical storms to develop multipliers to be applied to the 24-h PMP estimate for estimation of 48-h and 72-h PMP. The original 48-h and 72-h PMP estimates for the La Joie watershed are 387 mm and 501 mm which equate to 48-h/24-h and 72-h/24-h ratios of 1.418 and 1.835 respectively, for the original 24-h PMP estimate of 273 mm. As an initial approximation, the 1.418 and 1.835 multipliers can be applied to the 24-h PMP percentile estimates listed in Table 5 to produce percentile estimates for the 48-h and 72-h durations (Table 6) which would

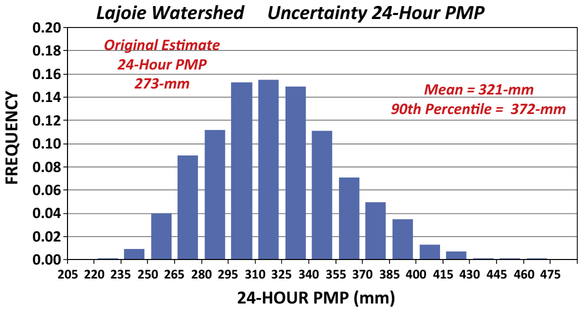

Fig. 8. Histogram of estimates of 24-h PMP for La Joie watershed based on 2000 simulations for five sources of uncertainty.

Table 5
Summary statistics for 24-h PMP uncertainty analysis for La Joie watershed.

Uncertainty percentile	24-h PMP (mm)	Ratio to originally estimated 24-h PMP of 273 mm
5%	265	0.971
10%	274	1.004
20%	289	1.059
50%	319	1.168
Mean	321	1.176
80%	352	1.289
90%	372	1.363
95%	388	1.421

Table 6
First approximation of uncertainty percentile estimates for 48-h and 72-h PMP for La Joie watershed.

Uncertainty percentile	48-h PMP (mm)	72-h PMP (mm)
5%	375	486
10%	388	503
20%	409	530
50%	452	585
Mean	455	589
80%	499	646
90%	528	683
95%	550	712

capture the majority of the uncertainty variance for the longer durations.

A more detailed uncertainty analysis for 48-h and 72-h PMP would include consideration of uncertainties associated with the possibility of sustained periods of moisture inflow similar to that discussed above for in-place moisture maximization. The prior discussion about storm efficiency would also apply to the longer durations. Consideration of these uncertainties would further widen the uncertainty bounds for the longer durations beyond what is listed in Table 6.

6. Derivation of the Probable Maximum Flood (PMF) for La Joie basin

Both the traditionally derived single-value PMP and the PMP range from the uncertainty analysis were used to determine the PMF for the La Joie Dam watershed. The philosophy of PMF estimation is to consider the most severe "reasonably possible" combination of a rainstorm, snow accumulation, melt rates, initial basin conditions, and a pre storm. It is an accepted practice in Canada (CDA, 2007) to maximize the primary component of the PMF (i.e. PMP or Probable Maximum Snow Accumulation) in combination with secondary components that do not exceed a frequency of 1/100 year (i.e. 1/100 rainfall or snow accumulation or temperature sequence). It is also conservatively assumed that at the beginning of the PMP event the entire snowpack is in ripe condition and that the watershed is fully saturated. The results of the analyses confirmed that the critical PMF scenario for the La Joie basin was the November scenario consisting of the PMP combined with 1/100 year snowpack accumulation.

The UBC Watershed Model (Quick, 1995; Micovic and Quick, 1999) was used to simulate the physical processes producing inflows to the La Joie reservoir and covert the precipitation input into runoff from the watershed. The model was calibrated using a daily computational time step for the long term continuous simulation and then refined using an hourly time step calibration for several largest historical flood events. The model refinement through an event-calibration using an hourly time step was necessary since the importance of certain algorithms, process representations and parameters is masked during the long-term continuous simulation using the daily time step, as suggested by Micovic and Quick (2009). The change in focus to the individual extreme events, and reduction in the computational time step from daily to hourly, revealed the importance of those parameters and algorithms which represent the infiltration limiting nonlinear increase in response. This important nonlinearity has implications for the extrapolation of model results to the extreme cases, such as the determination of PMF floods, where, due to the absence of "observed flow", there is usually no way to verify the accuracy of the model estimate.

The resulting PMF estimates derived using the traditionally derived single-value PMP as well as using the mean and 95-percentile PMP values from the uncertainty analysis are shown in Table 7. For comparison purposes, the largest historically observed flood (estimated to have 70-year return period) was shown besides PMF estimates in Table 7.

Table 7 shows that the uncertainty in PMP estimate has a significant effect on the final PMF estimate which represents the design flood in most of the North-American jurisdictions.

Even though the focus of the present study is the uncertainty associated with PMP estimates it should be noted that, besides the PMP input, there are other sources of uncertainty associated with the PMF determination. The watershed model used to convert precipitation input into reservoir inflows, although calibrated on the largest historically observed storms, may not accurately represent watershed's hydrological behavior. It must be acknowledged that extrapolation to PMF conditions has been largely untested, and the response of the basin may vary with storm/flood magnitude. For example, both the snowmelt runoff and the rainfall runoff response times were calibrated on the largest inflows on record, which are typically 5–6 times smaller than the derived 24-h PMF. It is possible that watershed would exhibit a different response during an extreme event such as the PMF. In addition, statistically derived 1/100 year snowpack and associated melt simulation contain uncertainty which may be increased when the impact of snowmelt due to rainfall is considered. Therefore, it is safe to say that the differences in PMF results (Table 7) resulting from the uncertainty of PMP estimates would be even more pronounced if other sources of uncertainties were considered. For example, a recent PMF study conducted in Thailand (Jothityangkoon et al., 2013) examined the sensitivity of the PMF to its input parameters. They reported that a 10% increase in PMP caused a 15% increase in PMF, while a 10% increase in deforestation resulted in a 3% increase in PMF.

7. Discussion and conclusions

PMP and PMF are important considerations for civil engineering purposes, particularly dam safety. PMP calculations are derived from a rather large array of variables and calculation techniques, many of which have rather high degrees of uncertainty. As a result, PMP, often reported as a single number, is best characterized as a range of values. In fact, we do not know at this time whether there is a physical limit to precipitation or if PMP is simply a convenient engineering concept.

This paper identifies sources of uncertainty in estimating PMP and discusses development of a methodology for assessing uncertainties and developing uncertainty bounds for a PMP estimate.

Table 7
PMF characteristics for different PMP inputs compared with the flood of record.

	Traditional single-value PMP	Uncertainty analysis (mean value)	Uncertainty analysis (95-percentile)	Flood of record (October 1984)
Max. hourly inflow (m^3/s)	2077	2503	3109	n/a
Max. 24-h inflow (m^3/s)	1753	2111	2619	386
Max. 4-day inflow volume (million m^3)	360	434	540	86

The findings of a site-specific application of the methodology for assessing uncertainties in PMP estimates is also presented as well as the resulting PMF hydrographs.

It should be noted that the PMP/PMF concept is a deterministic approach and as such cannot be used in risk analysis for dam safety. Risk-informed decision making requires development of a full flood frequency curves/hydrologic hazard curves for various flood characteristics up to and including extreme events, where scenarios of different hazards (not just overtopping) with different occurrence frequencies can be combined and assessed. In this way, different design criteria could be considered and evaluated at various flood frequency levels, thereby departing from widely used strict "pass/fail" design criteria.

However, the development of hydrologic hazard curves is a rather challenging task itself and it may take us some time to develop scientifically justifiable unified means of characterizing hydrologic hazards for use in risk analysis. In the meantime, the PMP/PMF concept will continue to be applied in many countries/jurisdictions. The presented approach shows the concept in a more transparent manner, so those who are still required to use it have a better idea of numerous uncertainties associated with it. It represents a clear advantage over the traditional methodology of a single PMP estimate and enables dam owners in jurisdictions requiring the use of the PMP/PMF concept to make more informed decisions regarding spillway capacity and dam safety for both new and existing dams.

To our knowledge, this is the first uncertainty analysis conducted for a PMP. We believe that the approach captures the basic characteristics of uncertainties in estimation of PMP based on current practices. It would be expected that other analysts would have differing views on the ranges of uncertainties and the shapes of the likelihood functions. However, it should be pointed out that uncertainties exist in every aspect of a very complex study such as the estimation of extreme precipitation and resulting floods. All of the hydrometeorological inputs used in the process have uncertainties. In addition, the watershed model algorithms contain uncertainties due to incomplete understanding of the underlying hydrological processes. Clearly it is very difficult, if not impossible, to capture the total uncertainty in the estimation of extreme floods. Multiple hydrometeorological variables as well as watershed model parameters could be represented as probability distributions by utilizing sampling approaches – the analysis of multiple samples will yield the uncertainty in the final output. There is obviously potential to incorporate even greater mathematical rigor into the uncertainty analyses, but more realistically, we should be pragmatic and hope to best capture the major contributors to the total uncertainty and to provide a basic picture of the magnitude of uncertainties. This is due generally to the small sample size of observed hydrometeorological data and particularly to the inherent lack of extreme precipitation events in the historical record. It has been stated before (Klemes, 1994) that no amount of "mathematistry" could compensate for a lack of information relevant to the models adopted.

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