Flood frequency and design flood estimation procedures in the United States: Progress and challenges*

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ABSTRACT: *Design flood estimation procedures in the United States have traditionally focused on two primary methods: frequency analysis of peak flows for floodplain management and levee design; and deterministic, probable maximum flood (PMF) estimates for design of dams and nuclear facilities. Federal Agencies in the United States, including the Bureau of Reclamation, US Geological Survey and Army Corps of Engineers, are currently examining potential changes to these standard flood hydrology procedures. This paper presents overviews of some ongoing investigations and data collection studies to support potential changes in design flood estimation. For floodplain management, the current guideline is Bulletin 17B, which specifies the use of an LP3 distribution, method of moments and regional skew information. Potential improvements to Bulletin 17B currently under consideration are: (i) use of historical and paleoflood information; (ii) adjusting for low outliers; (iii) improved plotting positions; and (iv) confidence intervals. Ongoing testing results are presented, highlighting the expected moments algorithm. In contrast to well-established, deterministic (PMF) extreme flood estimates for dam safety, agencies are now moving toward risk-based techniques. The Bureau of Reclamation has developed and applied several methods in order to estimate extreme floods and probabilities for large dams. Techniques used to date are summarised, along with those being considered by other US agencies. Improvements to extreme flood databases that provide inputs, including extreme storms and probable maximum precipitation estimates, precipitation frequency and paleofloods, are ongoing. Some challenges to updating design flood methods and data, including institutional effects, national scale, research to operations and use of new technologies, are described.*

1 INTRODUCTION

Extreme flood estimates are an important component in floodplain management and the evaluation of critical infrastructure. In the United States, there are two main areas of design flood estimation procedures. The first area is peak-flow frequency analysis, which is typically used for design of small hydraulic structures, for floodplain management, and levee design and assessments. Annual exceedance probabilities of flood flows typically range from 1-in-25 to 1-in-100, depending on the need. The second area of design flood estimation focuses on assessments of critical infrastructure, including dams and nuclear facilities, and utilises the probable maximum flood (PMF) as the flood estimate.

Over the past 10 years, various federal agencies within the United States have been exploring and investigating changes to guidelines and methodologies that are used in these two areas. In addition to techniques, databases that are used as inputs to extreme flood estimation techniques are being examined for updates. This paper presents an overview of ongoing work in extreme flood hydrology methods and data within the United States. Three areas are highlighted:

1. status of US National flood frequency guidelines
2. extreme flood probability methods for dam safety and nuclear facility risk assessments
3. efforts to improve databases for extreme flood estimation.

The present work is motivated by many factors. Some of these include: recent research in flood frequency; movement away from standards-based toward risk-based flood techniques; and a continuing desire to improve databases, particularly precipitation, that

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are over 30 years old. International extreme flood research and guideline improvements, especially Nathan & Weinmann (1999), indicate that changes to US guidelines and practices are warranted.

2 FLOOD FREQUENCY GUIDELINES IN THE UNITED STATES

The current guidelines for conducting flood frequency studies in the United States is Bulletin 17B (B17B) (IACWD, 1982). These guidelines are used for estimating peak-flow frequency curves for federal and non-federal flood-related projects, such as floodplain management, levee designs, river restoration and small dam assessments. The B17B guidelines have been in place over 27 years, with no changes.

2.1 Bulletin 17B and potential changes

The statistical method that is the basis of B17B evolved over time and was finalised in 1981. The log-Pearson Type 3 (LP3) distribution is assumed as the flood parent distribution. B17B recommends usage of the method of moments to estimate the flood distribution parameters, using the logarithms of the peak-flow data. The first three moments are used to estimate the LP3 parameters. These include the mean (μ), standard deviation (σ) and skewness coefficient (γ). The B17B LP3 parameters are potentially modified by the analyst in two situations: historical information cases and low outlier cases.Because of the relatively-large uncertainty in the at-site sample skewness coefficient (third moment), B17B recommends the use of a weighted skew coefficient G when fitting the LP3 distribution. Griffis & Stedinger (2007) provided details of the method and its evolution, and recommended some improvements. Stedinger & Griffis (2008) reiterated the list of additional studies recommended by IACWD (1982, pp. 27-28), and suggested that there was sufficient flood frequency research conducted since 1982 to update B17B.

Potential improvements to B17B are currently being investigated in the following five areas (England & Cohn, 2007; 2008):

- alternative procedures for treating historical information
- alternative methods for low outlier identification
- alternative procedures for treatment of low outliers
- more adequate computation procedures for confidence limits for the Pearson type 3 distribution
- investigation of plotting positions for historical information and low outlier cases.

The potential changes to B17B focus on using the expected moments algorithm (EMA) for parameter estimation and confidence intervals. In the 1990s, Lane & Cohn (1996) introduced a new moments-based fitting procedure EMA (Cohn et al, 1997; 2001; England et al, 2003a; Griffis et al, 2004) as a potential alternative. EMA is a generalised moments-based estimator, consistent with what is currently specified in B17B, but adapted to be able to accept interval data in addition to point estimates; it can accept threshold exceedance (or non-exceedance) censoring techniques to handle many types of flood data that standard method-of-moments approaches cannot accommodate. EMA has been found to be efficient and nearly unbiased (Cohn et al, 1997; England et al, 2003a). In particular, EMA is more efficient than B17B for historical and paleoflood data cases; works well in practice (NRC, 1999; England et al, 2003b); does well at handling low outliers, including zero flows; and can utilise regional skew information G (Griffis et al, 2004). Monte Carlo comparisons with L-moments and maximum likelihood estimators (Cohn et al, 1997) indicated EMA performed well. LP3 confidence intervals developed for EMA (Cohn et al, 2001) are more accurate than B17B confidence intervals, as they properly account for skewness in the distribution rather than using a normal approximation. EMA confidence intervals also account for historical information and low outliers. A comparison of EMA improvements and B17B is listed in table 1.

The present revision to B17B focuses on maintaining the essential method-of-moments LP3/regional skew scheme, with improvements in five areas mentioned above, rather than a major departure from this methodology, as articulated in detail by Stedinger & Griffis (2008). Recent evaluations of this regional skew scheme (Stedinger & Griffis, 2008; Griffis & Stedinger, 2009) indicate that it is effective and appropriate for US flood frequency, and competitive with L-moments regionalisation approaches. One area that is also being investigated for change is the use of Bayesian generalised least squares (GLS) for regional skew estimation (Gruber & Stedinger, 2008). Because B17B does not specify the regional skew estimation procedures, this work is being done separately from the present effort, and is not discussed here. Future revision efforts will provide guidelines for areas that B17B does not fully address, such as flow regulation, urbanisation impacts and other non-stationarity issues related to potential climate change.

2.2 Studies to support potential changes

The ongoing studies to investigate changes to B17B (England & Cohn, 2007; 2008) focus on using real data from 82 long-term gauging stations (figure 1). The gauge sites include locations throughout the United States, representing diverse climates and terrain.

The sites are classified into the following four groups:

1. Gauge Only, no historical data/low outliers (29 sites)

Table 1: Potential improvements to B17B with EMA, advantages and disadvantages.

Issue	Advantage	Disadvantage
Historical information/ high outliers	EMA gives 100-year flood estimates with smaller MSE and less bias than B17 historical weighting. EMA allows for direct use of more types of historical data including measurement uncertainty	As longer records are used, climate change and non-stationarity need to be investigated
Low outliers	EMA gives a consistent method for both low and high outliers; EMA is generally more efficient than conditional probability adjustment	Potentially revisit low outlier test that would define the censoring threshold for EMA
Confidence intervals	EMA employs correct approach for LP3 distribution	None

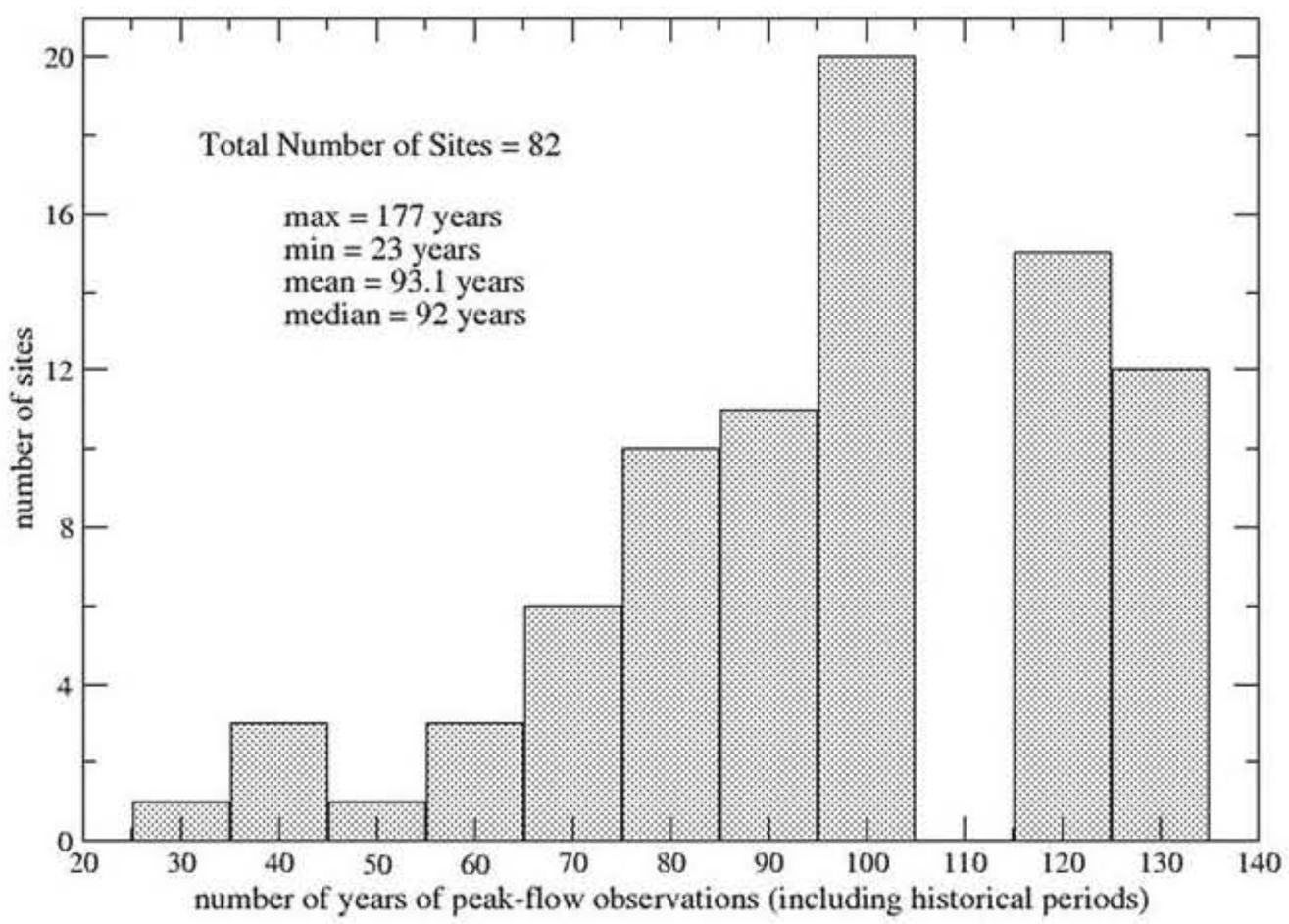

Figure 1: Distribution of peak-flow record lengths for the 82 testing sites.

2. Historical Data, no low outliers (24 sites)
3. Low Outliers and gauge base, no historical data (16 sites)
4. Historical and Low Outliers with gauge base (13 sites).

The "gauge only" case is used to test the EMA "base" procedures with B17B. Results should be nearly identical, as the base distribution and estimating procedure are the same for this case. The "historical data" case is used to test the historical data adjustment procedures. The "low outliers" case is used to compare EMA with the B17B conditional probability adjustment for low outliers, flows less than a gauge base and zero flow years. The "historical and low outliers" case enables one to compare the performance of the two procedures when adjustments occur simultaneously at both tails of the distribution.

An empirical testing criterion, the relative percent difference (RPD %) between B17B and EMA quantiles, is used for comparison of the two methods for the 82 sites. The first comparison is by each group listed above, using the complete record at each site. Results for the gauge only and historical data groups are shown in figure 2. As expected, there is little difference between the two methods for just gauge data. The median differences for historical data are also small (less than 4%), for quantiles within the record lengths (eg. Q_{100}). The RPD grows with increasing quantile and EMA gives consistently higher estimates than B17B for historical cases, confirming previous Monte Carlo results (Cohn et al, 1997; England et al, 2003a) that EMA pays more attention to the larger and more extreme floods.

Results for the two groups with low outliers are not shown, for brevity. Initial results indicate that EMA is sensitive to the low outlier threshold chosen, and improvements are being investigated to generalise the Grubbs-Beck test to account for multiple low outliers. Additional testing is ongoing, and includes split-sampling from the 82 sites and Monte Carlo simulation.

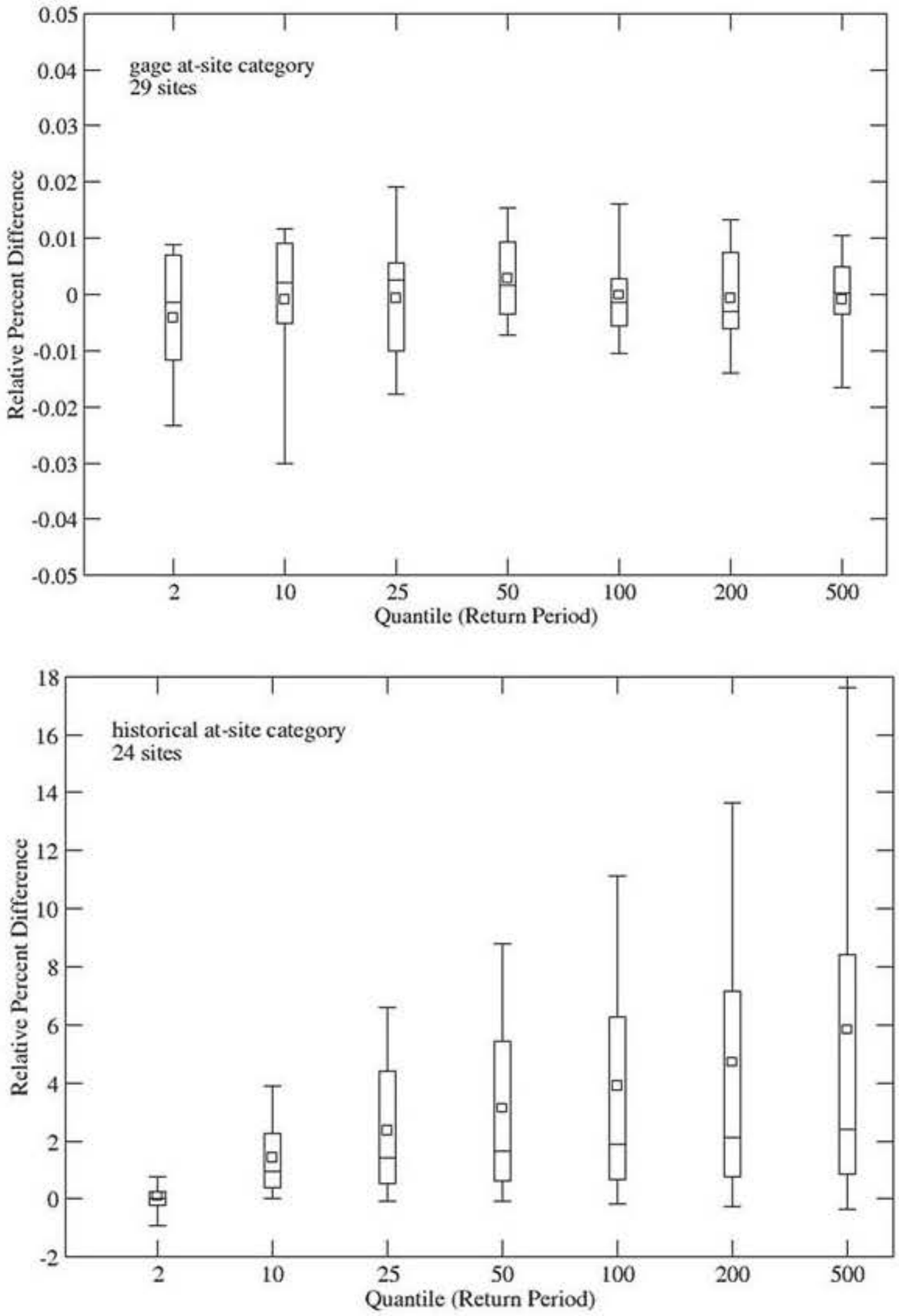

Figure 2: Relative percent difference box-plots for gauge and historical data groups.

3 EXTREME FLOODS FOR CRITICAL INFRASTRUCTURE

Historically, large dam design, analysis and assessment methods have focused on selecting a level of protection based on spillway evaluation flood loadings. Traditionally, the protection level in the United States is based on the PMF (Cudworth, 1989; FEMA, 1998). Nuclear facilities use similar deterministic criteria (USNRC, 1977). Major federal agency responsibilities and current flood design standards used are summarised in table 2. Most federal agencies still use the PMF as the standard for assessing critical infrastructure. The methods used to estimate the PMF as practiced in the United States (eg. Cudworth, 1989) have not changed in over 30 years.

3.1 Movement toward hydrologic hazard and risk

The Bureau of Reclamation and the Corps of Engineers have begun using risk-based techniques to assess the hydrologic hazards at existing dams. Reclamation began using risk analysis for dam safety in about 1995. The major motivating factors for Reclamation to move away from standards-based assessments using the PMF are the following: (i) many dams in Reclamation's inventory do not meet the PMF standard; (ii) costs of potential modifications to meet the standard are prohibitive; (iii) standard provides no insight how to prioritise modifications; and (iv) the standards do not include failure mode concepts. Other motivating factors include: US Office of Management and Budget focus on risk for evaluating public expenditures; and the investigation and development of extreme flood techniques for risk analysis (Bureau of Reclamation, 1999; Nathan & Weinmann, 1999).

Reclamation currently uses risk analysis to assess the safety of dams, recommend safety improvements and prioritise expenditures (Bureau of Reclamation, 2003; 2010). Risk analysis is used to determine an appropriate level of public protection by evaluating a full range of loading conditions and possible dam failure consequences. The flood loading input to a

Table 2: US federal agencies major flood-related infrastructure design standards.

Agency	Responsibility	Infrastructure	Design flood assessment standards
Bureau of Reclamation (Reclamation)	Water supply and power in 17 western states; management of agency infrastructure	Over 300 large and significant hazard dams	Hydrologic hazard for risk; PMF used as upper limit design
Corps of Engineers (USACE)	Flood control; management of agency infrastructure	Over 600 large and significant hazard dams; levees	PMF; hydrologic hazard screening; hydrologic risk for levees
Federal Energy Regulatory Commission (FERC)	Regulatory oversight of non-federal hydropower projects	Over 3000 dams	PMF; site-Specific PMP / PMF
Nuclear Regulatory Commission (USNRC)	Regulatory oversight of nuclear facilities	Over 65 major nuclear facilities	PMF

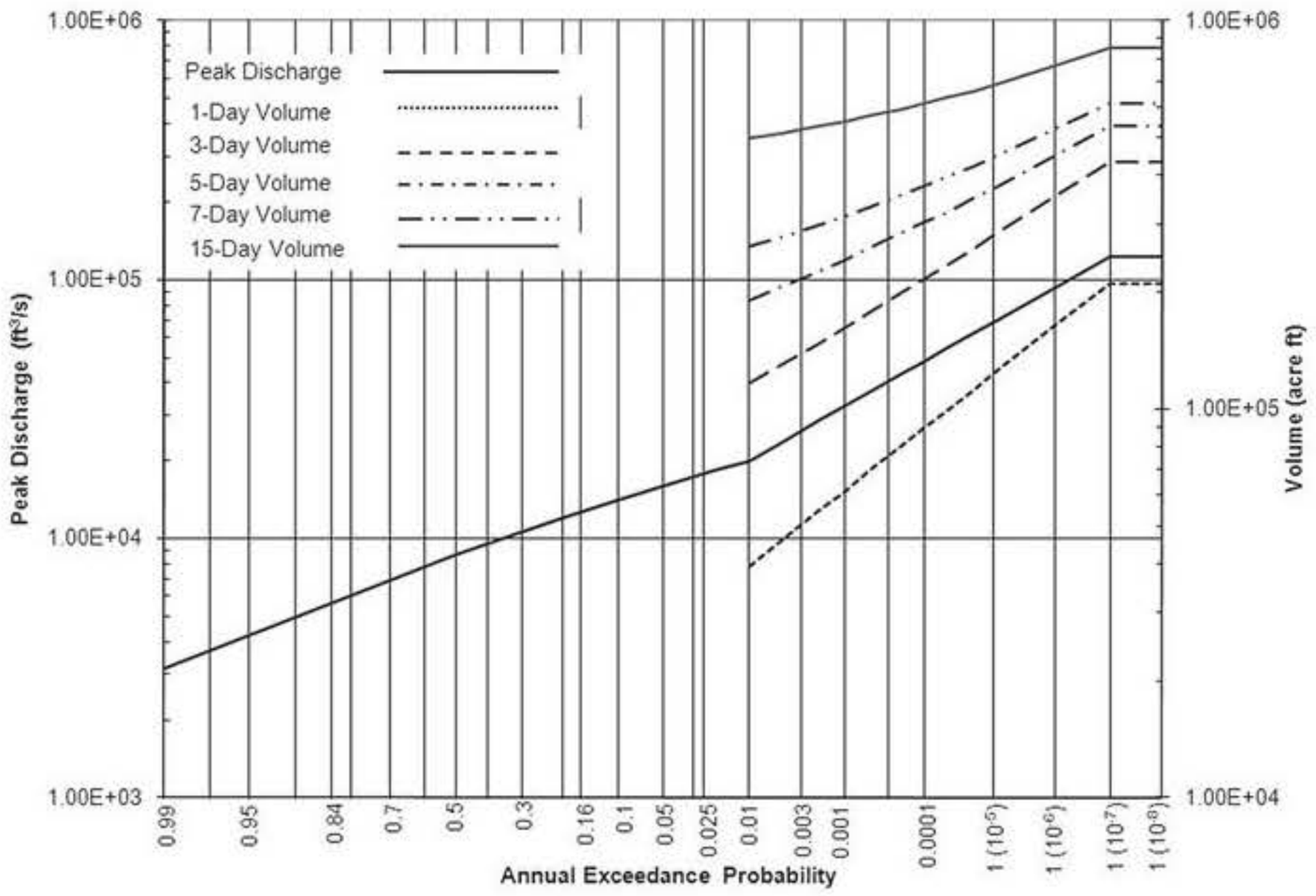

Figure 3: Example hydrologic hazard curves showing peak flow and volume probability relationships.

risk analysis is a hydrologic hazard curve. Hydrologic hazard curves are defined as graphs of peak flow and volume (for specified durations) versus annual exceedance probability (AEP) (figure 3). The range of AEPs that is displayed on these graphs is intended to be sufficient to support the decision making needs of the organisation, and provide a full probability distribution for the hazard. Hazard curves may also be provided for reservoir elevations. This is in contrast to the traditional approach of using upper bound events such as the PMF without regard to their likelihood of occurrence and without assessment of their incremental consequences. In this example, the relationships, based on a two-parameter log-normal distribution fit to peak flows and paleoflood data (graphical method, table 3), flatten at 1×10^{-7} AEP, as they are limited by the PMF peak flow. Reclamation's current policy is to use the PMF as an upper limit to hydrologic hazard curve extrapolations (Bureau of Reclamation, 2002a), without directly assigning an AEP to the PMF peak flow. The AEP of the PMF peak flow is determined as needed based on the extrapolation function and method, and varies from site to site. There is no fixed assumption for AEP of the PMF peak flow. In some cases, based on the data at hand, the AEP of the PMF is not estimated because the relationship is truncated at AEP < 10^{-8}. As noted below, Reclamation does utilise AEP of probable maximum precipitation (PMP), following Nathan & Weinmann (1999), in one method (table 3).

The US Army Corps of Engineers (USACE) started conducting risk analyses for some of its dams in 2007. Reclamation has assisted in sharing hydrologic hazard tools with USACE. The motivation for USACE in risk analysis is similar to Reclamation; it desired a way to effectively prioritise its inventory by using risk. Other federal agencies are considering hydrologic risk approaches, but have not yet attempted to do so. One barrier is education and familiarity with the hydrologic hazard tools and techniques. Another barrier is the lack of updated, readily-available data

Table 3: Current methods used by Reclamation to develop hydrologic hazard curves.

Class	Method of analysis and modelling (reference)	Hydrologic hazard curve product	Risk analysis/ design level[a]	Level of effort[b]
Streamflow-based statistics	Peak flow frequency analysis with historical/paleoflood data – graphical method (Swain et al, 2004)	Peak flow frequency, volume frequency; hydrographs	CFR, IE	Low
	Peak flow frequency analysis with historical/paleoflood data – EMA (Cohn et al, 1997; England, 1999; England et al, 2003a; 2003b)	Peak flow frequency	IE, CAS, FD	Low
	Peak -flow frequency analysis with historical/paleoflood data – FLDFRQ3 (O'Connell, 1999; O'Connell et al, 2002)	Peak flow frequency	IE, CAS, FD	Low
	Hydrograph scaling and volumes (England, 2003)	Hydrographs and volumes; based on peak flow frequency	CFR, IE, CAS, FD	Low
Rainfall-based statistics and runoff transfer	GRADEX nethod (Naghettini et al, 1996)	Volume frequency; hydrographs	IE, CAS, FD	Moderate
	Australian rainfall-runoff method (Nathan & Weinmann, 1999)	Peak flow and hydrographs; based on rainfall frequency and PMP	IE, CAS, FD	Moderate
	Stochastic event-based precipitation runoff modelling with SEFM (Schaefer & Barker, 2002; MGS Engineering, 2009)	Peak flow frequency; hydrographs; volume frequency; reservoir elevation frequency	CAS, FD	High
	Stochastic rainfall-runoff modelling with TREX (England et al, 2006; 2007)	Peak flow frequency; hydrographs; reservoir elevation frequency	CAS, FD	High

[a] CFR = comprehensive facility review, IE = issue evaluation, CAS = corrective action study and FD = final design; [b] Low = 10-20 staff days, Moderate = 21-75 staff days and High = more than 75 staff days.

sets such as extreme precipitation, for conducting hydrologic hazard assessments in the United States.

3.2 Hydrologic hazard methods and applications

Reclamation has developed and applied numerous methods to estimate extreme flood magnitudes and probabilities for dam safety, that are depicted as hydrologic hazard curves (Swain et al, 2004). These methods can be broadly classified into streamflow-based statistical approaches and rainfall-based with runoff statistical approaches. Current hydrologic hazard curve methods are summarised in table 3 and are generally ranked according to the level of effort involved. These methods currently include: flood frequency with paleoflood data using EMA (England, 1999) or FLDFRQ3 (O'Connell, 1999); GRADEX (Naghettini et al, 1996); rainfall-runoff with PMP AEPs from *Australian Rainfall & Runoff* (AR&R) (Nathan & Weinmann, 1999); stochastic event flood model (SEFM) (MGS Engineering, 2009); and TREX (England et al, 2006; 2007), with links to software provided in references. Improvements to these current methods and other tools and approaches may be added as project needs and experience dictates.

The USACE is using techniques for hydrologic hazards that are similar to methods Reclamation has implemented. Their methods are generally used in conjunction with gauged frequency analysis as a way of extending the gauged frequency curves out to events more rare than gauged data analysis would normally warrant. A list of methods that have been selected for potential inclusion to USAC Portfolio Risk Analysis for Corps dams are (USACE, 2008):

- extension of gauged frequency curves with historic/paleoflood information
- hydrologic modelling using frequency-based storm events
- the GRADEX method
- SEFM
- regional probability of the PMF.

Reclamation has applied the hydrologic hazard curve methods at numerous sites in the western United

States. Representative study sites, methods used and AEP ranges are listed in table 4. Most studies have provided flood frequency curves and hydrographs for risk analysis inputs. More detailed studies (CAS) provide reservoir elevation frequency curves to directly assess overtopping risk. It is notable that Reclamation has utilised hydrologic hazard curves for final design modifications at Folsom, AR Bowman, Glendo and Hyrum Dams (table 4). The final design AEP targets for these sites varies, and is a function of the hydrologic hazard curve, failure probability for the load range and consequences. In the case of Folsom Dam, very high consequences and the hazard curves from paleoflood studies (Bureau of Reclamation, 2002b) and SEFM (MGS Engineering, 2005), with AEPs ranging from 1-in-10,000 to 1-in-

Table 4: Representative Reclamation hydrologic hazard curve application sites.

Dam (state)	Study year	Method(s)	Study type	Target AEP or range	Frequency and risk inputs
Bradbury (CA)	1996	FFA – FLDFRQ3 (paleofloods)	CAS	1/10,000	Peak flow
AR Bowman (OR)	1997-1999	FFA – FLDFRQ3 (paleofloods); SEFM	CAS/FD	1/10,000; 1/100,000	Peak flow; volume; reservoir elevation; hydrographs
Rifle Gap (CO)	2002	FFA – EMA (paleofloods); Australian	IE	1/10,000	Peak flow; hydrographs
Folsom (CA)	2002	FFA – FLDFRQ3 (paleofloods); hydrograph scaling; SEFM; PMF	CAS/FD	1/10,000; 1/100,000	Peak flow; volume; hydrographs
Fresno (MT)	2003	GRADEX	IE	1/1,000,000	Volume; hydrographs
Glendo (WY)	2003	FFA – FLDFRQ3 (paleofloods); hydrograph scaling	CAS/FD	1/10,000; 1/1,000,000	Peak flow; hydrographs
Los Banos (CA)	2005	FFA – graphical (paleofloods); hydrograph scaling; GRADEX	IE	1/10,000	Peak flow; volume; hydrographs
Pueblo (CO)	2006	FFA – EMA (paleofloods); TREX	CAS	1/10,000; 1/1,000,000	Peak flow; hydrographs; reservoir elevation
Reach 11 Dikes (AZ)	2006	Regional rainfall frequency (NOAA Atlas 14) and extrapolation	IE	1/10,000,000	Volume; reservoir elevation
Blue Mesa (CO)	2007	Australian	IE	1/1,000,000	Peak flow; hydrographs
Lahontan (NV)	2007	FFA – FLDFRQ3 (paleofloods); hydrograph scaling	IE	1/100,000	Peak flow; hydrographs
Over 60 sites in western US	2002-present	FFA – graphical (paleofloods); hydrograph scaling	CFR	1/10,000; some to PMF	Peak flow; hydrographs
Whiskeytown (CA)	2008	SEFM; paleofloods	CAS	1/100,000	Peak flow; volume; reservoir elevation
Hyrum (UT)	2009	Australian; paleofloods	CAS/FD	1/100,000	Peak flow; volume; reservoir elevation
Trinity (CA)	2009	SEFM; paleofloods	CAS	1/100,000	Peak flow; volume; reservoir elevation

100,000, led Reclamation to select the PMF as the design flood. Final design floods for the other three sites varied and are less than the PMF.

4 ONGOING IMPROVEMENTS TO EXTREME FLOOD DATA BASES

Databases are crucial for extreme flood hazard estimation. Many of the hydrologic hazard techniques for risk analysis utilise precipitation or rainfall as a major input (table 3). For Reclamation facilities, there is a strong focus on paleoflood data, because of the ability to obtain the data in the western United States. There are ongoing efforts to improve the data used for extreme flood hazard assessments in the United States, particularly in three areas: extreme storms up to the PMP; precipitation frequency; and paleofloods.

4.1 Extreme storm databases

The basis for extreme storm rainfall estimates and PMP in the United States is depth-area duration (D-A-D) studies of notable extreme storms (eg. USACE, 1973). The D-A-D data and PMP methods are used to provide "generalised" PMP estimates over large regions of the United States (figure 4). The PMP estimates have been published in hydrometeorological reports (HMRs) (table 5).

For at least the past 50 years, the USACE, Reclamation and National Weather Service (NWS) (and others) have jointly collaborated in collecting and analysing storm rainfall data and publishing D-A-D data. These agencies have also collaborated in developing and improving PMP techniques. This work effectively ceased with the publication of HMR 59 for California in 1999. Data and methods for estimating extreme storms, up to and including the PMP, are currently lacking. Currently, there is no mechanism in place within federal agencies to routinely collect, analyse and archive extreme storm data that is useful for estimating extreme floods. In addition, there are no procedures in place to update storm data sets, methodology and reports that are used to develop generalised PMP estimates.

The data in table 5 indicate that there is a definite need for updated storm data collection and potential

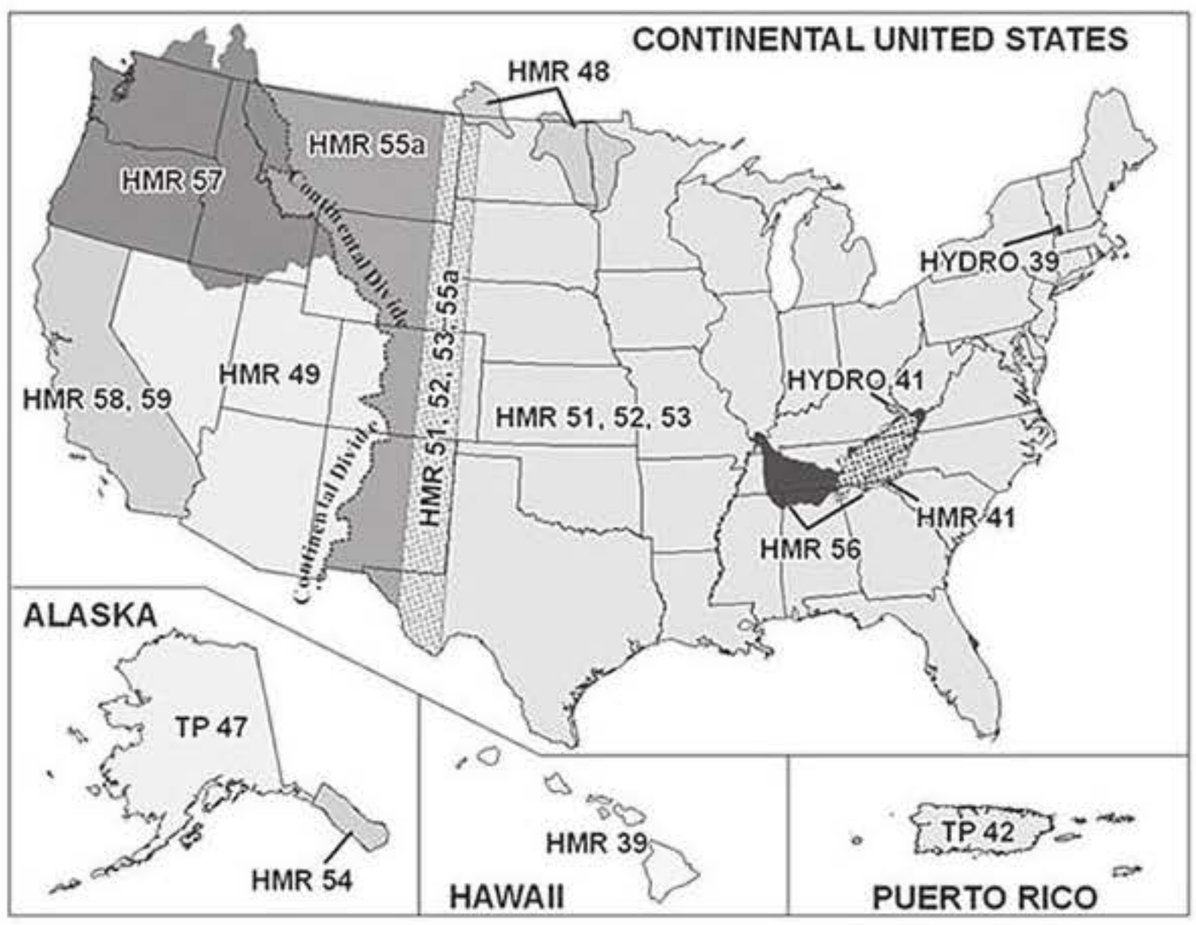

Figure 4: Regional coverage of generalised PMP reports in the United States (source: www.nws.noaa.gov/oh/hdsc/studies/pmp.html).

Table 5: Status summary of hydrometeorological reports for PMP estimation.

HMR No.	Publication date	Latest storm used	Comments
49	1977	3-7 September 1970	See HMR 50 for storm info; 1983 Prescott, AZ storm exceeds PMP
51	June 1978	19-23 June 1972	Replaced HMR 33 (1956)
55A	June 1988	1-4 August 1978	Replaced HMR 55 (1985) and TP 38 (1960)
57	October 1994	24-26 December 1980 (general); 16 August 1990 (local)	Replaced HMR 43 (November 1966)
59	February 1999	14-19 February 1986	Replaced HMR 36 (October 1961)

revision to the HMRs. In response to this need, an Extreme Storm Events Work Group under the Federal Subcommittee on Hydrology was formed in 2008. This work group is chartered to coordinate studies and develop databases for reviewing and improving methodologies and data collection techniques used to estimate design precipitation up to and including the PMP (England et al, 2008). Details on the Extreme Storm Events Work Group are available at http://acwi.gov/hydrology/extreme-storm/index.html. The initial effort focuses on collecting and reviewing extreme storm event data in the southeastern US that have occurred since 1972, and examining potential updates to HMR 51 (table 5) for the USNRC.

4.2 Regional precipitation frequency: NWS

Precipitation frequency estimates are one key input for extreme flood methods. Reclamation's use of AR&R Book VI PMP probability procedure depends on precipitation frequency estimates. In most areas of the western United States, precipitation frequency estimates are available for AEPs up to 1-in-100 in NOAA Atlas 2. However, these estimates were completed in 1973 based on data that ended in 1965. Over 40 years of additional precipitation information is now available. In the eastern United States, there are large areas covered by NOAA Technical Paper 40, completed in 1960. These estimates are also extremely outdated, and are being replaced in phases (figure 5). The NWS is currently in the process of updating precipitation frequency estimates with NOAA Atlas 14, using regional precipitation frequency with L-moments. The status of the nationwide studies is shown in figure 5; hatched areas are completed volumes. The completed volumes are available from a web interface, with *geographic information system* base layers also available. These data sets, as they become available for various regions, will help in hydrologic hazard curve estimation. Currently, Reclamation uses 1/500 and 1/1000 AEP estimates from NOAA 14 as inputs to the CRC-FORGE procedure. Precipitation frequency estimates from NOAA 14 are insufficient by themselves to estimate extreme floods beyond 1/2000 AEP (eg. AR&R Book VI). Updates on NOAA 14 status and methods used are available from NWS.

4.3 Paleoflood database

Paleoflood hydrology is the study of past or ancient flood events that occurred before the time of human observation or direct measurement by modern hydrological procedures (Baker, 1987). The paleoflood specialist studies the river geomorphology and soils/stratigraphy adjacent to the river that provides information on past floods, as well as the evidence of past floods and streamflow derived from historical, archaeological, dendrochronologic or other sources. Information on potential limits on magnitudes of past floods are also obtained (Levish, 2002). The advantage of paleoflood data is that it is often possible to gain information about events that are 10 to 100 times older than the observational record (eg. streamgauge). Floods much greater than those in the gauging record may be obtained, and the largest floods in the gauging record may also placed in proper time context.

There is currently no US national paleoflood database for use in estimating extreme floods. Reclamation routinely utilises paleoflood data collected at the site of interest in estimating hydrologic hazard curves. Since 1994, Reclamation has collected paleoflood data at and near large dams, where the data are

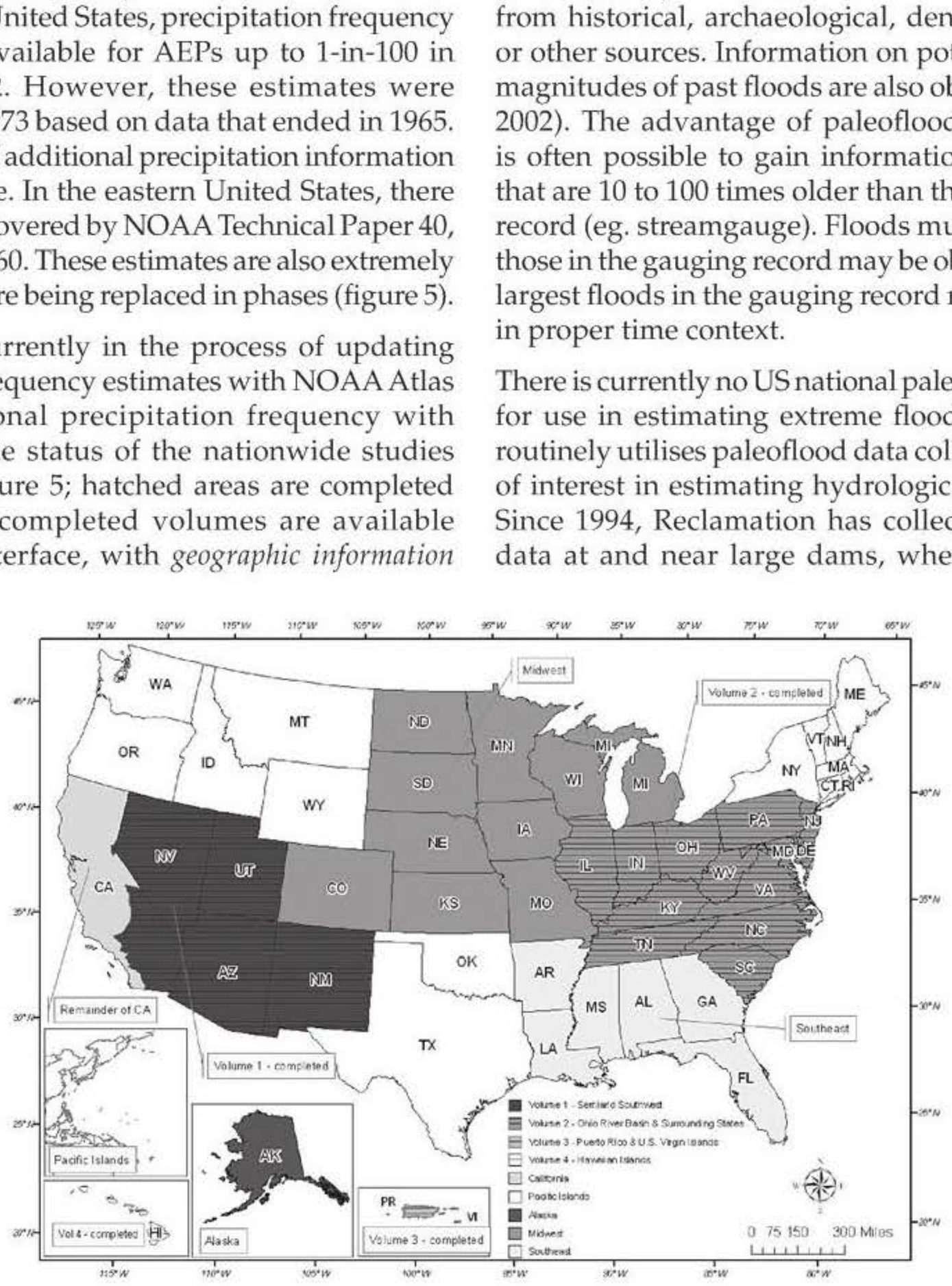

Figure 5: Status map of NOAA Atlas 14, precipitation frequency atlas in the United States (source: www.nws.noaa.gov/oh/hdsc/current_projects.html).

needed for hydrologic risk assessments conducted for individual sites (figure 6). Paleoflood data are collected in one of three levels: reconnaissance, intermediate or detailed studies. As the level of study increases, more stratigraphic and soils-age data are obtained, and hydraulic models used for discharge increase in complexity. Data are currently stored in paper copies and in computer databases (Klinger & Godaire, 2002). Regionalisation of flood frequency curves with paleoflood data is a challenge, because of the paucity of sites compared to streamflow gauges. For two studies, Folsom Dam in California (Bureau of Reclamation, 2002a) and Pueblo Dam in Colorado (England et al, 2006; 2010) index flood concepts were used to compare paleoflood frequency curves from four sites within each watershed. Current efforts now focus on performing broader regionalisation comparisons among watersheds with these data. Reclamation utilises paleoflood data as an independent extreme flood source to compare rainfall-runoff model extreme flood predictions (eg. England et al, 2006; Sutley et al, 2009). Detailed flood studies conducted by Reclamation to date (table 4) suggest that paleoflood data are representative for evaluating contemporary flood risk. Additional data collection and modelling studies are needed to provide further insight to this question, within a risk-based decision framework. In some cases, tradeoffs between bias, uncertainty and information content need to be considered.

5 CHALLENGES TO ADVANCING DESIGN FLOOD TECHNIQUES

There are several potential challenges to making progress and changes to US national flood guidelines, fully embracing hydrologic risk for critical infrastructure and updating flood-related databases. The previous sections have clearly highlighted the ongoing efforts toward some advances in these areas. The successful, long-term implementation of these advances within the flood hydrology community can be tempered with some (usual) challenges: institutional barriers; national scale; funding; research to operations; and new technologies/information.

Within the United States, there are some institutional barriers because various federal agencies have differing responsibilities and design standards, as noted in table 2. The regulatory agencies, while interested in risk, are moving at a slower pace compared to self-regulating agencies. This leads to some potential hurdles to change, as each agency has a different design or assessment standard. Data networks are also a bit dispersed; for example, precipitation, snowpack and streamflow information are stored at the agency or state level. Flood regimes in the US are spatially heterogeneous; this leads to challenges in developing consistent flood-related data sets on a national scale. For example, aggressive paleoflood data collection has been done in the western US for one agency (figure 6), but to a very limited extent in the eastern US. Likewise, precipitation estimates from radars are being synthesised in non-orographic areas (Nelson et al, 2010); challenges remain in much of the mountainous western US. As in many national scale efforts, funding is an issue because of the problem scale and differing agency responsibilities. The NWS has been successful in updating precipitation frequency estimates (as described above). However, progress is slow on extreme storm database development due to three main factors: lack of other agency support

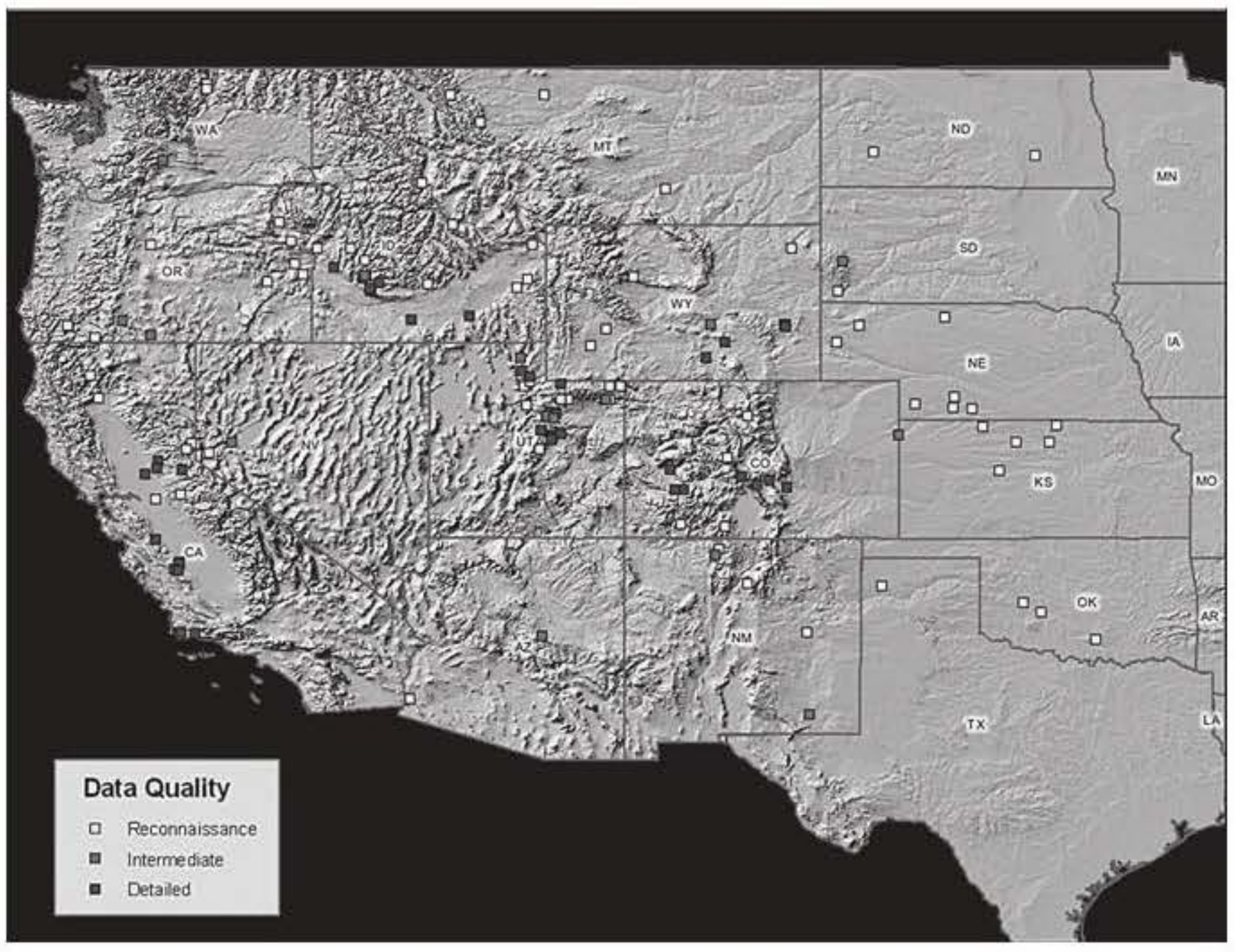

Figure 6: Reclamation paleoflood sites for dam safety in the western United States.

to NWS; staff skills and training needs in flood hydrometeorology, especially PMP; and ability to transition new tools and data sets from research to operational usage.

As in other fields, the ability to incorporate new/existing theory and concepts from research to operations in extreme flood hydrology remains a continual challenge. Lack of familiarity with newer computer programs, and limited documentation and training materials for those codes, are some challenges. There are ongoing policy and technical challenges on data and methods for addressing potential non-stationarity/climate change issues related to flood hydrology (eg. Brekke et al, 2009). Use of new flood science information, including potential climate change, is a challenge to timely revision of critical flood-related data sets and guidelines. For example, the schedule and potential revisions to B17B currently do not directly include a component to deal with non-stationarity. However, ongoing dialogue via workshops (Olsen et al, 2010) helps in order to eventually solve some of these problems.

6 SUMMARY

This paper presented an overview of extreme flood hydrology methods used in the United States, highlighting areas of potential change and ongoing work in three areas: US national flood frequency guidelines, extreme flood probabilities for dam safety and nuclear facilities, and database enhancements. For floodplain management, B17B provides guidelines for estimating flood frequency curves. These guidelines were published in 1982, and are under investigation for improvements in treating historical floods and low outliers, and confidence intervals. Studies to date suggest that EMA with LP3 may be used to update the guidelines. The Bureau of Reclamation and Corps of Engineers are using various streamflow-based and rainfall-runoff-based methods to estimate hydrologic hazard curves for dam safety risk assessments. While the PMF is still used as an upper limit for assessing the safety of facilities, the focus now is on estimating a full range of flood loadings (peaks, volumes, reservoir levels) and associated probabilities for risk assessment. There is ongoing work to improve databases for extreme flood estimation, including extreme storms, precipitation frequency and paleofloods. Challenges to fully implementing these updates include: institutional effects; lack of a consistent US national-scale data collection effort; training and education on moving from research to operational implementation; and use of new science and technology information.

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