The National Dam Safety Program

Research Needs Workshop: Hydrologic Issues for Dams

FEMA

Preface

One of the activities authorized by the Dam Safety and Security Act of 2002 is research to enhance the Nation's ability to assure that adequate dam safety programs and practices are in place throughout the United States. The Act of 2002 states that the Director of the Federal Emergency Management Agency (FEMA), in cooperation with the National Dam Safety Review Board (Review Board), shall carry out a program of technical and archival research to develop and support:

- improved techniques, historical experience, and equipment for rapid and effective dam construction, rehabilitation, and inspection;
- devices for continued monitoring of the safety of dams;
- development and maintenance of information resources systems needed to support managing the safety of dams; and
- initiatives to guide the formulation of effective policy and advance improvements in dam safety engineering, security, and management.

With the funding authorized by the Congress, the goal of the Review Board and the Dam Safety Research Work Group (Work Group) is to encourage research in those areas expected to make significant contributions to improving the safety and security of dams throughout the United States. The Work Group (formerly the Research Subcommittee of the Interagency Committee on Dam Safety) met initially in February 1998. To identify and prioritize research needs, the Subcommittee sponsored a workshop on Research Needs in Dam Safety in Washington D.C. in April 1999. Representatives of state and federal agencies, academia, and private industry attended the workshop. Seventeen broad area topics related to the research needs of the dam safety community were identified.

To more fully develop the research needs identified, the Research Subcommittee subsequently sponsored a series of nine workshops. Each workshop addressed a broad research topic (listed below) identified in the initial workshop. Experts attending the workshops included international representatives as well as representatives of state, federal, and private organizations within the United States.

- Impacts of Plants and Animals on Earthen Dams
- Risk Assessment for Dams
- Spillway Gates
- Seepage through Embankment Dams
- Embankment Dam Failure Analysis
- Hydrologic Issues for Dams
- Dam Spillways
- Seismic Issues for Dams
- Dam Outlet Works

In April 2003, the Work Group developed a 5-year Strategic Plan that prioritizes research needs based on the results of the research workshops. The 5-year Strategic Plan ensures that priority will be given to those projects that demonstrate a high degree of collaboration and expertise, and the likelihood of producing products that will contribute to the safety of dams in the United States. As part of the Strategic Plan, the Work Group developed criteria for evaluating the research needs identified in the research workshops. Scoring criteria was broken down into three broad evaluation areas: value, technical scope, and product. The framework adopted by the Work Group involved the use of a "decision quadrant" to enable the National Dam Safety Program to move research along to produce easily developed, timely, and useful products in the near-term and to develop more difficult, but useful, research over a 5-year timeframe. The decision quadrant format also makes it possible to revisit research each year and to revise research priorities based on current needs and knowledge gained from ongoing research and other developments.

Based on the research workshops, research topics have been proposed and pursued. Several topics have progressed to products of use to the dam safety community, such as technical manuals and guidelines. For future research, it is the goal of the Work Group to expand dam safety research to other institutions and professionals performing research in this field.

The proceedings from the research workshops present a comprehensive and detailed discussion and analysis of the research topics addressed by the experts participating in the workshops. The participants at all of the research workshops are to be commended for their diligent and highly professional efforts on behalf of the National Dam Safety Program.

Acknowledgments

The National Dam Safety Program research needs workshop on Hydrologic Issues for Dams was held on November 14-15, 2001, in Davis, California.

The Department of Homeland Security, Federal Emergency Management Agency, would like to acknowledge the contributions of the U.S. Army Corps of Engineers, Hydrologic Engineering Center, which was responsible for the development of the technical program, coordination of the workshop, and development of these workshop proceedings. A complete list of workshop facilitators, presenters, and participants is included in the proceedings.

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FOREWORD

The Federal Emergency Management Agency (FEMA) sponsored a workshop on Hydrologic Research Needs for Dam Safety. The workshop was held on 14-15 November 2001, at the Hydrologic Engineering Center (HEC). HEC was responsible for the technical program and workshop coordination.

Information on current practices for computation of Probable Maximum Precipitation (PMP), Probable Maximum Flood (PMF) and risk factors associated with dam safety and case examples were covered in the workshop. The workshop participants presented a variety of papers and information relating to research needs for dam safety. Corps participants included representatives from Headquarters, Districts and the HEC. Non-Corps participants were from the following offices:

1. Bureau of Reclamation (USBR)
2. Federal Energy Regulatory Commission (FERC)
3. Tennessee Valley Authority (TVA)
4. The States of California, Utah and Georgia dam safety programs
5. Pacific Gas and Electric (PG&E)
6. US Geological Survey (USGS)
7. University of California at Davis and Utah State University
8. MGS Engineering and Applied Weather Associates
9. Sinclair Knight Metz, Australia and BC Hydro, Canada
10. Somerset County, New Jersey

The workshop provided a forum for the exchange of ideas related to the risks involved with operation of small to very large dams. There were discussions on the reasonableness of the annual exceedance probability (AEP) of a PMF and how the computed value of the PMF compares to data from paleoflood analyses.

The focus of the workshop was to prioritize recommendations for research needs related to Dam Safety.

HYDROLGIC RESEARCH NEEDS
For
DAM SAFETY

EXECUTIVE SUMMARY

INTRODUCTION

A workshop on *Hydrologic Research Needs for Dam Safety* was held on 14-15, November 2001 at the Hydrologic Engineering Center (HEC) in Davis, California. The workshop provided a forum for the discussion of subjects important to the computation of a Probable Maximum Flood (PMF), the uncertainty of parameters used to compute a PMF, the continued use of the PMF as the "design flood", using risk analysis procedures to develop the design flood and hydrologic risks involved with dams and dam operations.

The main focus of the workshop was to generate a list of topics that are in need of research that may help in generating solutions to problems related to dam safety.

The workshop proceedings are included in this document.

PROBLEM STATEMENT

Research problems can be divided into areas for fundamental research and for application. The fundamental research problems could involve investigating approaches for improving the state-of-the-art. This would include some possible new approaches for either estimating the design inflow flood or in using risk analysis instead of the currently accepted use of the probable maximum flood. Any new approach that is proposed needs to be commensurate with the funding and resources available for the dam safety evaluation. Large organizations owning dams in a high hazard category (where there is a significant population at risk downstream), may be able to afford a sophisticated engineering analysis. However, smaller dams, whose owners do not have the resources for sophisticated analyses, need methods that can be applied that provide an adequate analysis commensurate with the value of the dam and the consequences of failure. Some possible avenues for research into developing simplified techniques that can provide useful answers given the most current thinking on hydrologic methods for dam safety analysis are discussed below.

Inflow Design Flood Estimates
The hydrologic problem typically addressed in dam safety analysis is the determination of the capacity of the spillway needed to prevent catastrophic failure of the dam due to overtopping. The PMF is generally accepted as the design inflow for evaluating the spillway when there is potential loss of life due to dam failure in high hazard situations.

The PMF represents an estimated upper bound on the maximum runoff potential for a particular watershed. In some sense, the inherent assumption is that a dam with a spillway designed to pass this flood has zero risk of overtopping.

The PMF design standard has been reexamined in the past and continues to be debated as a design standard up to the present time. One of the most significant initial reevaluations of this standard is described in NRC (1985)[1]. In this reevaluation, base safety analysis (an incremental deterministic evaluation) and risk analysis were explored as potential alternatives to the PMF criteria.

Since this reevaluation, a considerable amount of research, which examines the use of the PMF and explores the benefits of a risk approach, has been completed. Despite this research, significant hydrologic problems in dam safety analysis still need to be solved. These problems are apparent when considering: 1) mechanisms in addition to overtopping that might cause catastrophic failures of the dam; 2) the recent research into paleoflood estimates of the largest floods occurring in the past 10,000 years; and, 3) the need to estimate the exceedance probability of extreme floods when performing a risk analysis.

Mechanisms, other than overtopping, which have potential to cause failure of a dam, are erosion of the spillway or undermining of the spillway foundation. Certainly, these problems have been noticed in recent floods in the Kansas, Gila and Colorado River Basins. The potential for failure increases for these mechanisms as the duration of the flooding increases. Extended duration events could result in severe erosion of a spillway, with an insufficient intervening period to perform maintenance; and, consequently, cause dam failure. As an extreme example, the great Upper Mississippi Basin flood of 1993 included 5 major flood inflow events to Saylorville Reservoir on the Des Moines River over a period of 5 months. Examples like this illustrate that extended flow periods should be considered in the design process, as opposed to the current application of the single peak hydrograph of the PMF.

A possible approach to addressing this design problem is to consider estimating the probable maximum precipitation over multi-month periods. Inflow hydrographs could be developed by simulating patterns of historic precipitation proportioned to have an equal volume to the probable maximum amount over the duration desired.

Besides the volume issue, recent paleoflood evidence in the western United States indicates that the largest floods occurring in the past 10,000 years are significantly smaller than PMF estimates. This difference has caused some concern with regard to the magnitude of the PMF estimates. Possible reasons for this difference between the estimates might come from problems with models used to estimate peak flows from paleo-stage indicators or the area reduction factors used to convert point estimates of the probable maximum precipitation (PMP) to a total storm depth.

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[1] National Research Council, 1985. Safety of Dams, Flood and Earthquake Criteria, Committee of Safety Criteria for Dams, National Academy Press, Washington, D.C., 321p.

Risk assessment, if applied, requires estimating flood distributions for infrequent quantiles where estimation methodologies applied in statistical hydrology are not valid. Both the National Research Council (1988)[2] and IACWD (1986)[3] have addressed the problem of estimating exceedance probabilities for large floods, without providing any guidance for extending estimates beyond the 1/1000 exceedance probability. Paleoflood information has more recently been used, at least in the western U. S., to extend the flood distribution to the 1/10,000 exceedance probability. Additional research is needed to address how best to incorporate different sources of information (the gage record, stochastic precipitation and watershed models, and paleoflood information bounds) for obtaining estimates of extreme flood exceedance probabilities needed for risk assessment.

These problems provide a focus for hydrologic research needs for dam safety analysis. The focus might be on developing long duration design inflow hydrographs, explaining the reasons for differences between PMF and paleoflood estimates, and integrating different sources of information to obtain flood probability distributions needed for risk analysis.

Application Research

Application techniques are needed that reflect the current thinking on estimating the design inflow flood and can be applied commensurate with the resources available to perform the dam safety analysis. The need to develop simplified techniques is likely to be very important to owners of small dams who do not have the resources to formulate/apply sophisticated meteorologic and hydrologic models. Opportunities for developing these simplifying techniques may reside in regional analyses. For example, watershed characteristics might be related to existing estimates of the PMF. Obtaining these regional relationships would require studies much like those done in developing the U.S. Geological Survey regression equations for flow-frequency curves. In any case, the current research needs to develop methods that can be simply and economically applied given the appropriate dam safety analysis problem.

PRESENTATIONS

The majority of the workshop consisted of presentations by various agencies detailing what they felt are areas of research that could address the problems cited above. Federal Agencies, State and County Agencies, Private sector firms, and educational institutions made presentations. Presenters listed various problems encountered by their respective organizations and presented suggestions for areas of research.

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[2] National Research Council, 1988. “Estimating Probabilities of Extreme Floods, Methods and Recommended Research”, ISBN 0-309-03791-3, National Academy Press, Washington, D.C. 141p.

[3] Interagency Advisory Committee on Water Data (IACWD), 1986.“Feasibility of Assigning Probability to the Probable Maximum Flood”, Office of Water Data Coordination, U.S. Department of the Interior, Geological Survey, Office of Water Data Coordination, Reston, VA.

RESEARCH AREAS

Research needs were broken into three areas. These were Risk based, Standards and Meteorological needs. After a period of discussion, the workshop reassembled and each group boiled down the research needs presented in each paper and then presented their opinions. Some of the identified research needs are listed below. A more detailed list is located in the Discussion section of this document.

Risk Analysis Group – Items relating to uncertainty factors that influence reservoir inflow values and the computation of the Annual Exceedance Probability (AEP) of extreme floods.

- Storms and flood database
- Extension of flood frequency curves
- Develop regional hydrology parameters

Standards Group – Items relating to physical factors that influence the methodology for the computation of extreme floods, including the PMF.

- Improve technology transfer
- Develop regional database
- Loss rate function analysis

Meteorology Group – Items relating to rainfall analysis from both the standards based analysis and a risk-based analysis.

- Precipitation analysis
- Rainfall frequency analysis
- Real time storm analysis

Corps of Engineers Huntington District
Hydrologic Research Needs for Dam Safety Analysis

By
Jerry W. Webb[1]

Current Practices.

Huntington District utilizes standard methodologies to develop Probable Maximum Flood (PMF) for individual projects. Out of the 35 dams that have been constructed in the District, nineteen (19) are considered adequate under current criteria, seven (7) were altered to correct the deficiency, and nine (9) facilities remain that provide 53-79% PMF retention. Historically, the PMF was evaluated using the "then-current" standards and spillway adequacy was assessed. There have been several changes over the years in methodology and standards, which have impacted the magnitude of the PMF, which altered the extent of the deficiency and/or structural fixes required to correct the hydrologic deficiencies. The assessment of hydrologic deficiencies is funded under the Operations & Maintenance program and there is no specific allocation to provide any continuity to the program. The Dam Safety Assurance (DSA) requirements at Bluestone Dam will exceed $110 million. This single project exceeds the total construction cost of the seven altered facilities by a factor of five. There is a significant need to develop consistent, supportable guidelines and methodologies for development of a design storm to be used in Dam Safety analysis that is acceptable over a broad range of scenarios.

Problems with Existing Methodology.

Developing a Probable Maximum Flood (PMF) for any project continues to rely upon the proper application of current knowledge and the development of individual experience in the field of hydrology. The final hydrograph for any PMF continues to be subjective and judgmental due to a large number of factors such as:

Orographic Effects.

The Huntington District includes a mountainous area that suffers from orographic lifting, whenever the wind has an onslope component. The rate of the lifting is determined by the magnitude of the onslope component and the degree of slope. The determination of the height of the air column to be lifted orographically presents a problem when dealing with Probable Maximum Rainfall (PMR). Studies suggest that a 3,000-ft mountain barrier in the path of a strong wind should certainly produces an upward wind component that would persist above the 6-km. level. This situation has resulted in the Huntington District requesting special studies by the NWS to develop site-specific PMR for these projects. The peak discharge has been impacted by 0-7% when compared to standard procedures.

[1] Huntington District, U.S. Army Corps of Engineers

Lack of Historical Data for Extreme Events.

Historical stream flow data provides (when available) a means for calibrating the hydrology relating to the unit hydrograph development and stream routing procedures. The other variables (antecedent condition, initial and constant rainfall lose rate, etc.) cannot be readily determined for a Probable Maximum Flood event. Very few gaging stations provide data representative of extreme events, which suggests that calibration is of limited value in dam safety applications.

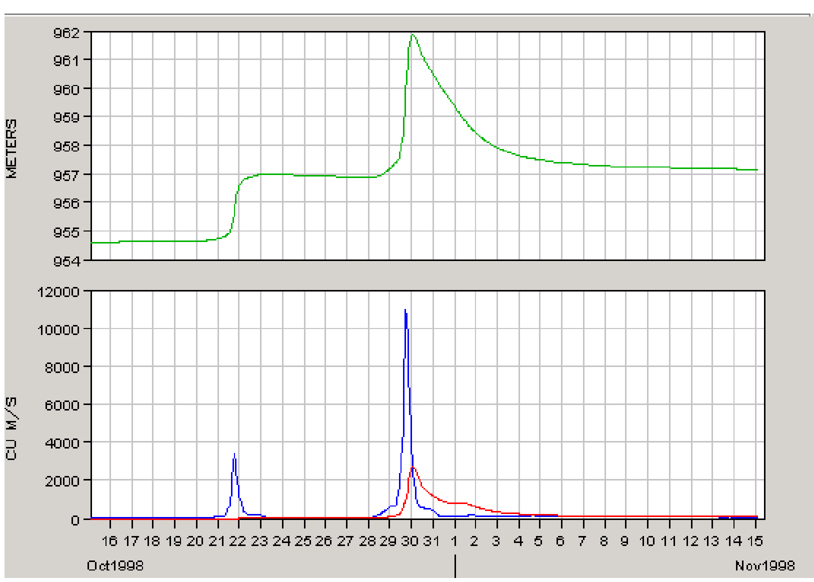
Variation in Operational Scenarios.

Huntington District develops daily forecasts for the purpose of making operational decisions. Most of our projects have not been operated for extreme events, and there is a perception that water control plans may be altered on a case-by-case basis during a major flood event. This consideration complicates the modeling process especially when dealing with the calibration issue. Current assessments are not consistent concerning operational assumptions during a PMF.

Antecedent Rainfall Conditions.

The rainfall breakdown for the design storm is not well documented relative to assumptions for antecedent rainfall that precedes the Probable Maximum Rainfall (PMR). The following National Weather Service criteria of incorporating the antecedent event into the total storm hydrograph is based on judgment (experience) and not supported by any particular study. The following diagram shows how the antecedent rainfall is currently used in the reservoir routing process. It provides a starting pool elevation prior to the main event.

30% PMR + 3- Day Dry Period + 100% PMR
39% PMR + 5-Day Dry Period + 100% PMR



Multiple Reservoir Systems.

A drainage basin with a system of reservoirs cannot be accurately modeled for Probable Maximum Storm (PMS) spillway deficiency using the single storm centering approach of HMR51 and 52. Large storm events will drop significant amounts of rainfall over a larger area than the single storm exhibits. A single storm centering will not capture this situation, when dealing with multiple reservoirs. The potential exists for multiple projects to receive significant amounts of rainfall during rainfall event frontal movements.

New Technologies.

Geographical Information System Interface.

The determination of basin hydrologic parameters (size, shape, slope, etc.) and hydrologic model development continue to improve with technology and ability to obtain digital mapping. The future looks very promising from this standpoint and should continue to improve with onset of ground verified rainfall radar imaging. There is a definite need to incorporate the PMR distribution into the HEC-HMS modeling software. The drainage area and latitude/longitude of the storm centering could be accurately assessed using currently available GIS utilities. Sensitivity to the design storm assumptions could be easily applied to dam safety studies.

Risk & Uncertainty Applications.

The application of risk and uncertainty principles in the prioritization of dam safety requirements appears to have some merit. Developing a portfolio of structures, including evaluations of risk and uncertainty of potential failure mechanisms and the consequences of such failures, provides a tool that can be used to justify incremental expenditures for correction of some deficiencies while leaving others to a later date. The ongoing R & D program in this arena will develop many tools that will assist dam safety officials nationwide in making decisions based on highest risk and/or highest consequences of failure. The concept can also be used to prioritize engineering studies necessary to assess deficiencies.

R&D / Policy Needs.

Address Current Known Problems & Inconsistencies.

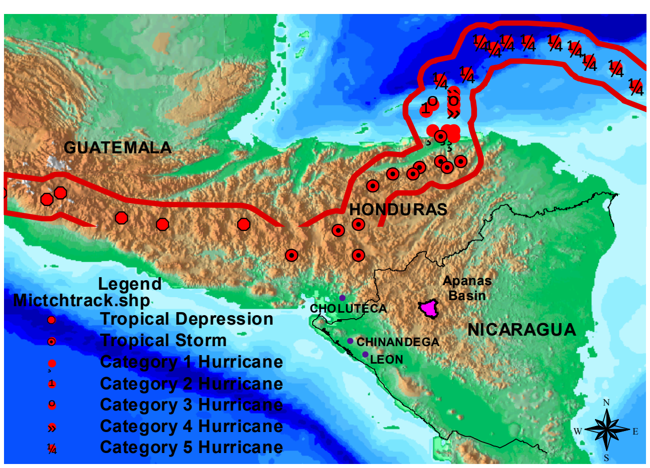
The problems discussed above support the need for consistent guidelines that consider orographic effects, large drainage areas subject to frontal movement storms, multiple reservoir systems, lack of historic data for calibration, antecedent rainfall conditions, and variations in operational scenarios for extreme events. The cost to correct observed deficiencies is directly related to the magnitude of the design event. Provisions for more objective evaluation procedures should be the goal of any new R & D initiatives. Policy should be developed that will allow the issues, raised above, to be addressed in an efficient and economical manner.

Extreme Event Volume/Duration/Frequency Criteria.

There is significant need to develop a better understanding of the probability/frequency associated with the PMF. There is a perception that some agencies have started using different evaluation criteria for dam safety, which disregards the current design standards. Extreme event frequency projections are absolutely essential to any dam safety analysis process.

Special Problem/Example.

The Huntington District has been involved in developing design storms to determine spillway adequacy for several reservoirs in Nicaragua. HMR51 and HMR52 were employed to achieve this assigned task even though they were developed by NWS for the mainland USA. Hurricane Mitch rainfall dropped extreme amounts of rainfall over a very large area. PMF storm amounts would not capture this condition when dealing with a large drainage area above an existing project. The outer isohyetal rainfall of the PMF did not approach the actual hurricane amounts. Special adjustments were made to final HMR52 rainfall amounts based on air moisture carrying capability and distance from the sea. The diagram demonstrates how the rainfall pattern was placed over one of the study areas.



Multiple Storm Tracks

Storm Centerng

Omaha District's Current Practices and Needs for Dam Safety Analysis

By
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CURRENT PRACTICES

Currently the Omaha District follows procedures determining Inflow Design Floods found in Engineering Regulation 1110-8-2(FR) dated 1 March 1991 and entitled: ***Inflow Design Floods for Dams and Reservoirs***. This document sets standards for four types of reservoirs and the data needed for their design. It also describes that an antecedent flood may occur and may be incorporated by assuming a full flood control pool or the pool elevation occurring five days after the occurrence of a rainfall of one-half the Inflow Design Flood (IDF). For dam rehabilitation, Engineering Regulation ER 1110-2-1155 dated 12 September 1997 entitled: ***Dam Safety Assurance Program*** was followed. This document describes the determination of the Base Safety Condition to be used to determine the need for dam safety modifications allowing for even high hazard dams to be designed for less than a PMF if conditions warrant (that dam failure does not exceed damages and loss of life from an event without dam failure).

Typically a study is initiated using a generalized Probable Maximum Precipitation (PMP) based on the most recent applicable guidance received from the National Weather Service (NWS). If questions arise concerning this study, the District could request a site-specific PMP study from the NWS.

PROBLEMS FACED

Problems concerning this process were encountered during a dam safety assurance study undertaken by the Omaha District in 1998 on Cherry Creek Dam in Denver, Colorado. Concerns were expressed during a Reconnaissance Study completed in 1993, that the PMP and Probable Maximum Flood (PMF) were too high for the Cherry Creek drainage basin. A site-specific study was requested by the Omaha District from the NWS and completed in 1995. Based on this study, the Omaha District began a dam safety evaluation study in 1998. In addition, the antecedent flood had a tremendous impact on the PMF routing. Again the Omaha District requested a site-specific antecedent flood study from the NWS and this was incorporated into the study. During the study numerous questions were raised about the PMP analysis and some of the these issues are summarized as follows:

- Paleoflood evidence was not used in the study. The evidence showed the largest paleoflood in the Cherry Creek basin was less than 100,000 cfs for the last 10,000 years.
- Local topographic conditions (Palmer Divide) would block inflowing moisture preventing large intense rainfalls from occurring.

[1] Omaha District, U.S. Army Corps of Engineers

- Storms used in HMR 55A and in the site-specific study had rainfall values that questionable or that were not transposable to the Cherry Creek basin. The amount and aerial distribution of the storm was too large for the Cherry Creek basin.
- Use of HMR 52 to orient the PMP was not appropriate.
- Centering of the storm was not appropriate since most extreme rainfall is tied to topographic/orographic features.
- The extreme frequency of a PMP/PMF event should not be used to determine the hydrologic adequacy of dams. The frequency was often quoted as being between 1 in a million or 1 in a billion.
- As a rule of thumb, the PMP is two to three times the 100-year rainfall: the site-specific study for Cherry Creek was seven times the 100-year rainfall event.
- The antecedent flood event study was not adequate.
- The NWS site-specific PMP study had not been independently reviewed.
- Dam safety risk analysis was not done

Cherry Creek Background

To adequately present the problems with the dam safety analysis a brief summary of the project will be presented. Congress authorized Cherry Creek Dam in 1944 with construction completed in 1950. The dam was located above downtown Denver and diverted spillway flows to the neighboring Sand Creek basin to provide Denver "complete protection" from large flood events. The original spillway design flood was based on the 1935 rainfall over the Republican River basin increased by 25-percent for a reliability factor. This data as well as subsequent studies are shown in Table 1. The original dam was also designed to include storage for irrigation that was never incorporated.

Table 1
Cherry Creek Dam Spillway Design Flood and PMF History

Event	**Rainfall in inches**	**Runoff in inches**	**Peak Discharge in cfs**
1944 Detailed Project Report HMR 13	11.5	8.1	180,700
1970 Dam Safety Evaluation HMR 44	23.9	9.7	376,00
1993 Reconnaissance Study HMR 55A	29.2	16.3	663,000
1998 Dam Safety Study 1995 NWS Site-Specific	24.7	12.8	524,000

The 1995 PMP was compared to historic storms in Colorado as "reality" check on the site-specific PMP. Table 2 shows these values. In 1999 the NWS met in Denver with various interested parties to present and discuss their PMP and antecedent rainfall studies. At that time the NWS agreed to withdraw their antecedent study. Comments from the meeting were either addressed at the meeting or later by the NWS, however, disagreements on the use of the "best science" persisted after the meeting. At the end of

1998, legislation has been introduced preventing the Corps of Engineers from completing the dam safety study. The State of Colorado, lead by the Colorado Water Conservation Board, has lead a team of interested parties reviewing the site-specific PMP study and pursuing various other methods including paleohydrology to perhaps be incorporated in the PMP study.

Table 2
Comparison of Average Rainfall Amounts for Historic Events in Colorado adjusted to a 386 square mile Basin (Cherry Creek)

Location (County)	Date or Type of Storm	Rainfall in inches 6-Hour	Rainfall in inches 12-Hour
Pueblo, CO (Pueblo)	June 4-5, 1921	7.0	10.3
Cherry Creek (Elbert)	May 30-31, 1935	9.9 (5-hour)	-
Hale, CO (Yuma)	May 30-31, 1935	8.4	9.2
Falcon, CO (El Paso)	June 16-17, 1965	10.0	-
Larkspur, CO (Douglas)	June 16-17, 1965	6.8	-
Pawnee Creek (Logan)	July 29-30, 1997	6.7	-
HMR 44-Cherry Creek	PMP	12.5	14.3
HMR 55A – Cherry Creek	PMP	17.8	22.1
Site-specific for Cherry Creek	PMP	15.5	18.4

R&D EFFORTS

As a member of the field review group for the Corps' R&D effort to develop procedures for performing risk analysis for dam safety, several research areas have been pursued. The highlights include ways to perform portfolio risk analysis, a framework for performing risk analysis, better ways to estimate the potential for loss of life, ways to extend discharge frequency curves beyond the 1000-year flood event level, and to develop probabilities for various types of failure mechanisms.

A POINT OF CONCERN

Often a frequency for the PMP/PMF is requested during dam safety investigations. Statistical studies have indicated that in various parts of the country the PMF has been estimated as between 1 in 1 million and 1 in 10 billion frequency of occurrence. These studies typically combine either rainfall or stream gage data from gages with records less than 200 years in length to estimate these extreme frequencies.

As a comparison, geologists are asked to perform the same estimate for the Maximum Credible Earthquake. Often these estimates are limited to less than a 1 in 10,000 frequency citing concerns over geologic changes during this time period. As hydrologists and meteorologists, we need to consider the impacts of climate change in the last 20,000 years in submitting the extreme frequencies for the PMP/PMF. Given the last ice age occurred between 10,000 and 15,000 years ago, do really have a sufficiently long set of independent events from which to forecast frequencies in the 1 in a million range? If not, what would be a suitable range? Perhaps the period from the last ice age? Even the period since the last ice age has had tremendous changes in climate. This will be an important point to consider for extending frequency curves to accomplished risk analysis for dam safety.

POLICY NEEDS

As Cherry Creek Dam demonstrates, policy for risk analysis and for the current PMP/PMF methodology need to consider the needs of specific areas and how they can be readily addressed by even the smallest dam owner. Can even federal agencies afford to perform site-specific PMP estimates when there seems to be much disagreement and judgment used in determining them? The Colorado PMP review was contracted for about $170,000. The same would be true for risk analysis since judgment will be needed in extending the frequency curve. At least policy needs to address:

- Concerns over site specific conditions such as topography impacting rainfall and runoff
- The need for independent review of work to overcome the potential disagreements from the use of judgment in the analysis
- How to make consistent, reproducible studies given the amount of judgment that will be needed
- How and when to include paleoflood evidence (when available) and the appropriate level of detail
- Consistency on the use of antecedent storm conditions
- When to use risk analysis and the level of detail needed to incorporate it

H&H Guidance for Safety of Dams

by
Ming Tseng[1]

1. **Existing USACE Guidance**
   a. **ER 1110-2-1155, Dam Safety Assurance Program, 12 Sept 1997**. This ER lays out the USACE Dam Safety. Hydrologic Criteria is on page 3, paragraph 7, and reflects the policies originally established in the policy letter dated 8 April 1895 (item 1f below).
   b. **ER 1110-8-2(FR), Inflow Design Floods for Dams and Reservoirs, 1 Mar 1991.** This ER establishes requirements for selection of Inflow Design Floods at USACE projects. The ER encompasses the principles contained in the FEMA report (item 3a below).
   c. **EP 1110-2-13, Dam Safety Preparedness, 28 June 1996.** This document contains general guidelines for implementation of the USACE Dam Safety Program.
   d. **IWR Report, Guidelines for evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies, June 1980.** This report contains guidelines for performing an incremental hazard analysis in conformance with policies set forth in items 1a and 1f.
   e. **HEC Report, Flood Emergency Plans, June 1980.** This report contains detailed guidelines for preparation of EAP for USACE dams with an example. It encompasses the principles contained in the FEMA report in item 3c below.
   f. **DAEN-CW/DAEN-EC Letter, Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies, 8 April 1985**. This is the original H&H Policy for evaluation of Hydrologic Deficiencies and is still in effect.

2. **Related USACE Guidance and Reports**
   a. **ER 1110-2-100,** Periodic Inspection and Continuing Evaluation of Completed Civil Works Projects, 15 February 1995.
   b. **Proceedings of a 1998 Workshop,** Modifications to Embankment Dams to Accommodate Inflow Design Floods, February 1998.
   c. **IWR Report 96-R-13,** Risk Analysis for Dam Safety Evaluation: Hydrologic Risk, March 1996

3. **Other Guidance (Non-Corps)**
   a. **FEMA National Dam Safety Program Report,** Selecting and Accommodating Inflow Design Floods for Dams, October 1998.
   b. **FEMA National Dam Safety Program Report,** Hazard Potential Classification Systems for Dams, October 1998
   c. **FEMA National Dam Safety Program Report,** Emergency Action Planning for Dam Owners, October 1998

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[1] Hydraulics and Hydrology Branch, Headquarters, U.S. Army Corps of Engineers

d. **USBR Guidelines Publication, Dams and Public Safety,** 1983 (Safety Evaluation of Existing Dams Program)

H&H Dam Safety R&D Needs

By
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General

For the purpose of this discussion, hydrology and hydraulics (H&H) dam safety related research and development (R&D) needs are divided into two areas. The first area is closely aligned with traditional methods (deterministic approaches), although they are also pertinent to risk analysis, while the second area is specifically related to the application of risk analysis (RA) methods to dam safety evaluations.

Traditional H&H

Flood Series and Flood Runoff Volume

There is a very real and pressing need to develop systematic procedures to evaluate the effect of flood series and flood runoff volumes on dam safety. The use of a single hypothetical flood such as the PMF to evaluate the susceptibility of a dam to overtopping may not be the appropriate approach in many instances. Further, the occurrence of a series of floods with significant total runoff volume may be a much more likely scenario than the occurrence of a single rare flood. Over the last 10 to 15 years many of largest floods that have occurred in the U.S. have been as a result of a series of storms passing over a given drainage basin. Examples of this type of flooding are: the Arkansas R. in Kansas and Arkansas in 1986, the Trinity River in Texas in1990, the Upper Mississippi R. basin in 1993, and the Central Valley of California in 1995 and 1997. In all of these cases the individual storms were not unusually large and each resulted in only moderate to heavy amounts of rainfall. Because of their persistence however, the cumulative effect of the runoff volume was substantial and threatened to exceed the capacity of the reservoir system. In addition, the analysis of such conditions may not be limited simply to an evaluation of total runoff volume over a given period of time but may also require the inclusion of the temporal and spatial distribution of the individual storms. Guidelines are needed to allow practicing engineers to address these kinds of problems in a consistent manner.

Spillway Erosion

Over the last 20 years numerous USACE dams have been subjected to instances of severe spillway erosion. Examples of the problem are: Grapevine Dam in Texas in 1981, Lewisville Dam in Texas in 1990, Sam Rayburn Dam in Texas in 1990, Saylorville Dam in Iowa in 1984 and 1993, Painted Rock Dam in Arizona in1993, Milford Dam in Kansas in 1993, and Tuttle Creek Dam in Kansas in1993. In each of these cases erosion

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was severe. There was a potential, if conditions of spillway flow persisted, to lose the spillway with possible rapid loss of the reservoir. In each instance costly remedial work was necessary to address the problem. Based on these experiences, there is a need to continue development and testing of predictive techniques to identify conditions defining the onset and progression of erosion and a need for the identification of cost effective fixes to resist erosion. The USSD (formally USCOLD) is now in the process of finalizing a technical bulletin on this subject that will provide a state of the art summary of current analysis procedures, but there is still much work to be done, particularly in the development of specific evaluation guidelines.

H&H Dam Safety Risk Analysis

The USACE is committed to pursuing a risk analysis (RA) approach to dam safety evaluation, but is also determined to accomplish this goal in a straightforward, deliberate manner. This commitment is demonstrated by the initiation, in 1999, of a five-year R&D program to address many of the unresolved issues related to RA for dam safety.

The use of RA, which is based on mathematical and statistical computations, implies a level of accuracy in the results and an understanding of the engineering uncertainty that does not, in my opinion, exist at this time. The risk analysis methods presently available require further R&D before they are ready for general application and use as decision tools. Prior to general application of RA by the practicing engineer in H&H dam safety evaluations, improved methods for estimation of the probability of extreme floods must be developed, uncertainty must be explicitly included in the computations, expected loss of life (LOL) estimates must be improved and decision criteria based on LOL and social and environmental consequences must be established.

As noted above, there are four areas of major concern with the H&H portions of the RA methods that are currently being applied in dam safety evaluations. These areas of concern are: 1) the lack of proven statistical methods to estimate probabilities of extreme floods, 2) the large amount of uncertainty in the analysis that is not explicitly considered in the analytical approach, 3) the estimation of potential loss of life (LOL), particularly the heavy reliance on generalized data and flood warning systems, and 4) the lack of widely accepted decision criteria.

A considerable amount of effort has been devoted to the problem of estimating extreme flood probability, which is the most critical component in the application of RA in H&H dam safety studies. Numerous methods have been used to develop discharge/frequency relationships for the range of possible reservoir inflows that could occur. Methods that have been employed to date have ranged from simple extrapolation of curves constructed based on finite periods of record, to the use of paleoflood hydrology, precipitation records, regional frequency analysis and stochastic hydrology to better estimate return periods that could serve as "anchor" points in extending the basic discharge/frequency curves.

The RA methods currently being applied are for the most part based on event tree analysis. This requires the assignment of probabilities of occurrence, often with little or no data, to each branch of the event tree constructed to describe the physical processes that might occur. Thus, there is a heavy reliance on “expert elicitation.” Further, engineers are not generally comfortable with assigning probabilities to physical events, so that the whole analysis becomes much more “art” than engineering. Yet, because RA leads to an end result made up of absolute numbers, the analysis takes on the appearance of providing far more understanding than is presently the case.

In estimating expected loss of life that would result from a dam failure, most of the estimates in current use are based on generalized studies with heavy emphasis on warning times. Loss of life estimates should be site specific, and to be complete, uncertainty in the estimates should be explicitly included in the analysis. In addition to warning time LOL should be based on depth and velocity of flooding, how the flooding will occur, egress from flooded areas, adequacy of warning plans and other site specific factors. USACE experiences with flood warning systems, as part of its flood damage reduction program, show that in general they have been less than satisfactory.

Finally, the decision criteria now being used are based on “best estimates” of lives lost per year and the estimated probability of a given loading occurring. This approach has the effect of masking the true impacts of a dam failure. The long-term social and environmental consequences that may result from a dam failure are not specifically considered. The most common decision criteria now in use are 0.001 lives lost per year and a failure probability of 0.0001. In other words, if the estimated LOL per year is less than 0.001 and the likelihood of failure is less than 0.0001, then there is not a compelling reason to pursue remedial work, regardless of the social and environmental impacts. Furthermore, if the numbers indicate that no work is required, what is the chance that a non-technical decision maker will support remedial work, no matter what the long-term social and environmental consequences might be?

H&H R&D Needs for RA

The most immediate R&D need in applying RA to H&H dam safety analysis is to develop the means to more accurately estimate extreme flood probabilities. To accomplish this R&D must be expanded in areas that show promise. We need to continue and expand work on paleoflood hydrology, stochastic hydrology and the use of meteorologic and historical flood data to extend the record length and at the same time identify new approaches.

Secondly, we must expand our efforts to better define H&H parameter uncertainties, including the explicit description of the error distributions associated with "best estimates." Successful application of RA is dependent on accurately defining the uncertainties associated with, but not limited to, flood volumes, antecedent flood conditions, antecedent soil moisture conditions, unit hydrograph uncertainties, flood routing coefficients, dam breach formation, flood wave propagation, and operational uncertainty associated with hydraulic structure and hydraulic machinery performance.

Thirdly, we must develop better ways to estimate LOL. Estimates must be site specific and address not only warning time, but how flooding will occur (residual risk considerations), rate of water surface rise, depth of flooding, flow velocities in flooded areas, availability of egress (initial and continuing conditions), and evacuation plan uncertainty.

Finally, decision criteria must be established that are meaningful and understandable and take into account the catastrophic social and environmental impacts that are likely in the event of a dam failure.

Improving H&H Dam Safety Assurance using RA

In summary, I believe that for the short term we should continue to use the incremental hazard analysis as an interim approach for addressing H&H dam safety problems. Over the long term, we need to develop an RA method that allows us to reduce uncertainty, determine the extent of problems and prioritize remedial work.

Such an approach would entail the following steps:

1. Complete the R&D necessary to develop statistically acceptable methods for determining probabilities of extreme floods.
2. Develop a method of analysis that explicitly addresses the uncertainty inherent in the currently available risk RA procedures.
3. Establish final risk-based decision criteria based on improved estimates of LOL and long-term social and environmental consequences.
4. Develop an acceptable RA method that will allow dam safety evaluations over the full range of hydraulic loadings that is compatible with addressing geotechnical and structural concerns.

FEMA Workshop on Hydrologic Research Needs for Dam Safety Analysis
Federal Energy Regulatory Commission

By
Michael S. Davis, P.E.[2]

The purpose of this paper is to discuss the Federal Energy Regulatory Commission's (Commission) current practice in evaluating the adequacy of the spillway capacity of hydroelectric projects under it's jurisdiction, and to suggest areas where future research would be a benefit to these projects.

Current Practice

Regulations and Procedures

Since Order 122 was issued in 1981[3], the current practice of the Commission to ensure that the spillway capacity of all high and most significant hazard potential project is adequate has been governed by Sections 12.35(b) and 12.35(b)(1) of the Commission's regulations, which are as follows:

> 12.35(b) *Evaluation of spillway adequacy.* The adequacy of any spillway must be evaluated by considering the hazard potential which would result from failure of the project works during flood flows.
>
> 1235(b)(1) If structural failure would present a hazard to human life or cause significant property damage, the independent consultant must evaluate (i) the ability of the project works to withstand the loading or overtopping which may occur from a flood up to the probable maximum flood (PMF), or (ii) the capacity of spillways to prevent the reservoir from rising to an elevation that would endanger the project works.

The Commission's regulations require that for all high hazard potential dams and most significant hazard potential dams[4], an independent consultant must inspect the project and evaluate its stability and spillway adequacy every five years. To give the Commission staff and the independent consultant guidance and criteria for this evaluation, the Commission developed the <u>Engineering Guidelines for the Evaluation of Hydropower Projects</u>.

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[3] Order 122 established the current regulations for independent consultants inspecting and evaluating projects on a five-year cycle.

[4] Any significant hazard potential dam that is less than 32.8 feet high and impounds less than 2,000 acre-feet is not subject to this regulation.

For most projects, the first step for the independent consultant is to develop the PMF for the project and to evaluate the spillway capacity and stability of the project during the PMF. If the project can safely pass the PMF, then the spillway is adequate and no further studies are needed. If, however, the PMF exceeds the spillway capacity of the project, then the independent consultant is required to perform a dambreak analysis in accordance with Chapter 2 of our engineering guidelines, or the licensee may choose to modify the dam to safely pass the PMF.

If the dambreak analysis for all flood flows between the existing spillway capacity and the PMF show that the incremental increase in downstream flooding due to the failure is not a threat to downstream life or could cause significant property damage, then the spillway is adequate and no further studies are needed. However, this may need to be re-evaluated during future inspections if there are any changes downstream.

If there is a potential hazard to life or property downstream for these flood flows, then remedial measures are required to either increase the spillway capacity or increase the stability of the project structures to withstand the overtopping. Usually, an inflow design flood (IDF) analysis is done considering various alternatives for increasing the spillway capacity or the stability of the structures, and the IDF can vary depending on the type of fix. But once a fix is proposed for a flood less than the PMF, the license must demonstrate that the incremental increase in downstream flooding due to failure of the dam for all flood flows between the IDF and the PMF is not a threat to downstream life or could cause significant property damage.

In a few cases, a PMF study is not needed if the consultant can demonstrate through a dambreak analysis that either the spillway capacity is adequate or that the IDF will be considerably less than any estimates of the PMF. But in most cases, a PMF study is needed to establish the upper bound of the IDF.

Probable Maximum Flood Studies

Chapter 8 of the Commissions Engineering Guidelines, entitled, “Determination of the Probable Maximum Flood”, was first developed in 1993, and was recently revised in September 2001. The purpose of these guidelines is to provide systematic procedures that will consistently produce a reasonable PMF hydrograph and appropriate reservoir flood levels for evaluation of project safety, given the limitations of basic hydrologic and meteorological data. Although the guidelines give procedures and make recommendations for parameters, alternate procedures and parameters outside the recommended ranges can be used provided they are justified for the basin under study and supported with adequate documentation.

Runoff Model. This chapter recommends the use of the unit-hydrograph theory as the preferred runoff model. It also recommends that the Corps of Engineer’s HEC-1 or

HEC-HMS computer programs be used to model the runoff because of their widespread use and experience.

Channel Routing. Channel routing should be done using the Muskingum-Cunge method, which is incorporated into these computer models. However, any acceptable dynamic routing model such as the National Weather Service (NWS) DAMBRK computer program can be used instead if the consultant chooses to refine the model.

Probable Maximum Precipitation (PMP). The PMP should be developed from the latest NWS Hydrometeorological Reports (HMR). However, a licensee may choose to develop a site-specific PMP study, although this is usually very costly. This may done if the basin under study (1) is not adequately covered by the HMRs, has unusual site conditions that may not be addressed by the HMRs, or can benefit from a refinement of the HMR PMP values. To conduct a site-specific PMP study, the Commission requires that a Commission-approved Board of Consultants consisting of at least a hydrologist, a meteorologist, and a hydrometeorologist review the study. As an example of an approved study, the Commission accepted the 1993 EPRI PMP study for the States of Wisconsin and Michigan, which resulted in PMP values as much as 15 percent lower than HMR No. 51. The 1993 EPRI study also refined the procedures in HMR 52 for developing the probable maximum storm from the PMP values. As a result, the PMF's for many projects in these two States were reduced considerably, resulting in a significant cost savings to the licensee's of these projects. Figure 8.8-1 of Chapter 8 shows the limitations of the latest HMRs and the 1993 EPRI study.

Antecedent and Coincident Conditions. Rather than route an antecedent storm through the model, this chapter recommends that the reservoir level be assumed at its annual maximum operating level and that saturated conditions exist in the entire basin at the onset of the PMP. Several alternatives for the starting reservoir level may be considered which would required an analysis of the historical records or routing of the 100-year 24-hour antecedent storm 3 days prior to the start of the PMP. In most cases, using the annual maximum operating level gives satisfactory results.

Loss Rates This subject received the most attention when Chapter 8 was recently revised. The preferred method is to use the uniform loss rate method. Consistent with the premise that saturated antecedent conditions exist in the basin prior to the start of the PMP, it is acceptable to assume the initial loss rate is set to zero.

The losses in a basin can be developed either by the area-weighted basin-averaging of the loss rates of the hydrologic soil groups, or by a distributed loss rate method. The basin-averaged method is the traditional method that has been used for many years, and simply involves computing the average loss rate based on the percentage of the four hydrologic spoil groups. Chapter 8 recommends that the minimum loss rates from the National Resources Conservation Services (NRCS) 1955 Yearbook of Agriculture be used unless higher loss rates could be justified.

Instead of lumping the loss rates together in each basin, the distributed loss rate method divides each basin into pseudo subbasins corresponding to each loss rate class. The rainfall is then applied to each pseudo subbasin to determine the rainfall excess hyetographs. Then the rainfall excess hyetographs for all pseudo subbasins within a basin are summed to determine the rainfall excess hyetograph for that basin. These rainfall excess hyetographs are then input in HEC-1 with the loss rates set to zero for that basin. This method also works for larger basins that are subdivided into subbasins.

The distributed loss rate method was developed in the 1990's primarily to address an inconsistency with the basin-average method. Our procedures allows you to calibrate loss rates based on 3 to 5 historical events that meet certain criteria. However, loss rates calibrated using the basin-average method were found to be storm specific, particularly for basins with spatially diverse characteristics. A basin with a calibrated average loss rate for a specific storm may actually have a significantly higher loss rate for the PMF since significantly more portions of the basin contribute to the runoff during the PMF than did during the specific storm.

The second reason this method was developed was to incorporate the availability of the digitalization of soil databases such as NRCS State Soil Geographic (STATSGO) database. The STATSGO database contains many properties of the soil for several layers up to 60 inches deep. One such property is the hydraulic conductivity, which is the rate of flow through saturated soil, normally given as a range of values. The Commission's current criteria is to use the minimum value of the range for the least permeable layer, unless higher values can be justified through calibration or additional investigation of the geological make-up of the soils, the review of more detailed soils information such as county or local soils maps, or actual data obtained from any site investigations within the basin.

Dam Break Studies

Guidelines and Criteria

The Commission's criteria for conducting dam break studies is discussed in Chapter 2 of the Engineering Guidelines. The NWS DAMBRK and FLDWAV computer programs are the recommended unsteady flow model computer programs that can be used to route the flow downstream of the dam. However, the Commission has accepted studies using other programs as well. The NWS SMPDBK program has been accepted in a few cases where the accuracy of the results is not as critical. In some cases, if a field reconnaissance shows that there are no structures downstream, a computer analysis is not necessary.

In general, the consequences are considered to be acceptable when the incremental increase in flooding on downstream structures due to dam failure is approximately 2.0 feet or less. However, the 2.0-foot increment is not an absolute decision-making point. Sensitivity analyses and engineering judgment are required. For instance, inhabited trailers sitting on blocks can be moved with less than 2.0 feet of rise, and should be considered in this evaluation.

The Commission's guidelines for breach parameters is given in Table 1 of Appendix A of Chapter 2. In general, the average breach width should be between 2 and 4 times the height of the dam for earth or rock fill dams, and one or more monoliths up to one-half the length of the dam for gravity dams. Failure times range from 0.1 to 1.0 hours for earth or rock fill dams, and from 0.1 to 0.3 hours for gravity dams. For arch dams, it's appropriate to assume the entire dam fails in 0.1 hours or less.

Because of the uncertainty of breaches, the consultant should perform a sensitivity analysis of these parameters. For projects with large reservoirs, conservative breach parameters should be adopted since the rate of draw down of the reservoir during a breach is significantly slower than it is for projects with smaller reservoirs. In some cases, larger breach widths with longer failure times should be considered, such as for a long 20-foot high earth embankment that impounds a large storage reservoir.

Common Modeling Problems

1. Failure to model the entire reservoir. If dynamic routing of the reservoir instead of level pool routing is done, the consultant needs to make sure the cross-sections extend upstream of the reservoir to the point where backwater effects no longer exist. The shape of the cross-sections also needs to be examined to make sure all the storage between the cross-sections is accounted for. In some cases, the consultant extended the cross-sections only part way into the reservoir, effectively negating the storage upstream that could be released through a breach.

2. No sensitivity studies. Although the selected breach width may be at the conservative end of the accepted range given in our criteria, a larger breach width may result in a substantially higher incremental rise downstream. If the incremental rise is highly sensitive to the breach width, then this needs to be considered when selecting the breach width.

3. Improper use of the Manning's n values. The NWS DAMBRK program requires the user to provide the composite Manning's n values at each elevation. Therefore, for out-of-bank flood elevations the consultant needs to compute the composite Manning's n value based on the weighted wetted perimeter. In many cases, the consultant will select too high of a Manning's value for the out-of-bank elevations. Although not a major factor, this can effect the results in some analyses.

4. Improper spillway rating curve. In some cases, the reservoir was allowed to draw down during the beginning of the routing because the consultant did not

adjust the rating curve for when the gates are closed to maintain the normal pool level. In other cases, the consultant adjusted the rating curve to correct this, but the simulation then appeared as though the licensee closed all the gates instantaneously when the reservoir receded below the normal maximum pool after the breach developed.

5. The breach was assumed to initiate on the rising limb of the inflow hydrograph. It's imperative that a non-failure case be run first so that the peak headwater elevation at the dam can be determined and used in the failure case. This becomes more complex when conducting a domino-type failure analysis of downstream dams.

Research Needs

The following items are research needs that should be considered:

Probable Maximum Flood Studies

1. PMP. Many of the HMR's cover very large areas that don't take into account local terrain affects that may reduce the PMP for that area. Other refinements can be done that could reduce the probable maximum storm such as the EPRI Wisconsin/Michigan study.

2. Snowmelt. The HMR's in the western states have very approximate methods for combining snowmelt with the PMP. More research is needed in this area as it may be too conservative in some cases to combine 100-year snowpack with extreme temperatures, and the PMP.

3. Loss Rates. The changes in our guidelines point out the need for more research in using the distributed loss rate method with STATSGO data, particularly since the PMF can be very sensitive to the selected loss rates.

Dam Break Studies.

1. Breach Parameters. More research is needed on the proper selection of breach parameters, particularly for earth and rock fill dams. The FEMA/USDA Workshop on Issues, Resolutions, and Research Needs Related to Dam Failure Analysis, in Oklahoma City, OK, June 26-28, 2001, addressed this concern.

2. Computer models. Research is needed on ways the current computer models for unsteady flow can be made easier to use and more flexible to allow users to model more complex dams with multiple spillways.

Hydrologic Research Needs for Dam Safety Analysis At the Tennessee Valley Authority

By
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Background

The Tennessee Valley Authority (TVA) was created in 1933 to provide for the unified development of the Tennessee River Valley. The purpose of the Act is stated as follows:

"That for the purpose of . . . and to improve navigation in the Tennessee River and to control the destructive flood waters in the Tennessee River and Mississippi River Basins, there is hereby created . . . the 'Tennessee Valley Authority' " - Preamble.

With respect to planning, Section 23 requires the President to recommend to Congress such legislation as he deems proper " . . . for the especial purpose of bringing about . . . in conformity with said general purposes (1) the maximum amount of flood control, (2) the maximum development of said Tennessee River for navigation purposes, (3) the maximum generation of electric power consistent with flood control and navigation; . . ."

On the subject of operation of reservoirs, Section 9a states: "The (TVA) Board is hereby directed in the operation of any dam or reservoir . . . to regulate the stream flow primarily for the purposes of promoting navigation and controlling floods. So far as may be consistent with such purposes, the Board is authorized to provide and operate facilities for the generation of electric energy . . . and the Board is further authorized, whenever an opportunity is afforded, to provide and operate facilities for the generation of electric energy in order to avoid the waste of water power, . . ."

TVA's structural approach to minimizing flood risk was the construction of dams with flood control allocations to "keep the floods away from the people." Today, TVA operates an integrated reservoir system of 49 dams (1 project in the Cumberland River basin), in the 41,000-square mile Tennessee River drainage basin covering portions of seven states. Since these dams were built, significant flood reduction benefits have been realized along the Tennessee River and its tributaries, and along the lower Ohio and Mississippi Rivers. TVA dams also provide additional benefits to the region including navigation, hydropower generation, water supply, recreation, water quality, and land use for economic development.

TVA's reservoir system has been effective in providing over $5B in flood damage reduction benefits. TVA also recognized that structural measures could not eliminate flooding, and that there were about 350 communities in the Tennessee Valley with some degree of flood risk and damage potential.

[1] Tennessee Valley Authority

In response to this situation, TVA initiated a floodplain management assistance program in 1953 based on the concept of averting local flood damages by careful land use planning. This approach of working with state and local governments to deal with flood problems was applied throughout the Tennessee River watershed. During this period, TVA promoted the concept of avoiding development within the 100-year floodplain and encouraging to the extent possible the adoption of higher setback and elevation standards.

In the late 1960s, TVA utilized its floodplain management experience to assist the Federal Emergency Management Agency (FEMA) with the development of what is today the National Flood Insurance Program (NFIP). TVA served as a contractor to FEMA for several years to develop flood information for many communities within the Tennessee Valley. During this period, TVA also demonstrated several different flood damage reduction measures at different communities including channel restoration/modifications, flood warning systems, acquisition and relocation, and flood proofing.

Current Floodplain Management Activities

Since 1994, TVA's floodplain management efforts have focused on the lands and projects that TVA holds in stewardship, and on the floodplains along the rivers and streams, which are affected by regulation from TVA dams. The objective of the program is to minimize flood damages, ensure the safety of floodplain residents (by keeping the people away from the water), preserve TVA's reservoir operating flexibility for flood control purposes, and ensure consistency with local floodplain regulations. TVA's reservoirs and the river reaches below the dams have seen substantial development over the last several years. Thus, flood risk is expected to continue to increase in the future from this one factor alone.

Dam Safety Program Development

TVA has maintained a dam safety program since its establishment in 1933. Following the failure of Teton Dam, President Jimmy Carter issued a 1976 memorandum to all Federal Agencies with responsibilities for dams to develop and implement formal guidelines for dam safety. After participating in the development of the interagency document, *Federal Guidelines for Dam Safety* (Reference 1), TVA formalized its dam safety program in 1982. At that time, TVA evaluated all of its dams for hydrologic and seismic safety, and determined that 23 of its then 53 dams had some degree of deficiency and could be made even safer, consistent with these guidelines. Since that time, TVA has spent more than $75M modifying these dams, with work underway at the remaining two projects to ensure its dams meet these guidelines. Because most of TVA's dams are high hazard structures with significant potential for loss of life and property damage, TVA chose to modify its dams to safely pass the Probable Maximum Flood (PMF).

TVA recognized the need to have an outside authority provide estimates of the Probable Maximum Precipitation (PMP). Further, TVA recognized the need to have studies performed specific to the region rather than using generalized estimates for PMP. The National Weather Service (NWS) was funded by TVA to study two categories of extreme precipitation for the Tennessee Valley which included PMP and a standardized less extreme rainfall referred to as the "TVA precipitation." At this time, the NWS completed Hydrometeorological Reports (HMR) 41 (Reference 2); 47 (Reference 3); and 56 (Reference 4). HMR 45, superseded by HMR 56 in 1986, was used in studies prior to HMR 56. These reports provided estimates of precipitation for large areas such as that above the City of Chattanooga (approximately 21,400 square miles) and for basins up to 3,000 square miles. These reports defined depth-area-duration characteristics and antecedent storm potentials.

Current Research Needs

One of the most controversial aspects of the TVA reservoir system is the annual operating cycle for the tributary projects. There are 10 tributary projects, which have a summer-to-winter fluctuation of from 35 to as much as 90 feet. The seasonally varying allocation of flood storage was designed primarily to provide flood protection for the City of Chattanooga, the major damage center in the Tennessee Valley. These reservoirs provide over 4 million acre-feet of flood storage space needed during the flood season from mid-December through early April. However, the economic benefits attributable to use of these reservoirs have changed over the years and now include enhanced lake front property value, recreational boating, fishing, swimming, wildlife habitat, minimum flow and dissolved oxygen (DO) enhancements, and related functions.

Stakeholders, for many years, have questioned the need for this flood storage (saying it is too conservative) and have requested a delay of the drawdown of these reservoirs until later in the fall. These reservoirs are typically at their highest level by June 1 of each year depending on rainfall/runoff. During June and July, they are gradually drawn down to support downstream water quality and hydropower generation. After August 1 of each year, the reservoirs have an unrestricted drawdown to lower them to their January 1 flood storage levels.

In 1991, TVA completed the *Tennessee River and Reservoir System Operation and Planning Review*, an Environmental Impact Statement (EIS) that resulted in changes to its reservoir operating policies. This was the first comprehensive re-evaluation of reservoir operating policy since the projects were built. However, the focus of this review was on maintaining minimum flow below dams at critical times and locations, increasing DO below 16 dams by aerating releases, and to delay unrestricted summer drawdown until August 1 on ten tributary reservoirs. While flood control was a consideration in review of these alternatives, no alternatives were considered which would change the winter flood storage allocations. However, the review did formalize the requirements for a minimum of one inch of flood storage space during the summer months at 10 of the tributary reservoirs.

TVA established a Regional Resource Stewardship Council in March 2000 under the Federal Advisory Committee Act (FACA). The purpose of the Council was to provide advice to TVA on policies, priorities, and practices for managing its land and water resources and programs as part of its public responsibilities. The Council is made up of 20 representatives from across the Valley. They represent a range of interests in TVA's stewardship activities, including representatives of the Governors of the seven TVA states, power distributors, industry, business, environment, recreation, consumers, and educational and community leadership.

This summer (2001) the Council recommended that TVA undertake a study of its reservoir operating policy to determine if changes could create greater overall value for TVA customers and stakeholders without reducing gains which had been realized in water quality. The study will include evaluation of costs and benefits. The TVA Board responded to this recommendation in October with a commitment to perform a comprehensive evaluation of reservoir operating policy in two years. This study will be conducted within the National Environmental Policy Act (NEPA) framework as an (EIS).

One of the major issues to be addressed will be the evaluation of potential change in flood risk that could result from a change in reservoir operating policy. The evaluation must ensure that the tools and analysis process must be capable of providing a clear understanding of how the flood risks could change. This should include impacts on flood frequency throughout the full range of flood potential from the annual event through the PMF, effect on local floodplain regulations as part of the NFIP, elevation and flow duration, and impact on dam safety.

At this time there are several studies underway to address similar issues across the country (Upper Mississippi River Flow Frequency, Savannah River, and Lower Colorado River Authority). Many factors are driving this need including: (1) the Nation's floodplains continue to be developed increasing the flood risk and damage potential; (2) advances in weather forecast capabilities are viewed by the public as a reliable basis for reservoir operations well in advance of actual events; (3) studies raise questions about previously completed flood frequency analysis and whether these changes in turn should result in changes to published information used for local floodplain regulations for 100- and 500-year flood boundaries and floodways; (4) the hydrologic period of records are increasing, coupled with more sophisticated computational methods and modeling capabilities; and (5) a growing interest on the part of the stakeholders that live along or use the water resource to change the allocation of benefits based on economics.

Conclusion

Research is needed to focus on flood risk assessment methodology that can be supported by the technical community, general public, and local, state, and federal land- and water-use decision makers.

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The Utah Hydrological Experience

By
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The Utah Dam Safety Section is fairly deterministic in requiring the PMF to be routed by all High Hazard dams. Incremental damage assessments can be used to reduce the design flood, especially for debris basins and smaller flood control structures. The HMR – 49 Local storm PMP that is required for the PMF calculations has been revised to accommodate a state specific areal reduction developed by Dr Don Jensen at Utah State University. In the event that the 6-hour local storm PMP is less than the general storm, 72-hour PMP, the general storm becomes the design event, with its lower peaks, larger volume and longer runoff characteristics.

Problems that we have encountered in design storm calculations include the lack of rain and flow gages that make statistical analysis and calibration difficult, if not impossible. Our typical calculation involves black box solutions such as synthetic unit hydrographs, curve numbers or constant infiltration rates. We need more physically based runoff models tied to soil types, vegetation, spatial and temporal precipitation distributions, probably in a GIS type format with hydraulic, finite element, geographical routing. We need calibrated models that give accurate results as well as effective graphics.

An example of long-term spillway outflows is the typical spring-time snow melt event in many of Utah's high mountain dams. Drainage basins typically produce as much as 33 cfs per square mile in continual runoff, sometimes for weeks at a time. Rain on snow events can compound these flows and if the spillway is clogged with snow and ice, the dam can eventually overtop and fail, as was postulated for the failure of the Trial Lake dam in 1985 (although the failure was officially deemed an act of God).

Another hydrologic modeling example was our experience with the Quail Creek Dike failure. After completing all the modeling classes given by HEC and the NWS we experienced a large dam failure and subsequent flood. When we tried to simulate the breach and the flood with our models we had a difficult time recreating the reality that had been observed. Breach size, timing, piping initiation and breach migration were difficult to reproduce. Routing required huge Manning numbers to simulate roughness and we had difficulty accurately portraying the observed hydraulic jumps, attenuation and timing of the flood wave. If we had such a hard time modeling a flood we experienced first hand, how could we have faith in our models of hypothetical floods?

Again, we need to have physically based models that can be calibrated and tied to reality. We need improved methods that take advantage of new technology such as 2d and 3d models, hydraulic routing, GIS, and NEXRAD radar, to match the apparent veracity of the amazing graphics and animations of the input and output. We need to

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[1] Utah DNR, Dam Safety Hydrologist

honestly express our confidence limits, sensitivity and fuzziness of our answers. We need to get out of our boxes to observe and mimic the complex ways that nature works.

The Utah Hydrological Experience

By

Matthew C. Lindon, P.E.[1]

Design Inflow Flood Calculation

Deterministic calculation of PMP/PMF for High Haz

Some Incremental Damage Assessment

Small reservoir, large dams,
Debris basins, Flood Control
100 year storm minimum design storm

Some Risk Assessment

Prioritize resource allocation,
Bang for the Buck

Local and General Storm - 6 - 72 hour

Curve Number and Constant Infiltration rates
Little gaging and calibration
HMR 49 and State Specific PMP
Black Box Spatial and Temporal Distribution

State specific PMP

Morgan Storm of August 1958

Dr Jensen, USU review

7 inches in 1-hour hub cap study
Base storm for HMR-49 - western USA
20 or 200 square miles

Dr Jarrett review

No Paleo evidence of the storm locally or regionally
Point precip possible??

[1] Utah DNR, Dam Safety Hydrologist

Revised Areal Reduction

Revised Temporal reduction from storm data

Reduces Local 6 hour storm LT 15 sq miles

Defaults to General Storm - 72 hr HMR-49

Smaller peaks, more volume, longer duration

Site/State Specific General Storm study done

Canned PMP programs for consistent calculations

PMF Improvements

Close only counts in Horseshoes and Hand Grenades

Calibration, Correlate, Verify

Little rain gage info and correlated flow gage
Less history or storm data base
Curve number and Infiltration rates
Cook Book temporal and spatial distribution
Black Box Solution Methods

Better Models Better Modelers

Physically based - no black box
Spatial and temporal data - GIS coverage
Hydraulic routing - combine RAS and HMS
Input quality matches output
Apparent Veracity - Know what model does
Computers lie and liars use computers

Trial Lake Spillway

Negligent Overtopping or Act of God

Long, Cold winter

North facing spillway
Clogged with snow and ice

Late Spring

Rain on snow event
Model overtopping with no spillway/outlet flow

Organic foundation contact blamed

Design for long duration snow melt flows

General Storm long duration flows

Quail Creek Experience

God have mercy on the man who doubts what he's sure of.

Competed HEC I, II, DAMBRK, BREACH...

Try to recreate the Breach and inundation

BREACH

Initiation piping channel size
Trapezoidal migration of Breach
Timing and size of breach

HEC I - backwater and attenuation

HEC II - constant flow - no hydrograph routing

DAMBRK

Manning Numbers bulking, bridges, debris, eddies
Timing of flood
Hydraulic jumps
Time steps

Adjust reality to fit the model

Computers lie and liars use computers

Physically based models - no black boxes

Calibrate, Correlate, Verify - tie to reality

Educate Modelers to what the model does
Garbage in Groovy out - Apparent Veracity

Express confidence, sensitivity, fuzziness

Use new technology and methods

2d, 3d, hydraulic routing
GIS coverages for soils, vegetation, elev, slope...
Combine HECRAS and HECHMS

Get out of the box and see how nature works

FEMA Workshop on Hydrologic Research Needs for Dam Safety Analysis

Hydrologic Practices in the State of Georgia and other states east of the Mississippi River

By
Francis E. Fiegle II, P. E.[1]

State of Georgia

The Georgia Safe Dams Act regulates high hazard dams that are either 25 feet tall or store more than 100 acre-feet of water at maximum pool. These regulated dams are evaluated to determine if they have adequate spillway capacity and wave action freeboard at maximum design pool to pass the design storm as defined by the Georgia Safe Dams Act (Act) and Rules for Dam Safety (Rules). The spillway capacity is prescribed in the Act based on the height of the dam and/or its maximum storage capacity.

1) Small dams - Those dams with a storage capacity not exceeding 500 acre-feet and a height not exceeding 25 feet - 25 percent PMP spillway design capacity.

2) Medium dams - Those dams with a storage capacity exceeding 500 acre-feet but not exceeding 1000 acre-feet or a height exceeding 25 feet but not exceeding 35 feet - 33 percent PMP spillway design capacity.

3) Large dams - Those dams with a storage capacity exceeding 1000 acre-feet but not exceeding 50,000 acre-feet or a height exceeding 35 feet but not exceeding 100 feet - 50 percent PMP spillway design capacity.

4) Very large dams - Those dams with a storage capacity exceeding 50,000 acre-feet or a height exceeding 100 feet - 100 percent PMP spillway design capacity.

Typically, the Georgia Safe Dams Program develops Visual Inspection Reports which are a streamed lined version of the old USACOE Phase I reports that were done in the late 1970's and early 1980's for state dam safety programs across the United States. In that report, our Program evaluates the spillway capacity of existing dams with respect to compliance with the Act and Rules. Except in rare instances, the hydrology evaluation uses the NRCS/SCS Curve Number, Lag Time methodology. Of note, because the spillway capacity requirements are set forth in the Act, and the design storm is restricted to the 6-hour PMP, the Program requires the use of Antecedent Moisture Condition III for the evaluation of spillway capacity. This dramatically affects the Curve Numbers used. We use HMR 51/52 to develop the design storm. The spillway rating curves are done using standard hydraulic practice accounting for weir, orifice, and full pipe flow for principal spillway pipes/open channel flow in earth emergency spillways, etc. This

[1] Program Manager - Georgia Safe Dams Program

information is imputed into the HECI model with a Type II distribution to evaluate the hydraulic adequacy of the dam.

On very large drainage basins, a unit hydrograph is developed based on existing stream data on the particular stream or one in the area with similar watershed characteristics.

For more detailed information, please see the attached section on Hydrology and Hydraulics, pages 28 to 33 of the Georgia Safe Dams Program's Engineering Guidelines. The Guidelines were developed in conjunction with consulting engineers who are involved with the design of dams in Georgia.

Other states east of the Mississippi River

Because there is a need for the state dam safety regulators to provide significant input on practices, research needs and development needs in the field of hydrology and hydraulics modeling, I polled 26 states east of the Mississippi River including: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, Ohio, Michigan, Indiana, Illinois, Wisconsin, Kentucky, West Virginia, Tennessee, Virginia, North Carolina, South Carolina, Florida, Maryland, New Jersey, Mississippi, Louisiana, Arkansas, and Puerto Rico. Delaware and Alabama were not polled because they had no dam safety laws or programs. I received 19 state responses.

The following questions were asked in the survey and where appropriate, the number of responses are tallied. In some cases, a state regulatory agency may use/accept more than one methodology.

1. **What Hydrologic Model(s) are used/accepted by your state? Do you accept more than one methodology?**

    a. NRCS/SCS Curve Number/Lag Equations - 16
    b. HECI - 17
    c. HECHMS - 10
    d. USGS/State Regression Equations - 9
    e. Unit Hydrographs - 6
    f. Synder Unit Hydrograph - 5
    g. SITES - 6
    h. TR20- 5
    i. TR55 - 3
    j. HydroCAD 5.11 - 3
    k. Others - 1

2. **What are the difficulties/problems you encounter with these models**?

a. HEC1
    - DOS based program - glitches sometimes when loaded on a Windows Operating System.
    - PM card record is outdated for PMF determination in conjunction with the use of HMR51/52.
    - Time distribution of rainfall losses.
    - Unit hydrograph for eastern shore needs to be modified.
b. Lack of site specific data (mentioned 5 times.)
c. HECHMS
    - Does not have the ability to run multiple storm events
    - Bizarre results sometimes.
d. Engineers who do not know how to use the model appropriately. Identified as an issue by six states.
e. Hydro CAD 5.11/SCS unit hydrograph is limited a 24 hour duration storm, surcharge flows are not allowed.

Of note, two states reported no difficulties.

3. **Are extended flow periods (days) vs. single events an issue? Is it dependant on the size of the drainage basin or the location of the dam?**

Yes - One
No - Ten
Maybe - (extremely large drainage basin) - Seven

4. **Please rank the following issues in priority:**

a. low cost/rapid assessment of inflow flood (47 points)
b. extensive detailed investigative assessment of the inflow flood (54 points)
c. risk assessment vs. PMF (34 points)
d. determinate inflow design flood (55 points)
e. all equally important (20 points)

*To evaluate the responses, I assigned a point value of 5 to 1 for the priority ranking with 5 being the highest priority and 1 being the lowest priority.

5. **Any suggestions for short and long terms hydrologic needs and development?**

Short term hydrologic needs

A. HECHMS needs the following:

- level pool routing/results & summaries

- overtopping subroutine
- breaching subroutine
- multiplan feature
- printout of inputs
- other routing subroutines (Muskingum-Cunge)
- link HECRAS to HECHMS
- add Arcview
- develop multiple stage outlet modeling

B. Comparison of USGS Regression inflow curves vs. other methodology. Publish results for different parts of the country.

C. Cooperation between NWS and HEC and other Federal agencies.

Long-term hydrology needs

A. Update NRCS/SCS Curve Number methodology.
B. What is the appropriate time period of the design storm event? PMP is variable across the country and changes within a region.
C. Define what ancedent moisture condition is appropriate for what type of design storm.
D. Couple NEXRAD or IFLOWS for river basins for real time hydrologic forecasting (Virginia).
E. Further development of the Green-Ampt loss rate function nationwide.
F. Additional continuous stream gaging streams.

Conclusions and Recommendations:

The majority of the dams in the United States are regulated by the states. Hydrologic research should focus on creating models for design storms that will produce reasonably accurate results that do not involve extensive data gathering and interactive modeling. The results should be reproducible from universally accepted data sources.

I believe the short terms needs include the following:

- Complete HECHMS model development. Make it compatible with other software and link it to HECRAS, ARCVIEW, and NWS DAMBREAK.
- Improve cooperation between Federal Agencies to develop hydrologic data and software models that states can use.
- Do detailed comparison of various hydrologic methodologies that produce inflow floods including sensitivity evaluations. Make the comparison meaningful by region/sub region. Publish results.

Long term hydrologic needs include further development of certain hydrologic models/modeling methods.

- Update NRCS/SCS Curve Numbers and lag time routines.
- Better regionalization of PMP rainfall events.
- Define and update Antecedent Moisture Conditions.
- Further development of the Green-Ampt loss rate function nationwide. If this was as usable as the NRCS/SCS Curve Number/soils mapping methodology, modeling long terms storm event would be doable with reasonable results.

While I believe that accuracy in hydrologic modeling is important, so is a certain measure of conservatism to account for the undefined and unknown variables that exist in every drainage basin when dealing with public safety.

Hydrologic Research Needs for Dam Safety Analyses

by
Joseph J. Skupien, PE, PP[1]

Somerset County Dam Safety Program

The following describes both the current scope and research needs of the dam safety program of Somerset County, New Jersey. The County encompasses 305 square miles in the central portion of the state and has a population of approximately 300,000, yielding a population density of approximately 1000 people per square mile. The County has experienced significant land development pressure since the 1970's with no significant abatement expected in the foreseeable future.

Somerset County's dam safety program includes the analysis, operation, inspection, and maintenance of nine Significant Hazard dams ranging in height from 13 to 40 feet with drainage areas ranging from approximately 50 acres to 10 square miles. Eight of these dams serve as regional stormwater detention facilities that help offset the adverse hydrologic impacts of land developments within their watersheds. The remaining dam is a former water intake dam located on property acquired from a private water purveyor and converted into a County park. Since their original design, engineering activities at the dams include the determination and periodic reassessment of their hazard classifications and Spillway Design Floods (SDFs) as well as any subsequent revisions to their Emergency Action Plans (EAPs). These activities are performed in accordance with the Dam Safety Standards (N.J.A.C. 7:20) of the Dam Safety Section of the N.J. Department of Environmental Protection (NJDEP).

In addition to the dam safety activities described above, the County Planning Board also regulates that stormwater management aspects of all new land developments in the County that front on a County road and/or drain to a County bridge or culvert. These regulations typically result in the design and construction of one or more onsite stormwater detention basins that can range up to approximately 15 feet in height and up to 100 acres in drainage area. While the design of such basins do not normally require a dam break and downstream inundation analysis, the design does include the determination of emergency spillway size and top of dam elevation. This is done using County-based emergency spillway criteria at all dams not subject to the NJDEP Dam Safety Standards noted above. An unofficial survey indicates that there are presently more than 500 such basins in County, most close to residential, commercial, and/or industrial structures.

[1] Principal Hydraulic Engineer, Division of Engineering, Somerset County, New Jersey

Current State and County Practices

As noted above, all County-owned dams are regulated by the Dam Safety Standards of the NJDEP's Dam Safety Section. Similar to the FERC's Engineering Guidelines for the Evaluation of Hydropower Projects, these state standards classify dams by Hazard Class based upon the threat posed by a dam failure to downstream structures and roadways. A summary of the various NJDEP Hazard Classes is presented in Table 1 below.

Table 1

Summary of Dam Hazard Classes and Spillway Requirements
NJDEP Dam Safety Standards

Hazard Class	Downstream Failure Threat	Spillway Design Storm
I – High	Loss of Life or Extensive Property Damage	PMP
II- Significant	Significant Property Damage	One-Half PMP
III – Low	Minor Property Damage	100-Year NRCS Type III
IV – Small Dams	Height < 15 Feet, Storage < 15 Acre-Feet, Drainage Area < 150 Acres*	100-Year + 50 Percent NRCS Type III

* Class IV Dam criteria only applicable if Class I or II threats do not exist.

According to discussions with NJDEP Dam Safety personnel, PMP rainfall amounts are typically obtained from HMR No. 51. For the majority of projects, spatial distribution of the rainfall is not necessary and the rainfalls are temporally distributed in accordance with a variety of storm distributions, including the NRCS Type III distribution and the U.S. Army Corps of Engineers PMP distribution as contained in HEC-1 Flood Hydrograph Package. One foot of freeboard is required above the routed SDS water surface. The NRCS Runoff Equation and Dimensionless Unit Hydrograph are typically used to compute losses and convert the rainfall to runoff. Antecedent Moisture Conditions are typically assumed to be either average (AMC II) or high (AMC III). Sources of dam failure parameters vary, with those published in the FERC Engineering Guidelines or derived from the Froelich equations utilized most frequently.

Downstream discharges and water surface profiles are typically computed using steady flow assumptions with HEC-1 used for discharge and failure computations and either HEC-2 Water Surface Profiles or HEC-RAS River Analysis System used for profile computations. Unsteady flow computations using either DAMBRK or FLDWAV are used on approximately 10 percent of the projects, which typically involve large dams and drainage areas. Downstream failure impacts are typically assessed based upon the difference in water surface with and without a dam failure, with a difference greater than two feet considered excessive. A minority of projects utilizes the Downstream Hazard Classification Guidelines published by the Bureau of Reclamation.

As noted above, the Somerset County dam safety criteria, which were originally established in 1975, apply to all structures subject to County Planning Board approval unless superceded by the NJDEP regulations described above. Hazard classification for all dams is assumed to be Class B as defined by the NRCS unless a reconnaissance of downstream conditions warrants a higher classification. Safe spillway capacity and freeboard requirements are based upon routing Emergency Spillway (ESH) and Freeboard (FBH) Hydrographs through the facility based upon 24-hour rainfalls of 10 and 17 inches, respectively. These rainfalls were derived from the same equations used by the NRCS to develop the Service's 6-hour ESH and FBH rainfalls. It should also be noted that the County's 17 inch FBH rainfall is equivalent to one-half of the 24-hour PMP for the County.

Problems and Research Needs

A summary of technical and operational problems and related hydrologic research needs of both the NJDEP and Somerset County dam safety programs is presented below. The NJDEP problems and needs were identified during interviews with representatives of the NJDEP's Dam Safety Section. Resolution of these problems and needs, either through research and/or policy decisions, will help improve the effectiveness and efficiency of both programs.

1. Perhaps the most significant operational problem facing the State and County dam safety programs is the lack of hydrologic and hydraulic expertise in many of the engineers performing dam failure, inundation, and hazard classification studies and/or preparing emergency spillway designs. In the last 20 years, both the sophistication and availability of computer-based models to perform such studies and designs has increased significantly, along with the data to base them on. Unfortunately, these models and databases have exceeded, in many instances, the knowledge and expertise of the modelers and designers of small dams. This "ability gap" leads to inaccurate studies and designs and prevents many dam safety programs from realizing their full potential, thereby negating the efforts of researchers and regulators to create advanced, effective dam safety programs. Under such conditions, further technical advances can be expected to only widen this gap.

Research Request: Investigate the feasibility of establishing minimum education and/or experience requirements for engineers performing dam safety studies and designs for small dams. Alternately, develop a basic set of small dam hydrology and hydraulic courses that can be presented by state and/or local dam safety officials to engineers within their jurisdictions.

2. A technical problem that has grown more acute in recent years involves the presence of concrete corewalls within older earthen dams that have come under closer scrutiny by dam safety personnel. Similar problems also arise with older dams that have been constructed with masonry or concrete walls along their upstream face. These walls were commonly utilized to prevent seepage from the upstream impoundment and, while they theoretically have little structural strength, experience has shown that some have been able to remain intact even after the loss of large portions of the downstream fill material. Such dams, due to their age, typically have principal spillways that are inadequate under

present standards and, as such, are prone to failure due to overtopping. However, modeling this failure can be difficult, particularly in the selection of failure width and time due to the presence of the concrete wall within or upstream of the earthen fill. While conservatively large width and short time parameters can be selected, their use may result in overestimates of hazard class and Spillway Design Storm. This, in turn, may require the construction of excessive remedial measures that the owners, who are predominantly private individuals or organizations, may find cost-prohibitive.

Research Request: Develop typical failure parameters and/or policies for dams with corewalls and upstream face walls that can be utilized or adopted by local and state dam safety programs.

3. Standard computation methods for drainage area Time of Concentration (TC) are typically intended for use in estimating flood peaks and hydrographs for frequencies up to the 100-Year storm. However, both theory and experience suggest that shorter TCs should be used when computing peaks and hydrographs from larger, less frequent events such as the PMF, due primarily to the greater flow depths and velocities. As such, the standard computation methods may be yielding lower peak flow estimates for such events, which can lead to inaccurate hazard classification and underdesigned remedial measures.

Research Request: Investigate accuracy of standard TC computation methods under extreme storm conditions. If necessary, develop alternative methods or policies for estimating drainage area TCs for such extreme events.

4. Since the majority of dams subject to local or state dam safety regulations have drainage areas less than 10 square miles, questions arise over the most appropriate temporal rainfall distribution to utilize in a hazard classification and/or Spillway Design Storm analysis. These questions include concerns whether the NRCS design storm distributions are appropriate for extreme rainfall amounts and whether other popular storm distributions such as the Corps of Engineers' Standard Project Storm is appropriate for small drainage areas.

Research Request: Investigate suitability of popular design storm distributions for extreme rainfall amounts falling over small drainage areas. Develop appropriate distribution for such rainfalls and areas through research and/or policy.

5. As noted above, the majority of water surface profile computations downstream of a dam failure are based upon steady rather than unsteady flow assumptions. In most instances, however, the selection of steady over unsteady flow is not based upon theoretical grounds but rather on the difficulty in performing the unsteady flow computations with the DAMBRK and FLDWAV computer programs (see 1 above). The recent inclusion of unsteady flow in HEC-RAS offers an opportunity to address this problem. However, limited training has been available to date to small dam designers and analysts and local and state dam safety personnel.

Research Request: Develop guidelines and limitations for use of steady flow models in dam safety studies. Also develop effective HEC-RAS unsteady flow and FLDWAV training courses for small dam analysts and designers and local and state dam safety personnel.

6. The most significant and, at times, prohibitive cost of an accurate hazard classification or Spillway Design Storm study for a small dam is incurred during the development of the hydraulic model of the downstream waterway. Costs associated with field surveys, topographic mapping, and model data development often exceed the remaining study costs.

Research Request: Develop inexpensive techniques to develop waterway and floodplain topography and cross sections in a digital format that can readily be input into available hydraulic computer models.

7. According to the FERC's Engineering Guidelines, dam failures should not be assumed to begin on the rising limb of the inflow hydrograph. Instead, the presumably more conservative assumption of failure starting at the maximum water surface should be made. However, instances have arisen where greater discharges are computed when the failure is assumed to occur somewhat before the maximum water surface is achieved. This is particularly true at certain small dams with very short (10 to 15 minute) failure times. In these instances, the rapid enlargement of the dam breach begins while the water surface is still rising, leading to ultimately greater heads and resultant peak outflows due to the failure. While these greater peak outflows can be identified through sensitivity analyses of failure starting times, such analyses can increase costs for small dam projects.

Research Request: Determine the sensitivity of starting water surface elevation to peak outflows from small dam failures and establish parameters to identify the most conservative starting water surface assumptions.

Acknowledgements

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Research Needs in Dam Safety Analysis

Samuel L. Hui[1]

Introduction

As pointed out by Dave Goldman in his write-up of May 2, 2001 on problem definitions for this workshop, the research needs for hydrology in dam safety analysis can be divided into two areas:

1. Applied research to develop simplified techniques that can provide useful answers for dam safety analysis
2. Fundamental research to bring process-level improvements to the dam safety analysis

Coming from the industrial sector, I would like to discuss two items that belong to the applied research category: simplifying the processes required in developing basin runoff models and parameters, and providing guidance related the use of confidence limits in flood frequency analyses. On the fundamental research side, I would like to have the participants to consider the urgent need to improve the analytical techniques in simulating dam break mud-wave propagation resulting from the failure of tailings dams.

Applied Research Needs

Basin Runoff Models and Parameters

The selection of a proper basin runoff model for use in the development of the inflow design flood (IDF) hydrograph is always a challenge, particularly for an un-gauged basin. While large organizations can devote a great deal of effort in seeking out regional data that could be useful in the development of the appropriate basin runoff model, the smaller firms, which bid the job competitively, cannot afford to do so. The easiest means, without an exhaustive research, is to use the dimensionless unit hydrograph suggested by the Natural Resources Conservation Service (NRCS) as currently provided in HEC-HMS. In fact, the soon-to-be-released draft of the Federal Energy Regulatory Commission (FERC) Engineering Guidelines: Chapter 8 – Guidelines for Probable Maximum Flood (PMF) Determination allows the use of the NRCS dimensionless unit hydrograph for un-gauged watersheds provided that:

- there are no regional data available
- drainage area at the dam site is 100 square miles or less and each of the sub-basins, if the basin is sub-divided, does not exceed 20 square miles in area

[1] Bechtel Corporation, San Francisco

We know that the NRCS dimensionless unit hydrograph is applicable for “average” basin conditions. Its applicability to steep terrain without proper adjustments is problematic and could lead to under-estimation of the flood peak discharge. For dams in a high hazard category, a drainage area of 100 square miles is a sizable area. The failure of such dams could be devastating to the community and inhabitants downstream.

For the practitioners who use the NRCS dimensionless unit hydrograph “liberally” for flood analyses, they need to have easy access to data on regional basin runoff parameters. I do know many, if not all, of the districts of the U.S. Army Corps of Engineers (USACE) have unit hydrographs for use in flood studies for watersheds in their respective districts; likewise, the U.S. Bureau of Reclamation (USBR), Tennessee Valley Authority (TVA) and some of the districts of the U.S. Geological Survey (USGS) as well as the NRCS. FERC also has regional basin runoff data from dam owners submitted through Part 12 of the Federal Dam Safety Program and so do many states. Major utilities, such as Pacific Gas & Electric (PG&E) Company, Southern California Edison Company, Southern Services, New York Power Authority, etc. have their own regional basin runoff model and parameters. The compilation and publication of these data in one place will go a long way in improving dam safety analyses in this country.

Many of you may remember a publication by the USACE back in the 1950(?), which provides the Snyder coefficients C_t and C_p for many of the river basins in this country. I envision that similar efforts will be required. But, this effort will be more comprehensive since it would involve many federal and state government agencies, major utilities and deal with a host of different basin runoff models and parameters.

Flood Frequency Analysis

As risk assessment (RA) is gaining more support from the engineering community as the preferred approach for dam design, a frequently asked question is how we can accurately predict the exceedance probability of large floods, such as the 1,000-year flood event. From my own perspective, before we address the problems related to exceedance probability of large floods, we need to first address a fundamental issue related to frequency analysis: the uncertainty intrinsic to the frequency analysis.

We all recognize that a specific record of flood peak discharges at a site provides for a limited random sample of the underlying population of the flood peak discharges at that location. The statistics developed from this limited sample reflect only those of the sample and are only approximations of those of the population. There is a good chance that the developed flood peak discharges would either over- or under-estimate the “true” flood statistics of the population. Confidence bands are, therefore, constructed to bracket, with some degrees of certainty, the “true” population statistics. The flood peak discharge commonly referred to is the expected probability value.

Looking at the four test cases given in the User's Manual of Flood Frequency Analysis (HEC-FFA) published by the USACE Hydrologic Engineering Center, for a 500-year flood, the 5% upper bounds of the confidence limits are higher than the respective expected probability values by 32% to 104%. One would expect that the spread between the upper bounds of the confidence limits and their respective expected probability values would grow even larger for more infrequent floods. The logical question asked is how we should incorporate these uncertainties in the development of an inflow design flood and in the ensuing risk assessment. No guidance statement is given in this HEC-FFA User's Manual. The only statement found in Bulletin No. 17 B - Guidelines for Determining Flood Flow Frequency states "Application of confidence limits in reaching water resources planning decision depends upon the needs of the users." This is by no means adequate as guidance for the less-sophisticated practitioners who want to incorporate the confidence limits in the design or risk assessment. I am sure that there are guidance documents available within many of the government agencies. They should be made available more readily to the hydrologic engineering community. A standardized approach in incorporating the confidence limits in frequency analysis will certainly help the practitioners in the industrial sector, who conduct dam safety analyses.

Fundamental Research Needs

Dam Break Analysis for Mud-Wave Propagation in Rivers

One of the dam safety issues often neglected is that regarding tailings dams because they are usually located in remote areas with scarce population or in developing countries, which may have different regulatory requirements. The way tailings dams are constructed (using highly erodible sand fractions recovered from the tailings); their heights, large storage capacities and locations (in many seismic active areas of the world) put them directly in the high hazard category. If my memory serves me correctly, it was the failure of a tailings dam in Buffalo Creek back in 1968 (?) that triggered the implementation of the dam safety program in the United States. However, historically, we seldom treat tailings dams with the urgency and vigorous regulatory requirements demanded of water impoundment dams. I am not aware of any requirements for the development of Emergency Action Plan (EAP) for river reaches downstream of tailings dams, like those required for water impoundment dams. I surmise that, maybe, we are not quite sure how to determine the propagation of the mud-waves resulting from the failure of tailings dams.

Specifically, if we are to use risk assessment and/or the "incremental hazard evaluation" to determine inflow design floods for the design of dams, including tailings dams, we need to develop analytical approaches or computer codes that would allow the simulation of mud-wave propagation in a river channel. I do not know of any such methods or computer codes. The Dam Break Model marketed by BOSS International has an option for considering mud-wave propagation using Bingham Plastic Flow Theory, but it does not appear to work satisfactorily. Since we are building tailings dams higher and higher, we must have the necessary analytical tools that enable us to address the safety issues related to this type of dam, particularly how they could affect the downstream community and inhabitants when they fail. (Bechtel has recently completed, in high Chilean Andes, a 120-m high tailings starter dam, which will be built-out to an ultimate height of 175 m high in 8 years, and retain more than 60 million cubic meters of tailings consisting of fine soil particles and slime.)

The development of such computer codes is, by no means, an easy undertaking. It will involve hydrologic and hydraulic engineers, geotechnical engineers as well as mining process engineers. But it is a task we must do in order to improve our state-of-the-art knowledge in dam safety analysis.

Closing Remarks

I have stated, from my own perspective as a practitioner from the industrial sector, the applied and fundamental research needs for hydrology in dam safety analysis. They are:

- the compilation and publication of regional basin runoff models and parameters
- the provision of guidance in incorporating confidence limits in flood frequency analysis
- the development of computer codes for the simulation of dam break mud-wave propagation in river channel resulting from breaching of tailings dams

I hope that we can give these topics serious considerations and include them in the list of research needs for dam safety analysis to be formulated by this Workshop.

Hydrologic Analyses Related to Dam Safety

By
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Abstract

Hydrologic design of dams involves consideration of risks and costs associated with dam failure due to hydrologic factors. This paper presents a procedure to characterize dams on the basis of hydrologic risk associated with potential failure. Methods are presented to estimate economic risks associated with different design-basis floods lower than the probable maximum flood (PMF). Practical difficulties in estimating appropriate parameters to be used for the determination of the PMF and to assess the appropriateness of the estimated PMF are described. A fuzzy set approach is presented, which includes consideration of both tangible and intangible risk factors in determining risk-based design basis flood for a dam. Research needs related to risk analysis for hydrologic safety of dams are identified.

Introduction

In most cases, hydrologic safety of dams is assessed in terms of their capability to safely pass the probable maximum flood (PMF) or a fraction thereof depending on the size and hazard potential of the dam. The PMF is defined as a hypothetical flood that can be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in a region. It is derived from the probable maximum precipitation (PMP) using an event-based rainfall-runoff model. The 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 certain time of the year.

Hydrologic Categorization of Dams

From the standpoint of hydrologic safety and risk analysis, dams may be divided into three categories (ASCE, 1988).

(i) Category 1 includes dams where potential loss of life, economic loss, and social and environmental damages resulting from failure are unacceptable. For these dams, PMF is the design-basis flood (DBF) and a detailed risk analysis, other than hydrologic analysis to estimate the PMF, may not be necessary. Of course, the potential for overtopping and severe scour or erosion due to a long-term PMF event or more than one successive storm events less severe than the PMP must be evaluated as part of the hydrologic analysis.

(ii) Category 2 includes dams where the DBF is PMF unless it can be demonstrated that a smaller DBF results in total costs (including failure consequences) lower

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than the PMF design. These dams require detailed risk analysis (USACE, 1988; Prakash 1992).

(iii) Category 3 includes dams where failure is not expected to result in loss of life and significant economic, social, and environmental damages. For such dams, regulatory guidelines prescribed by the respective state and federal agencies may be adopted. However, the owner/operator must be made aware of the risk of failure during the life of the project. This can be done using the risk probability equation:

$$R = 1 - (1 - P)^n \qquad (1)$$

in which R = probability that one or more events of exceedance probability, P, would occur during n years of project life. The exceedance probability, P, refers to events more severe than the DBF. Such severe hydrologic events should include those where dam failure is likely due to overtopping or erosion and scour on the downstream toe.

Risk-Based Economic Analysis

Determination of the DBF for Category 2 dams must include economic considerations and intangible factors associated with the risk of failure during the PMF or equivalent event. The intangible factors may include potential community disruption, population at risk, political and institutional consequences of potential dam failure, loss of capital invested in dam construction, and loss of benefits which the community would derive from safe operation of the dam. The economic factors can be evaluated using hydrologic and economic analyses. The intangible factors have to be evaluated using subjective criteria. Hydrologic and economic analyses to determine the DBF for Category 2 dams may be conducted using one of the following approaches:

(i) Expected Value Approach (NRC, 1988)- In this approach damages associated with reservoir outflows of different probability densities or frequencies are weighted by the respective frequencies up to the exceedance probability of the DBF. Economic consequences of dam failure are weighted by the frequencies of floods between the DBF and PMF. The sum of these two gives the expected annual damage or costs associated with the DBF, which is less than PMF. This approach camouflages the enormity and catastrophic nature of damages resulting from extreme flood events, including dam failure, by weighting them with the respective low exceedance probabilities. However, the consequences of such a single event may be so severe that the owners and other impacted parties may not be able to recover from the catastrophe. This most relevant and significant event for them is de-emphasized in this approach.

(ii) Indemnification Cost Approach- This approach provides for the establishment of an escrow account sufficient to compensate for monetary damages resulting from dam failure during the life of the dam, which is designed for a DBF less than the PMF. Variations of this approach include considerations such as the owner opting or not opting to indemnify himself against the loss of his investments and escalation in economic consequences of dam failure with time (ASCE, 1988; Prakash, 1992; Prakash, 1990).

(iii) Modified Expected Cost Approach- This approach considers the probabilities of specific economic damages occurring within the life of the dam rather than the absolute probabilities in evaluating the expected cost of dam failure.

The aforementioned economic and intangible factors may be included in a rectangular matrix including subjective relative scores of all evaluation factors for each alternative DBF as its elements and a column vector including weights for different evaluation factors. The product of this rectangular matrix and column vector gives the weighted score or rank of each alternative DBF. The decision making process may involve delphi and fuzzy-set approaches to assign due scores and weights to all relevant tangible and intangible factors.

Hydrologic designs based on industry or agency standards provide an implicit protection against liability for failure consequences. Such liability protection may not be available in risk-based designs. Therefore, it may be desirable to include indemnification or insurance costs against potential failure consequences in risk-based designs and analyses. Other difficulties associated with risk analysis for dams include uncertainties and subjectivities in the estimation of the PMF peak and volume, probability of PMF and other extreme flood events, and rates development and sizes of potential breaches used for risk analysis.

Reasonableness of PMF Estimates

Generally, the reasonableness of the estimated PMF is assessed by comparing the PMF peak with peak flows estimated by other alternative methods. Alternative methods to estimate peak flows approaching the PMF peak include those based on enveloping equations, e.g., Creager, Crippen, Matthai, Myer/Jarvis equations, and previous estimates of PMF peaks for other facilities in the region. A second set of alternative methods includes estimates based on statistical analysis of reported peak flows and those estimated by tree-ring and paleoflood analyses. Usually, the range of values estimated by various enveloping equations and previously estimated PMF peaks is fairly wide so that only a ballpark assessment is possible (Prakash, 1994). A common difficulty with the estimates based on statistical, tree-ring, or paleoflood analyses is that these estimates are often found to be significantly lower than those obtained by event-based rainfall-runoff modeling, particularly for large watersheds comprised of several sub-watersheds. Possible reasons for this under-estimation include the following:

- The historic flood may reflect the response of a severe storm event covering only a portion of the watershed.
- The historic flood may reflect the response of a storm event of shorter duration.
- The historic flood may reflect the response of a severe storm of a different temporal distribution of precipitation.
- The historic flood may reflect the response of a storm cell moving upgradient through the watershed.
- The historic flood may reflect drier antecedent moisture conditions.

- The band of uncertainty on the reported flood peaks used in these analyses may be relatively large. The reported standard errors associated with the USGS regional regression equations based on statistical analysis of reported peak flows provide an indication of the magnitude of potential uncertainties. The reported standard errors range from 15% to 135%, most values being above 25% (USGS, 1993).

In some exceptional cases, statistical data for peak flows may include extraordinarily high peak flows resulting from catastrophic events such as dam-break or ice-jam break, etc. In these cases, treatment of outliers becomes a problem. Peak flows caused by such abnormal events may not be relevant to statistical analysis of natural floods, which must be caused by events such as high precipitation or rain with snowmelt. Usually, storm runoff hydrographs are developed assuming uniform distribution of precipitation on the respective sub-watersheds or contributing drainage areas (CDAs). In most, cases, the depth, duration, areal coverage, and temporal distribution of the storms associated with historic peak flows are not known. The result is that T-year storm events do not always produce peak flows equal to the T-year peak flows estimated by statistical, tree-ring, or paleoflood analyses.

Parameters for PMF Estimation

At present, there are no consistent methods to estimate the parameters used to develop the PMF hydrograph. There are numerous methods to develop sequences of incremental precipitation for PMP and to estimate basin lag times and loss rates. Use of different sets of methods and assumptions often results in widely different estimates of PMF peak and runoff volume (Prakash, 1986). Future applied research should focus on developing guidelines such that consistent estimates are obtained by different hydrologists.

Duration of PMP

The determination of storm duration appropriate for a given watershed is mostly subjective. For instance, design storm duration used for the Pacoima Dam watershed of 28.2 sq miles and Lake Wholford watershed of 8 sq miles in California was 72 hours; 48 hours for a drainage area of 807 sq miles for Lyman Dam watershed in Arizona; 48 hours for a drainage area of 206.6 sq miles for Jiguey Dam watershed in the Dominican Republic; 24 hours for a drainage area of 184 sq miles for Harriman Dam watershed in Massachusetts; and 6 hours for a drainage area of 54 sq miles for Sutherland Dam watershed in California.

An analysis of the annual maximum discharge records of selected streams in Maryland concluded that a 24-hour storm duration may be appropriate for drainage areas in the range of 2 to 50 sq miles (Levy and McCuen, 1999). Similar studies need to be conducted for watersheds of different sizes in other regions. At the preset time, the times of concentrations of different sub-watersheds along with travel times through interacting channels are used for a preliminary estimate of the design storm duration. But, there are wide variations in the estimation of the times of concentration and travel times based on different empirical equations (Prakash, 1996).

Parameter Estimation Based on Joint Probabilities

One approach to assess the reasonableness of the events or data used to develop the PMF hydrograph using an event-based rainfall-runoff model and route it through the reservoir includes estimation of the joint probability of combined events. The estimated joint probability is compared with the heuristic probability of the PMF. Relevant events may include antecedent moisture condition, loss rate, PMP depth and its temporal distribution, and wind wave activity (NRC, 1985; Prakash, 1983). For the sake of simplicity, it is assumed that these events are independent of one another. Thus,

$$P(PMF) = P(A)\,P(B)\,P(C)\,P(D) \qquad (2)$$

in which P(PMF) = combined or joint probability of PMF; P(A) = probability of the occurrence of selected antecedent moisture condition; P(B) = probability of the occurrence of selected loss rate; P(C) = probability of PMP and its temporal distribution; and P(D) = probability of selected wind wave activity. The probability of PMP itself, P(C), is reported to vary form 10^{-12} to 10^{-19} in the eastern United States and from 10^{-5} to 10^{-14} in the western United States (ASCE, 1988). With probabilities of less than 1.0 assigned to the other three events, the combined probability of the PMF may approach much lower than the expected probability of about 10^{-6} to10^{-8} for the PMF. If all the factors are appropriately considered, the probability of the estimated PMF may be unreasonably low. The above probability may be further modified if probabilities of other events, such as times of concentration and travel times are considered. Evidently, additional research is needed in the probability aspects of PMF determination.

PMF Peak and Volume

The statistical, tree-ring, and paleoflood analyses and estimates based on enveloping and regression equations provide estimates of peak flows. To evaluate the hydrologic safety of dams, estimation of the PMF hydrograph is extremely important. Methods and guidelines are needed to assess the reasonableness of PMF hydrograph as also its peak. Some times, a hydrograph with a slightly lower peak but much larger runoff volume may be more critical. In such cases, the aforementioned tests of the reasonableness of PMF peak may not be adequate.

Long-Duration or Successive Flood Events

It is reported that the Upper Mississippi River Basin flood of 1993 included five major inflow flood events experienced by the Saylorville Reservoir on the Des Moines River over a period of five months. Such successive or long-duration flood events may cause greater scour and erosion downstream of the spillway than a single flood event. This suggests that the effect of two or more successive flood events and long-duration floods should also be evaluated, particularly on potential downstream scour and erosion. It appears logical to select these successive or long-duration flood events in such a way that their probability of occurrence is commensurate with that of the PMF.

If two or three independent flood events within a period of three months or so are to be considered, then their probability of occurrence should be about 10^{-6} or so. Assuming the flood events in a region to be a Poisson process, the probability that three 100-year flood events would occur in a period of three months, would be about 3×10^{-9}; the probability that three 50-year flood events would occur in a period of three months, would be about 2.1×10^{-8}; and the probability that three 25-year flood events would occur in a period of three months, would be about 1.67×10^{-7}. This suggests that three 25-year floods in a 3-month period may have a probability equivalent to that of the PMF. One or three 25-year floods may or may not cause scour and erosion comparable to a single PMF event. Also, additional research is needed to estimate scour and erosion for different types of rock, concrete, vegetation, and soil protection due to long-term exposure to high velocities or exposure to successively occurring high velocities several times during a given period.

Determination of a long-duration PMF requires estimation of the long-duration PMP. Methods to determine one-month or 5-month duration storm events equivalent to the PMP have yet to be determined. Available information includes PMP durations of only up to 4 days or so.

Conclusion and Research Needs

Determination of a reasonably safe DBF for a dam should be based on economic and several intangible factors associated with the consequences of dam failure. Economic consequences may be estimated using analytical approaches outlined in this paper. Evaluation of the relative significance of all tangible and intangible factors is subjective. A combination of the delphi and fuzzy-set approaches may be useful in considering all relevant factors with due weightage assigned to each based on input from the interested or impacted parties.

The methods and assumptions used for hydrologic analyses related to risk-based designs of dams are inherently subjective. As a result, different hydrologists may obtain widely different results from risk analysis for one and the same dam. Research efforts must focus on reducing this inherent subjectivity so that results of risk analyses performed by different hydrologists are as close to one another as practicable. This requires development of guidelines and methods for each specific computational element of risk analysis. Research needs relevant to this goal are indicated below:

- Identification of methods to identify categories of dams where risk-based hydrologic design is acceptable and preferable to that based on industry or agency standards related to size and hazard classification. It must be recognized that designs based on standards imply a certain degree of protection to designers, operators, and owners against liability for failure consequences.

- Identification of consistent methods and assumptions related to PMF determination including magnitude, duration, and sequencing of PMP and estimation of lag times and loss rate parameters for different types and sizes of watersheds.

- Development of consistent methods for estimation of the probability of PMF and similar extreme flood events.
- Identification of methods to estimate the reasonableness of the estimated PMF peak and volume so that consistent estimates are obtained by different hydrologists.
- Development of consistent methods to estimate combined events equivalent to the PMF in probability of exceedance and magnitudes of peak flow and volume , e.g., severe rainfall combined with snowmelt; wind wave activity combined with a severe storm event; successive storm events which may cause erosional damages similar to or more severe than the PMF, etc.
- Development of methods to estimate long-duration storm events equivalent to PMP and PMF, which may generate larger volumes of reservoir inflows.
- Identification of methods to select plausible modes of dam failure and rates of development and sizes of breaches for different field conditions.
- Identification of methods to incorporate both economic (i.e., tangible) and intangible consequences of dam operation and potential dam failure in risk analysis and evaluation of dam safety.
- Development of methods to include indemnification or insurance costs to cover dam failure consequences in risk analysis.
- Development of methods to arrive at consensus on how to account for potential loss of life associated with dam operation or failure in risk-based hydrologic design of dams.

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Hydrology for Dam Safety – Private Sector

By
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INTRODUCTION

Although dams have been designed and built by private engineering consultants throughout the world, the concept of hydrology for dam safety for owners of existing dams have never really been addressed until perhaps in the late 1960s. Although the state of California has an existing dam safety program implemented by the Legislature in 1929, its function was more of issuance of certificate of operations to dam owners to guarantee the safe operations of the reservoirs. However, in 1966 after the failure of Baldwin Hills Dam, the law was revised to include off-stream dams to be under the jurisdiction of the Division of Safety of Dams. At the same time a program of dam inspection and review of design criteria was implemented.

Pacific Gas and Electric Company (PG&E) which owned some 200 dams at that time for the largest private dam owner in the country began discussing with the California Division of Safety of Dams in 1967 to implement the new dam safety program. Inspection programs and criteria for dam safety were evaluated and investigated. Hydrologic criteria were one of them.

At that same time also, the Federal Power Commission (now known as the Federal Energy Regulatory Commission) Order No. 315 was passed in 1969. The Order requires the inspection and review of safety of non-federal dams by an Independent Consultant. FPC Order 315 was later superseded by FERC Order 122 which expanded the safety evaluation of dams under FERC jurisdiction
.
This paper will give an overview of existing methods in developing the flood potential at a dam, especially the methods employed in PG&E from 1968 to comply with the requirements for dam safety by the Federal Energy Regulatory Commission and the California Division of Safety of Dams. Advantages and disadvantages of each procedure together with their inherent problems or limitations will be mentioned. Research needs for some items are discussed throughout the paper. A comparison and a set of guidelines to determine reasonable values are also described.

HYDROLOGIC CONSIDERATIONS

The design and evaluation of dams against hypothetical floods requires the determination of the hydrologic response (infiltration, base, flow, routing and runoff) of watersheds to intense rainfall or snowmelt, verification based on historical storm and runoff data (flood hydrograph analysis). It also requires the determination of the hypothetical storms, infiltration, base flow, channel and reservoir routing. Routing involves the investigation of the adequacy of existing structures above and below the dam under investigation to safely pass the hypothetical floods.

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Rainfall-Runoff Relations

Each drainage basin requires a separate study to determine the rainfall-runoff relation of that basin. There is often great variation of rainfall-runoff relations between neighboring drainage areas. This variation may be caused by physical characteristics which are not readily apparent, such as snow accumulation in high elevations bands in mountainous regions similar to the Sierra Nevada in California.

Hydrologic Response

The hydrologic response of the watershed to precipitation is usually determined and verified from historical flood records. In 1969, PG&E embarked into a major project of "reconstituting" historical floods to determine the hydrologic response to extreme rainfall. Reconstitution of historical large floods substantiate the use of the runoff model to estimate extreme floods up to the probable maximum flood (PMF). PG&E obtained through the California Division of Safety of Dams (DSOD) a newly developed computer program by Leo Beard of the Hydrologic Engineering Center called "Unit Hydrograph and Loss Rate Optimization." The first few studies were limited to small drainage basins (35 sq mi) and the results were shared with DSOD. Later when the program was incorporated into the new HEC-1, further studies included unimpaired flows from larger drainage areas. Figures 1 to 4 show four examples of reconstituted flood from major historical floods using the computer program, HEC-1, "Flood Hydrograph Package." (1) Between 300 to 500 floods from 1938 to 1986 in California Sierra Nevada slopes were reconstituted with HEC-1.

Development of Design Flood

The development of a design flood from the selected design storm involves several tools of meteorology, hydrology and hydrologic engineering. Since the workshop is composed of experts in hydrology, the detailed process of development will not be discussed anymore.

HYPOTHETICAL STORMS

It is the general practice to obtain design flood hydrographs from design storms. Two general types of design storms are used: (a) the frequency-based storm, and the (b) probable maximum precipitation, PMP.

Frequency-Based Storm

This design storm is defined as the depth of rainfall with certain return interval in years ranging from 2 to 100 years. The depths are obtained from generalized studies prepared by the National Service such as those in references 2 and 3.

To comply with California DSOD criteria, PG&E uses the frequency-based design storm derived in accordance with the method introduced by James D. Goodridge in 1969 and later published as Bulletin No. 195. (3) The method estimates the frequency-based storms for a specific precipitation station up to the 1,000-year event using the Pearson Type III probability distribution. The bulletin even provides estimates of statistical PMP for each rain station based on the concept introduced by David Hershfield of the former U.S. Weather Bureau. In some cases, when the hazards downstream are high, DSOD extrapolates storms beyond the 1,000-year event.

Probable Maximum Precipitation

All of PG&E dams have been evaluated against the probable maximum precipitation derived in accordance with the U. S. Weather Bureau, Hydrometeorological Report (HMR) No. 36. (4) Recently, a few dams have been evaluated against the new National Weather Service (NWS), Hydrometeorological Report No. 58 and No. 59. (5,6). The PMPs from these publications have durations up to 72 hours.

In HMR 36, estimates of the PMP are prepared for the months of October, November, December, January-February, March and April. For the small drainage areas of PG&E reservoirs, the October PMP controls. For larger drainage areas, the November PMP provides the controlling flood.

In HMR 58 & 59, estimates of the PMP are prepared for the 12 months of the calendar year. Recent estimates for the summer and fall months (May through September) appear to create problems for reservoirs with small drainage areas. The estimates appear to provide higher rainfall and thus would require revised operating rule curves for these reservoirs. This is where, the writer feel that additional research needs to be done.
An additional PMP estimate is done using what is called the thunderstorm type of a PMP. This type of storm is very critical for all reservoirs with small drainage areas (up to 500 sq mi) because of the high intensity, short duration rainfall that it produces. The thunderstorm has a duration of six hours.

FACTORS THAT AFFECT FGLOOD ESTIMATES

There are several factors which affect the determination of hypothetical floods up to the PMF. The major ones are the areal and temporal distribution of the design storm, the loss rates or infiltration rates, the unit hydrograph, the size or subdivision of the basin, the presence or absence of snow, antecedent or subsequent storms, and channel routing methods.

Areal Distribution

The storm area used for the point-to-area adjustment is critical. This adjustment compensates for the fact that storm covering larger areas will have lower average intensities. Such a relationship between storm area and average intensity can be determined for different frequency storms in a region, using historical precipitation statistics. Thus, the storm area used should be that area which is tributary to the river location in question. This requires separate storm centerings (areas) for each location where floods are to be computed.

For areas where an elliptical pattern of design storm is given, such as in HMR 52, the contribution for each sub-basin in a stream system is easily estimated because they are already areally reduced. However, in orographic areas such as in HMR 36 or the new HMR 57 & 58, there are no standard techniques to distribute the PMP among sub-basins in large drainage areas. PG&E uses the isohyets of a major storm in the area to determine the areal distribution of the PMP.

Temporal Distribution

To compute the flood hydrograph for a given design storm, it is necessary to specify the time sequence of the precipitation. These increments should be arranged in a sequence that will result in a reasonably critical flood hydrograph. Ideally, the design storm sequence should be modeled after historically observed storms if such storms show that major storm rainfalls have a predominant pattern. Therefore, the hydrologist is left to adopt his own distribution pattern. This is where significant differences in answers of peak flows will occur.

HMR 36 (4) shows five acceptable time sequence of storms. These time sequences are also adopted for HMR 57 & 58. If all of these sequences are tried, one would produce the most severe flood hydrograph, but not necessarily the most reasonable. Engineers would have a tendency to adopt the most conservative; meaning, one with the highest peak flow. However, this conservative value might not be the most reasonable because it could be the result of compounding too many low probability events. Figure 5 shows the time sequences recommended in HMR 36, 57 and 58.

Loss Rates or Infiltration Rates

The many methods that have been proposed to account for rainfall losses are also the causes of the variations of estimates of the probable maximum floods. These methods range from the simple empirical to complex conceptual models of the surface and soil system. The simplest method is the "initial and uniform" technique which has a single soil moisture (and interception) deficit which must be satisfied before runoff can occur. Once this initial deficit is satisfied, runoff will occur for all rainfall intensities which exceed a given "uniform" infiltration rate.

The U. S. Soil conservation Service's (now National Resources Conservation Service) Curve Number technique was developed for determining total runoff volume from total rainfall volume; but, the technique has been widely used for incremental rainfall infiltration as well. It has received much attention because of its simplicity and because the curve number (infiltration rate) can be obtained from readily measurable geographic characteristics (soil type and land use). The "curve number" computations neglect the effects of rainfall intensity.

The variable loss rate function introduced by the Corps of Engineers ($L = KP^E$) and is part of the computer program HEC-1 is used by DSOD and PG&E in all their studies.

Unit Hydrograph

The most common method of transforming rainfall excess to runoff is the unit hydrograph technique. This technique is the biggest cause of differences in PMF determination because there are several methods of deriving a unit hydrograph for a basin. When there is no measured streamflow hydrograph of a major flood at the study basin from which a unit hydrograph can be derived, the hydrologist resorts to synthetic unit hydrograph.

The most common synthetic methods are the SCS triangular unit hydrograph method (7), Clark's method (8), Snyder's method (9), and the Bureau of Reclamation's dimensionless graph-lag method (10). All of these unit hydrograph techniques are defended by their practitioners as acceptable. However, if the unit hydrograph is not calibrated or verified against a major flood event, the synthetic method will overestimate (or even underestimate in some cases) the PMF peak flow considerably. As a matter of fact, there are instances when the triangular method will estimate a flood twice that derived by the calibrated Clark'' method.

As mentioned earlier, PG&E began the studies of some 300-500 major floods in California. This was done to develop unit hydrographs for the small basins of their reservoirs. With the aid of the computer program HEC-1, the Clark's unit hydrograph coefficients of TC and R were calibrated and related to the basin characteristics of $LLca/S^{1/2}$ where: L is the length of the longest watercourse from the point of interest to the watershed divide in miles; Lca is the length of the watercourse from the point of interest to the intersection of the perpendicular from the centroid of the basin to the stream alignment in miles and S is the overall slope of the longest watercourse in foot per mile. The ratio of R/(TC + R) was assumed as the average for a particular rivershed or watershed so that a specific R can be obtained for a sub-basin using this relationship in the basin under study. Figure 6 shows a typical plot of Clark's TC for the Kings River Basin only. Each river watershed in the western slopes of California where PG&E have reservoirs has a plot of this unit hydrograph. The author determined that the variability of runoff within each river watershed justified a separate plot of derived unit hydrographs. The river watershed where the author has plotted calibrated unit hydrographs similar to Figure 5 are: Pit and McCloud Rivers, North Fork Feather River, West Branch of the Feather River, South Fork American River, Yuba River, Mokelumne River, Stanislaus River, San Joaquin River above Millerton Lake and the Kings River. There are other isolated small watersheds in California where these were performed also.

Snow

In California where snowfall is part of the meteorological process of precipitation, it is important that an antecedent snowpack and coincident snow be considered in the estimation of design floods. Generally, the National Weather Service reports such as HMR 36, HMR 58 and 59 provide also the coincident wind and temperatures for snowmelt process.

The presence of snow on the ground will determine whether there should be larger runoff or less. In areas of high elevation the presence of snow could reduce the runoff because as the elevation band increases to higher elevation, the coincident temperatures become colder by the lapse rate. Therefore, there would be more rainfall that would be changed into snow rather than runoff.

The publication "Snow Hydrology" from the North Pacific Division of the U. S. Army Corps of Engineers has been a very useful reference. However, the publication was issued in June 30, 1956. It appears that it needs some kind of an update based on current information on snow hydrology in the western region.

For current practices in PMF determination, the Federal Energy Regulatory Commission recommends the use of an antecedent 100-yr snowpack. The effect of the 100-yr snowpack depth is minimal since the melt is dictated by the available melting coefficients and parameters under the PMP event. The requirement for a 100-yr snowpack is more of a criteria rather than a physical characteristics in the meteorological process. The snow can melt only as much as the temperatures or wind coincident with the PMP can melt. However, a deeper snowpack should affect the loss rate function in the basin during the PMP event.

Antecedent or Subsequent Storms

The application of detailed analysis requiring routing of antecedent or subsequent storms are applicable only to large watersheds because the critical storms for these watersheds are usually due to long duration storms. PG&E reservoirs have small watersheds so it is generally assumed that the reservoirs are full prior to the occurrence of the PMP or other design storms.

Channel Routing

Another major technique that causes a major difference in the estimate of hypothetical floods is the method chosen for channel routing. HEC-1 has currently several methods of channel routing. Each of these methods is acceptable but would give varying degrees of results to the routed floods. If one performs channel routing with an unsteady flow model, the answers would also be different.

HYDROLOGIC CRITERIA

When PG&E started evaluating all their reservoirs against hypothetical floods, there were no hydrologic criteria for dams under regulatory jurisdiction. At that time the PMF concept was an exclusive specialty of the Corps of Engineers. Additionally, all PG&E reservoirs have small drainage areas and the imposition of the PMF at the start appeared too severe. The California Division of Safety of Dams came up with a minimum 1,000-yr storm event as the minimum design criteria for all dams in California.

Current criteria for hydrologic safety design of dams usually relate dam height, storage volume, and the downstream potential for loss of life and economic damage to a design flood. Although the approach is generally adopted throughout the country, the specific criteria vary significantly. In addition, although the PMF is usually adopted for design of dams where the potential economic and social consequences of failure are large, the estimate of the PMF by different engineers or federal agencies may vary significantly, as discussed earlier.

The ANSI/ANS 2.8 Standards

The first attempt to provide a uniform approach in developing a probable maximum flood was made by the American Nuclear Society Working Group ANS 2.8. The American National Standard Institute (ANSI) published the work as the "American National Standard for Determining Design Basis Flooding at Power Reactor Sites." (11) However, because it carried the name of the nuclear industry, it was never available to the ordinary dam safety program. In addition, it was probably the belief that the criteria suggested in the standard would be very conservative in order to be compatible with other nuclear standards.

The National Research Council Report

The report prepared by the Committee on Safety Criteria for Dams under the auspices of the National Research Council (12) provided new insights into the present thinking in the selection process of inflow design floods. The "blue book" as it became to be known has made an impact on the current thinking of choosing a spillway design flood. However, the book contained only the criteria for the so-called "high-hazard" dams owned by the Corps of Engineers and Bureau of Reclamation. There were no criteria for small to medium hazard dams.

The ICODS Report

An Ad Hoc interagency committee on dam safety of the Federal Coordinating Council for Science, Engineering, and Technology, prepared "Federal Guidelines for Dam Safety," (13) which were published in June 1979. To provide general guidelines on procedures for selecting and accommodating inflow design floods (IDF) for use by Federal Agencies, the Interagency Committee on Dam Safety (ICODS) formed a working group on inflow design floods. The result of their work is published in a manual called, "Federal Guidelines for Selecting and Accommodating Inflow Design Floods for Dams." (14)

ASCE Guidelines

In October 1984 the Surface Water Hydrology Committee of the Hydraulics Division of the American Society of Civil Engineers formed the Task Committee on Spillway Design Flood Selection in response to the growing national concern for dam safety and the hydrologic procedures used in evaluation. After three years of work and peer reviews, the committee released the publication "Evaluation Procedures for Hydrologic Safety of Dams," in 1988. (15) A quantitative risk assessment was the basis for the proposed procedures. The design selection process was based upon the three categories of dams which depend on the failure consequences and the level of effort required to select a design flood.

FERC Guidelines

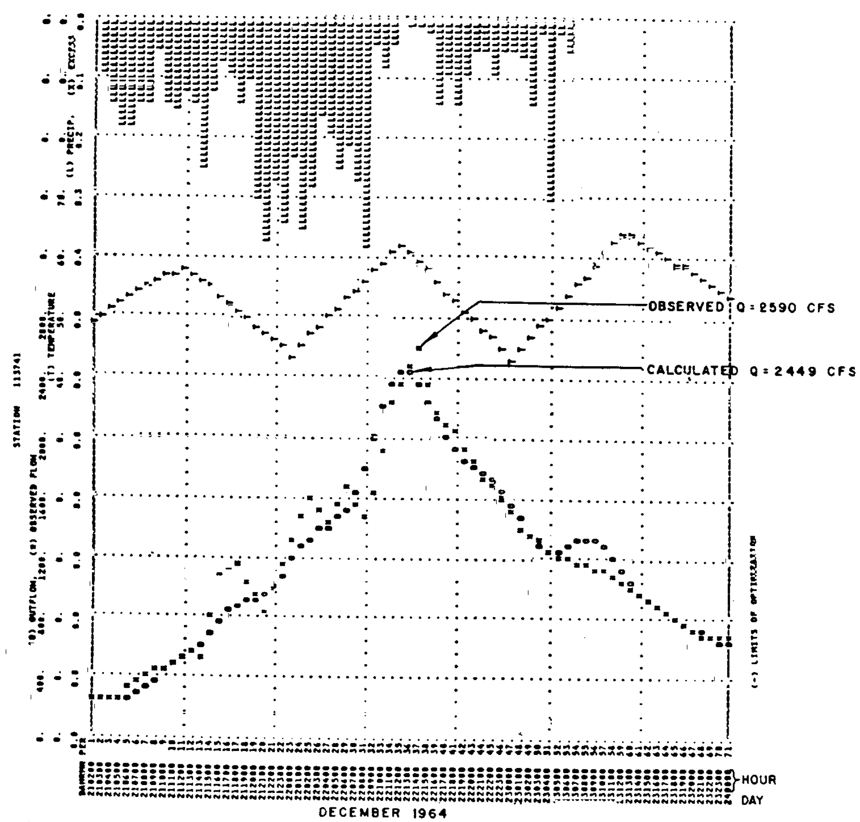
In 1993, the Federal Energy Regulatory Commission (FERC) issued their own guidelines in determining the Inflow Design Flood and the Probable Maximum Flood. These guidelines are contained in their "Engineering Guidelines for the Evaluation of Hydropower Projects." (16) All dams under the jurisdiction of FERC apply the guidelines in evaluating the hydrologic safety of dams.

CONCLUSION

Even with all these activities, the dam safety community still needs more research in developing better approach and selection of the appropriate spillway design flood of a dam. The author recommends the following research activities for funding:

- Update "Snow Hydrology" previously published by the Northwest Division of the U. S. Army Corps of Engineers.

- Update Sacramento District 1962 studies, "Generalized Snowmelt Runoff Frequencies."
- Continue to upgrade the hydrologic models used for dam safety evaluation such as the Corps of Engineers HEC-1, HEC-2, HEC-HMS and HEC-RAS. The HEC-1 model needs to be retained because it contains the snowmelt computations required for hypothetical floods in the Western Regions such as California, Oregon and Washington.
- Develop a uniform method of areal distribution of the PMP especially applicable in orographic areas.
- Technical review of the recently published PMP (HMR 57 and 58) reports for reasonableness.
- Develop a temperature sequence for PMP estimates with snow so that it reflects the diurnal variation of temperatures.
- Develop a "Windows-based" dambreak model. This is very important because the model is used for Inflow Design Flood selection process. Danny Fread has retired from service and the continuation of the program development of his world-renowned DAMBRK is unknown. Additionally, this model is DOS-based only.



INFLOW, OUTFLOW, AND OBSERVED FLOW IN CUBIC FEET PER SECOND (CFS)
TEMPERATURE IN DEGREES FAHRENHEIT (°F)
PRECIPITATION IN INCHES (IN.)

DRAINAGE AREA. . . . . 75.6 SQUARE MILES
SNOWMELT . . . . 1.24 INCHES
SNOW EXCESS . . . . . . 0.24 INCHES
RAIN . . . . 6.18 INCHES
RAIN EXCESS . . . . . . 1.46 INCHES

BASIN MEAN ANNUAL PRECIPITATION = 43.02 INCHES
PRECIPITATION PATTERN STATION(S) = 7292 RED BLUFF
7295 REDDING ISE
8135 SHASTA, 9390 VOLTA P.H.
TEMPERATURE PATTERN STATION(S) = 9390 VOLTA P.H.

NOTE:

RECONSTITUTION OF FLOOD PERFORMED WITH THE AID OF THE U.S. ARMY CORPS OF ENGINEERS, "HEC-1 FLOOD HYDROGRAPH PACKAGE," COMPUTER PROGRAM 723-X6-2010. THE HYDROLOGIC ENGINEERING CENTER, DAVIS, CALIFORNIA; SEPTEMBER 1981, REVISED JANUARY 1985.

NO.	DATE	DESCRIPTION	GM	DWN.	CHKD.	SUPV.	APVD.
1	12-15-86	ISSUED	—	[illegible]	[illegible]	[illegible]	[illegible]

REVISIONS

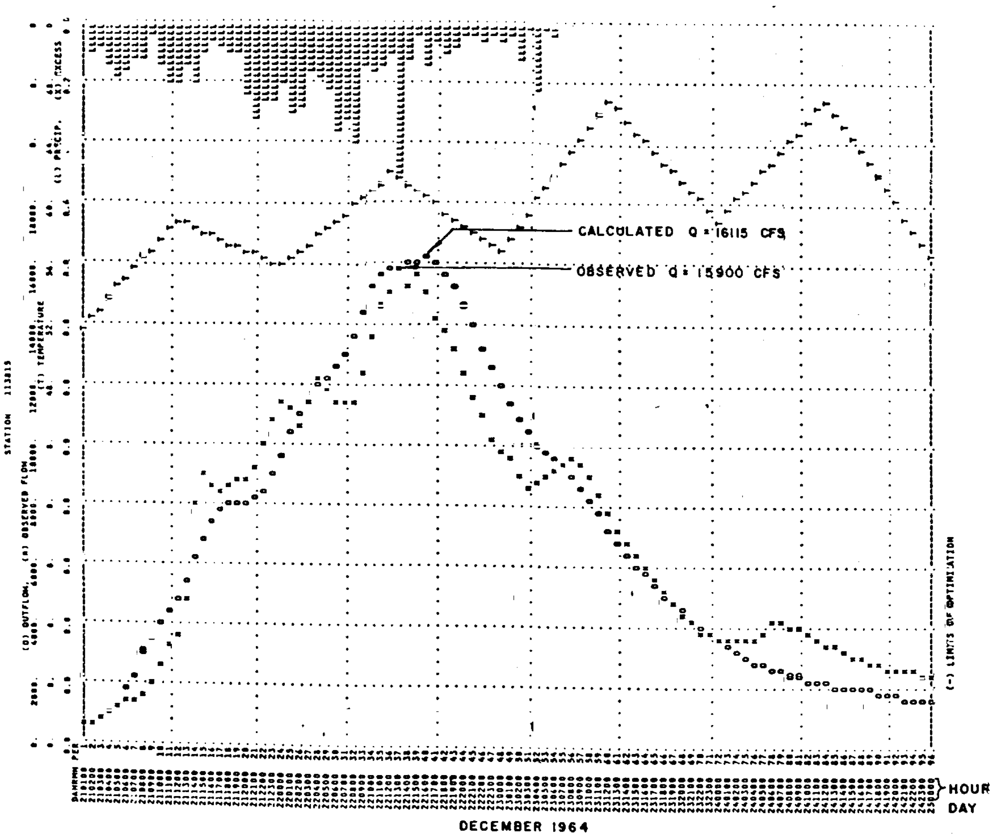
APPROVED BY	ACTY 3182
	SUPV. G.SINGH
	DSGN. K.TSAY
	DWN. Y.S.GEE
	CHKD. B. Y. Lu
	QK. [illegible]
	DATE 12-15-86
	SCALES AS NOTED

CIVIL
FLOOD HYDROGRAPH RECONSTITUTION
DECEMBER 21-24, 1964
113741 BEAR CREEK NEAR MILLVILLE
DEPARTMENT OF ENGINEERING
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CALIFORNIA

SHASTA DIVISION

MICROFILM	
BILL OF MATL	
DWG LIST	
SUPSDS	
SUPSD BY	
SHEET NO. 108918	SHEETS REV. 1

FIGURE 1



INFLOW, OUTFLOW, AND OBSERVED FLOW IN CUBIC FEET PER SECOND (CFS)
TEMPERATURE IN DEGREES FAHRENHEIT (°F)
PRECIPITATION IN INCHES (IN.)

DRAINAGE AREA. . . . . 131.0 SQUARE MILES
SNOWMELT . . . . 1.87 INCHES
SNOW EXCESS . . . . . 1.68 INCHES
RAIN . . . . 7.44 INCHES
RAIN EXCESS. . . . . . . 6.37 INCHES

BASIN MEAN ANNUAL PRECIPITATION = 45.64 INCHES
PRECIPITATION PATTERN STATION(S) = 7295 REDDING, 7292 RED BLUFF
8135 SHASTA & 9390 VOLTA PH.
TEMPERATURE PATTERN STATION(S) = 7292 RED BLUFF

NOTE:

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1	12-15-86	ISSUED	—	4	BYL	[illegible]	[illegible]

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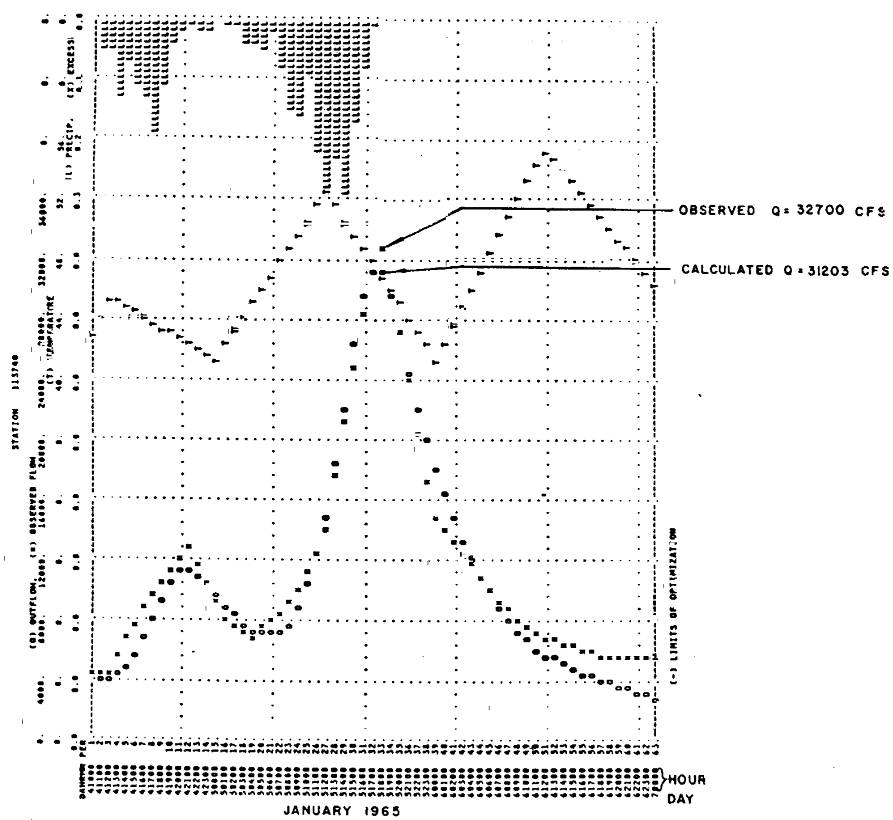
APPROVED BY
ACTY 3182
SUPV. G.SINGH
DSGN. K.TSAY
DWN. S.C.TIGBAO
CHKD. B.Y.L.
DATE 12-15-86
SCALES AS NOTED

CIVIL
FLOOD HYDROGRAPH RECONSTITUTION
DECEMBER 21-25,1964
113815 MILL CREEK NEAR LOS MOLINOS
DEPARTMENT OF ENGINEERING
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CALIFORNIA

SHASTA DIVISION
MICROFILM
BILL OF MATL
DWG LIST
SUPSDS
SUPSD BY
SHEET NO. 108919 SHEETS 1 REV.

FIGURE 2



INFLOW, OUTFLOW, AND OBSERVED FLOW IN CUBIC FEET PER SECOND (CFS)
TEMPERATURE IN DEGREES FAHRENHEIT (°F)
PRECIPITATION IN INCHES (IN.)

DRAINAGE AREA . . . . . 425.0 SQUARE MILES
SNOWMELT . . . . 0.10 INCHES
SNOW EXCESS . . . . . . 0.10 INCHES
RAIN . . . . 2.48 INCHES
RAIN EXCESS . . . . 2.20 INCHES

BASIN MEAN ANNUAL PRECIPITATION = 43.04 INCHES
PRECIPITATION PATTERN STATION(S) = 7792 RED BLUFF,
7295 REDDING I SE,
9390 VOLTA P.H.
TEMPERATURE PATTERN STATION(S) — 9390 VOLTA P.H.

NOTE:

RECONSTITUTION OF FLOOD PERFORMED WITH THE AID OF THE U.S. ARMY CORPS OF ENGINEERS, "HEC-1 FLOOD HYDROGRAPH PACKAGE," COMPUTER PROGRAM 723-X6-2010, THE HYDROLOGIC ENGINEERING CENTER, DAVIS, CALIFORNIA, SEPTEMBER 1981, REVISED JANUARY 1985.

NO.	DATE	DESCRIPTION	GM	DWN.	CHKD.	SUPV.	APVD.
1	12-15-86	ISSUED	—	8	BYL	92	

REVISIONS

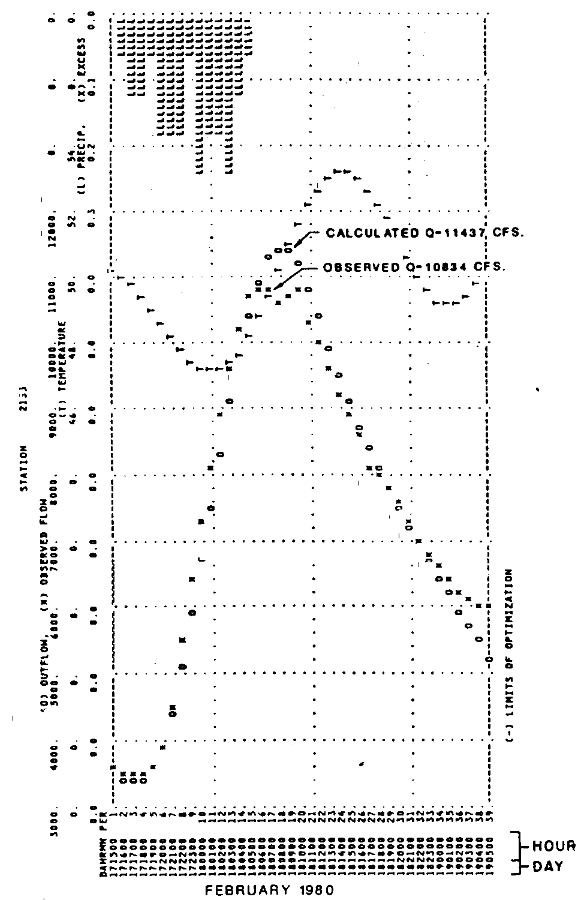
APPROVED BY

ACTY 3182
SUPV. G. SINGH
DSGN. K. TSAI
DWN. Y. S. GEE
CHKD.
DATE 12-15-86
SCALES AS NOTED

CIVIL
FLOOD HYDROGRAPH RECONSTITUTION
JANUARY 4–7, 1965
113740 COW CREEK NEAR MILLVILLE
DEPARTMENT OF ENGINEERING
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CALIFORNIA

SHASTA DIVISION
MICROFILM
BILL OF MATL
DWG LIST
SUPSDS
SUPSD BY
SHEET NO. 108922
SHEETS
REV. 1

FIGURE 3



INFLOW, OUTFLOW, AND OBSERVED FLOW IN CUBIC FEET PER SECOND (CFS)
TEMPERATURE IN DEGREES FAHRENHEIT (°F)
PRECIPITATION IN INCHES (IN)

DRAINAGE AREA ..... 956 SQUARE MILES.
SNOWMELT .... 0.36 INCHES.
SNOW EXCESS .... 0.14 INCHES.
RAIN .... 0.67 INCHES.
RAIN EXCEES .... 0.37 INCHES.

BASIN MEAN ANNUAL PRECIPITATION= 33.9 INCHES.
PRECIPITATION PATTERN STATION(S)= 4176, HUNTINGTON LAKE; 3093, FLORENCE LAKE.
TEMPERATURE PATTERN STATION(S)= 449, BALCH POWER HOUSE.

NOTE:

RECONSTITUTION OF FLOOD PERFORMED WITH THE AID OF THE U.S. ARMY CORPS OF ENGINEERS "HEC-1 FLOOD HYDROGRAPH PACKAGE," COMPUTER PROGRAM 723-X6-L2010, THE HYDROLOGIC ENGINEERING CENTER, DAVIS CALIFORNIA, SEPTEMBER 1981, REVISED JANUARY 1985.

NO.	DATE	DESCRIPTION	GM/SPEC	DWN.	CHKD.	SUPV.	APVD. BY
1	12-15-86	ISSUED	ED2907		RGF	MMC	

REVISIONS

APPROVED BY

ED 2907
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DWN. J.R.C./R.D.M.
CHKD. R.G. Fogliasso
O.K. M. Callejas
DATE 12-15-86
SCALES AS SHOWN

CIVIL-HYDROLOGIC ENGINEERING
FLOOD HYDROGRAPHIC RECONSTITUTION
FEBRUARY 17-19, 1980
112135, KINGS RIVER
ABOVE NORTH FORK NEAR TRIMMER
DEPARTMENT OF ENGINEERING
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CALIFORNIA

MICROFILM

SUPSDS
SUPSD BY
SHEET NO. 108412
SHEETS
REV. 1

FIGURE 4

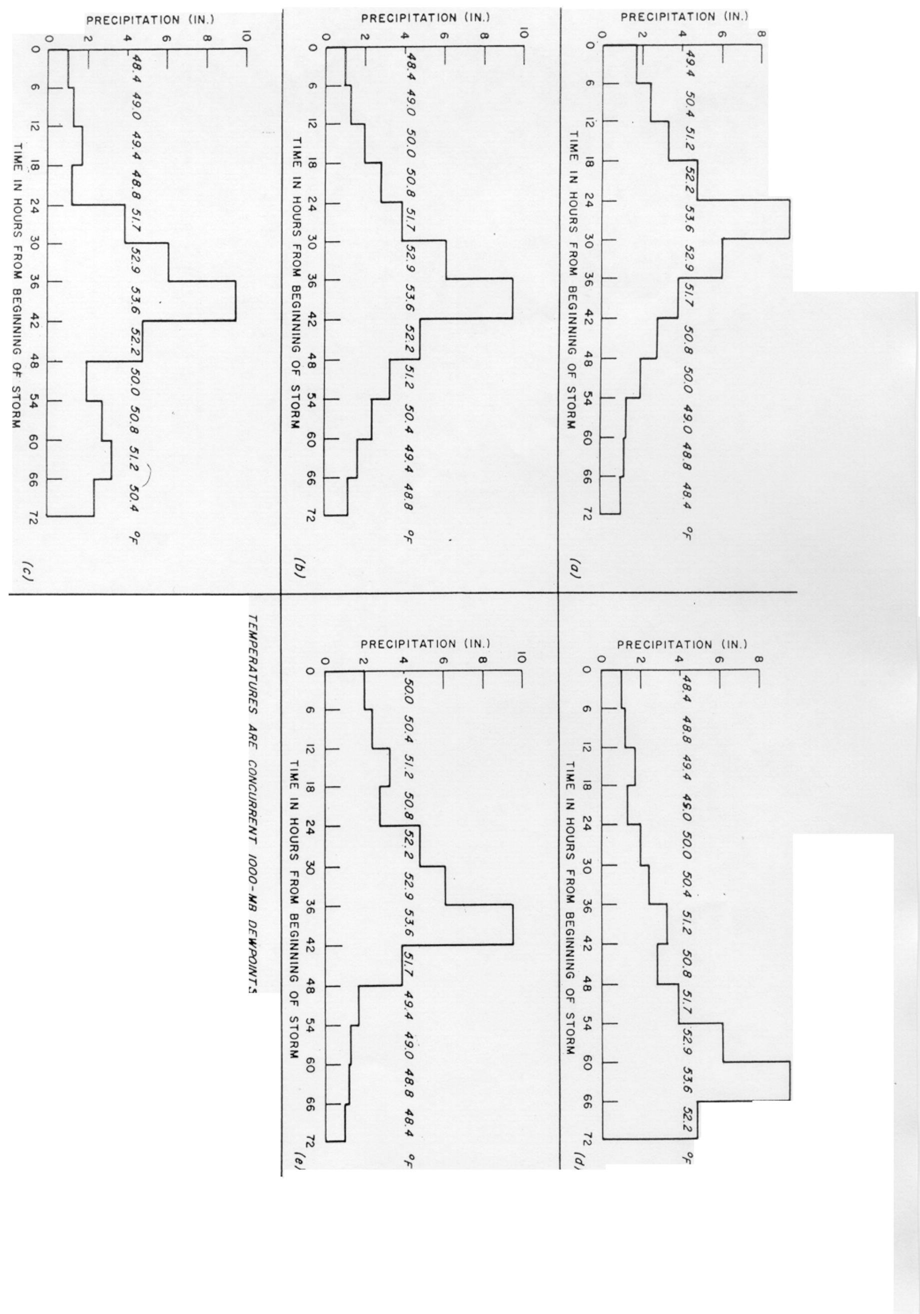
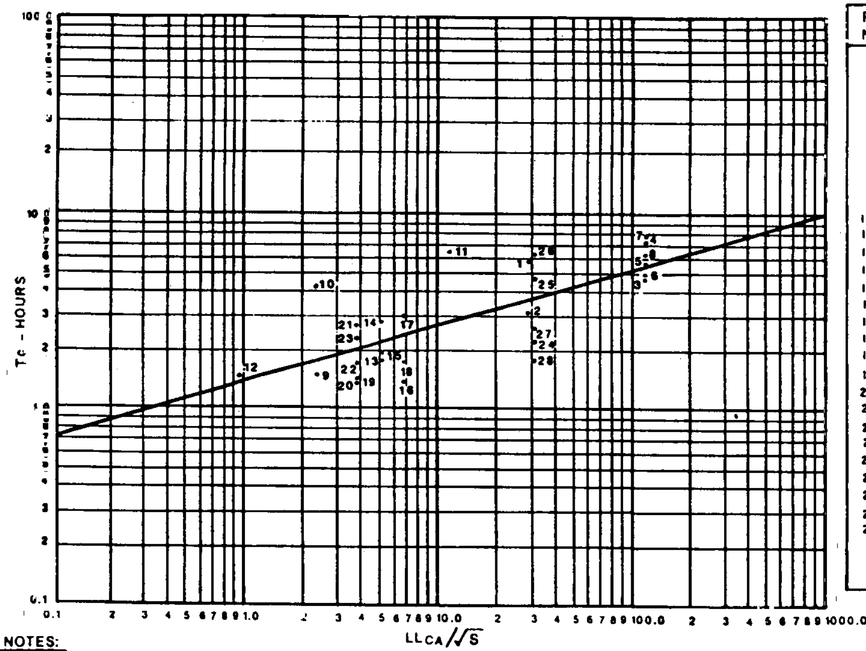


FIGURE 5 – SAMPLE PMP TIME-SEQUENCES



PT NO.	U.S.G.S. NO.	SUB-BASIN	DRAIN AREA (SQ.MI.)	DATE OF STORM	Tc (HR.)	$\frac{LLCA}{\sqrt{S}}$
1	112125	SOUTH FORK KINGS RIVER NEAR CEDAR GROVE	408.0	NOV. 18-20, 1950	5.85	29.60
2	112125	SOUTH FORK KINGS RIVER NEAR CEDAR GROVE	408.0	DEC 22-24, 1955	3.14	29.60
3	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	DEC. 22-24, 1955	4.60	115.70
4	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	DEC. 22-23, 1964	7.07	115.70
5	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	DEC. 23-25, 1964	5.48	115.70
6	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	JAN. 12-13, 1980	4.67	115.70
7	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	FEB. 17-19, 1980	7.83	115.70
8	112135	KINGS RIVER ABOVE NORTH FORK NEAR TRIMMER	956.0	SEP. 25-27, 1982	6.12	115.70
9	112140	NORTH FORK KINGS RIVER BELOW MEADOWBROOK	37.7	DEC. 23-24, 1964	1.50	2.33
10	112140	NORTH FORK KINGS RIVER BELOW MEADOWBROOK	37.7	SEP. 4-6, 1978	4.10	2.33
11	112150	NORTH FORK KINGS RIVER NEAR CLIFF CAMP	181.0	NOV. 17-20, 1950	6.53	11.30
12	112168	ROCK CREEK AT DINKEY CREEK	7.6	DEC. 23-24, 1964	1.49	0.94
13	112170	DINKEY CREEK AT DINKEY MEADOW	50.7	APR. 11-12, 1982	1.79	5.10
14	112170	DINKEY CREEK AT DINKEY MEADOW	50.7	SEP 25-27, 1982	2.76	5.10
15	112170	DINKEY CREEK AT DINKEY MEADOW	50.7	DEC. 22-23, 1982	1.94	5.10
16	112200	BIG CREEK ABOVE PINE FLAT RESERVOIR	70.0	DEC. 22-24, 1955	1.39	6.84
17	112200	BIG CREEK ABOVE PINE FLAT RESERVOIR	70.0	JAN. 24-26, 1956	3.00	6.84
18	112200	BIG CREEK ABOVE PINE FLAT RESERVOIR	70.0	DEC 4-7, 1966	1.80	6.84
19	112205	SYCAMORE CREEK ABOVE PINE FLAT RESERVOIR	56.1	JAN 24-26, 1956	1.46	3.94
20	112205	SYCAMORE CREEK ABOVE PINE FLAT RESERVOIR	56.1	JAN. 31-FEB. 1, 1963	1.39	3.94
21	112205	SYCAMORE CREEK ABOVE PINE FLAT RESERVOIR	56.1	DEC. 5-7, 1966	2.67	3.94
22	112205	SYCAMORE CREEK ABOVE PINE FLAT RESERVOIR	56.1	JAN. 18-20, 1969	1.70	3.94
23	112205	SYCAMORE CREEK ABOVE PINE FLAT RESERVOIR	56.1	FEB. 24-25, 1969	2.34	3.94
24	112217	MILL CREEK NEAR PIEDRA	120.0	JAN. 31-FEB. 1, 1963	2.30	30.90
25	112217	MILL CREEK NEAR PIEDRA	120.0	JAN. 24-26, 1969	4.83	30.90
26	112217	MILL CREEK NEAR PIEDRA	120.0	APR 10-12, 1982	6.26	30.90
27	112217	MILL CREEK NEAR PIEDRA	120.0	DEC. 22-23, 1982	2.68	30.90
28	112217	MILL CREEK NEAR PIEDRA	120.0	JAN. 22-23, 1983	1.88	30.90

NOTES:

1. POINTS OBTAINED FROM RAINFALL-RUNOFF STUDY IN ACCORDANCE WITH THE PROCEDURE IN SECTION 4 OF USERS MANUAL OF REFERENCE 1.
2. STRAIGHT LINE GRAPH OBTAINED BY "LEAST SQUARES CURVE FIT" OF REGRESSION EQUATION. $T_C = A(LL_{CA}/\sqrt{S})^B$ WHERE: A = 1.392 AND B = 0.291

REFERENCES:

1. U.S. ARMY CORPS OF ENGINEERS, "HEC-1 FLOOD HYDROGRAPH PACKAGE," COMPUTER PROGRAM 723-X6-2010, THE HYDROLOGIC ENGINEERING CENTER, DAVIS, CALIF., SEPT., 1981, REVISED JAN., 1985.
2. WETHERELL, R.M., "LEAST SQUARES CURVE FIT" OF SIX CURVE TYPES, COMP. 183, P.G.&E., SAN FRANCISCO, CALIF., 1967.
3. U.S. ARMY CORPS OF ENGINEERS, "HYDROGRAPH ANALYSIS," VOL. 4, HYDROLOGIC ENGINEERING METHODS FOR WATER RESOURCES DEVELOPMENT, THE HYDROLOGIC ENGINEERING CENTER, DAVIS, CALIF., OCT., 1973.

DEFINITIONS:

T_C - CLARK'S UNIT HYDROGRAPH TIME OF CONCENTRATION IN HOURS.

L - LENGTH OF LONGEST WATERCOURSE FROM POINT OF INTEREST TO WATERSHED DIVIDE IN MILES.

L_{CA} - LENGTH OF WATERCOURSE FROM POINT OF INTEREST TO INTERSECTION OF PERPENDICULAR FROM CENTROID OF BASIN TO STREAM ALIGNMENT IN MILES.

S - OVERALL SLOPE OF LONGEST WATERCOURSE IN FT./MI.

$LL_{CA}/\sqrt{S}$ - BASIN CHARACTERISTICS

NO.	DATE	DESCRIPTION	GM/SPEC	DWN.	CHKD.	SUPV.	APVD. BY
1	12-15-86	ISSUED	ED2907	[illegible]	RGF	mmc	[illegible]

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	CALC. FANG WU
	DWN. R.D.M. / J.R.C.
	CHKD. RGFocq [illegible]
	O.K. mmCallejas
	DATE 12-15-86
	SCALES AS SHOWN

CIVIL-HYDROLOGIC ENGINEERING
CLARK'S TIME OF CONCENTRATION VS. BASIN CHARACTERISTICS
KINGS RIVER SYSTEM
DEPARTMENT OF ENGINEERING
PACIFIC GAS AND ELECTRIC COMPANY
SAN FRANCISCO, CALIFORNIA

MICROFILM
BILL OF MATL
DWG LIST
SUPSDS
SUPSD BY
SHEET NO. SHEETS
106908 REV. 1

FIGURE 6

REFERENCES

1. U. S. Army Corps of Engineers, "Flood Hydrograph Package," HEC-1 Computer Program, Hydrologic Engineering Center, Davis, California.
2. National Weather Service, "Precipitation Frequency Atlas of Western United States," NOAA Atlas 2, Washington, D.C., 1974.
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4. U. S. Weather Bureau, "Interim Report – Probable Maximum Precipitation in California," *Hydrometeorological Report No. 36*, Washington, D.C., October 1961 with revisions of October 1969.
5. U. S. National Weather Service, "Probable Maximum Precipitation for California – Calculation Procedures," *Hydrometeorological Report No. 58,* Silver Spring, Maryland, October 1998.
6. U. S. National Weather Service, "Probable Maximum Precipitation for California," *Hydrometeorological Report No. 59,* Silver Spring, Maryland, February 1999.
7. Soil Conservation Service, "Hydrology," SCS National Engineering Handbook, Section 4, Washington, D.C., August 1972.
8. Clark, C. O., "Storage and the Unit Hydrograph," ASCE Transaction, Vol. 110, 1945, pp. 1419-1488.
9. Snyder, F. F., "Synthetic Unit-Graphs," Transactions, American Geophysical Union, Vol. 19, Part 1, August 1938, pp. 447-454.
10. U. S. Bureau of Reclamation, "Design of Small Dams," 2nd Edition, Denver, Colorado, 1973.
11. American Nuclear Society, "American National Standard for Determining Design Basis Flooding at Power Reactor Sites, ANSI/ANS 2.8, 1976.
12. National Research Council, 'Safety of Dams: Flood and Earthquake Criteria," Committee on Safety Criteria for Dams, Water Science and Technology Board, Commission on Engineering and Technical Systems, National Academy Press, Washington, D.C., 1985.
13. Federal Coordinating Council for Science, Engineering and Technology, "Federal Guidelines for Dam Safety," Ad Hoc Interagency Committee on dam Safety, 1979.
14. Federal Emergency Management Agency, "Federal Guidelines for Selecting and Accommodating Inflow Design Floods for Dams," Prepared by the Working Group on Inflow Design Floods, Subcommittee 1, Interagency Committee on Dam Safety, 1986.
15. American Society of Civil Engineers, "Evaluation Procedures for Hydrologic Safety of Dams," A report prepared by the Task Committee on Spillway Design Flood Selection of the Committee on Surface Water Hydrology of the Hydraulics Division of the American Society of Civil Engineers, New York, New York, 1988.
16. Federal Energy Regulatory Commission, "Engineering Guidelines for the Evaluation of Hydropower Projects," Office of Hydropower Licensing, Washington, D.C.

Estimation of Extreme Hydrologic Events in Australia: Current Practice and Research Needs

Rory Nathan, Sinclair Knight Merz, Australia

Introduction

Recently two important documents relating to the assessment of flood-induced failure of dams have been released in Australia. Firstly, Book VI of Australian Rainfall and Runoff (Nathan and Weinmann, 1999) has been revised and updated by the Institution of Engineers, and secondly the guidelines on the selection of acceptable flood capacity for dams was released by ANCOLD (2000).

Book VI provides guidance on the derivation of Large to Extreme Floods for Australian catchments. The focus of the Book VI guidelines is on the estimation of floods with annual exceedance probabilities (AEP) rarer than 1 in 100. As such, they are relevant to the assessment of dam safety. In effect, Book VI describes the basis of the hydrologic techniques required to estimate the range of floods relevant to the selection of acceptable flood capacity for dams. The relevant factors and issues to be considered in the assessment of dam safety are covered in the ANCOLD (2000) guidelines.

One of the salient changes common to both of the aforementioned guidelines is the explicit consideration of risk. In the past, the assessment of hydrologic safety was based on deterministic standards in which the safety of the dam was assessed by reference to its ability to pass a flood of a given magnitude. The new guidelines have moved towards a risk-based approach, in which attention is focused on establishing the probability of the largest flood that can be safely passed by the spillway.

This change in focus from a standards-based approach to a risk-based one has necessitated a revision to the conceptual framework underlying flood estimation practice. In the past we focused on estimating a "probable maximum" type of event to use as a benchmark to compare with the flood capacity of the spillway. The common benchmark used was the "Probable Maximum Flood" (PMF), which was defined as the limiting value of flood that could be reasonably expected to occur (Pilgrim and Rowbottom, 1987). Book VI has introduced the concept of the Probable Maximum Precipitation Design Flood (PMP DF), which is the flood derived from the PMP under "AEP-neutral" assumptions, that is, under assumptions that aim to ensure that the AEP of the flood is the same as the rainfall that caused it. The PMP DF represents the upper limit of the flood frequency curve and it is estimated to have the same AEP as the PMP.

The objective of this paper is to summarise the nature of the methods used to characterise risk for evaluation of dam safety, and to highlight those areas of research that are considered to be of most importance in the short term.

Overview of Flood Estimation Procedures

The procedures can be loosely grouped into three classes of flood magnitude over the range of AEPs under consideration. The type of available information, degree of uncertainty, and hence nature of procedure that can be used in the analysis varies with flood magnitude. The notional classes are summarised in Figure 1. This figure broadly divides the floods and rainfalls of interest into Large, Rare, and Extreme ranges, though it should be stressed that the adopted classes represent a continuum of increasing uncertainty and not discrete intervals.

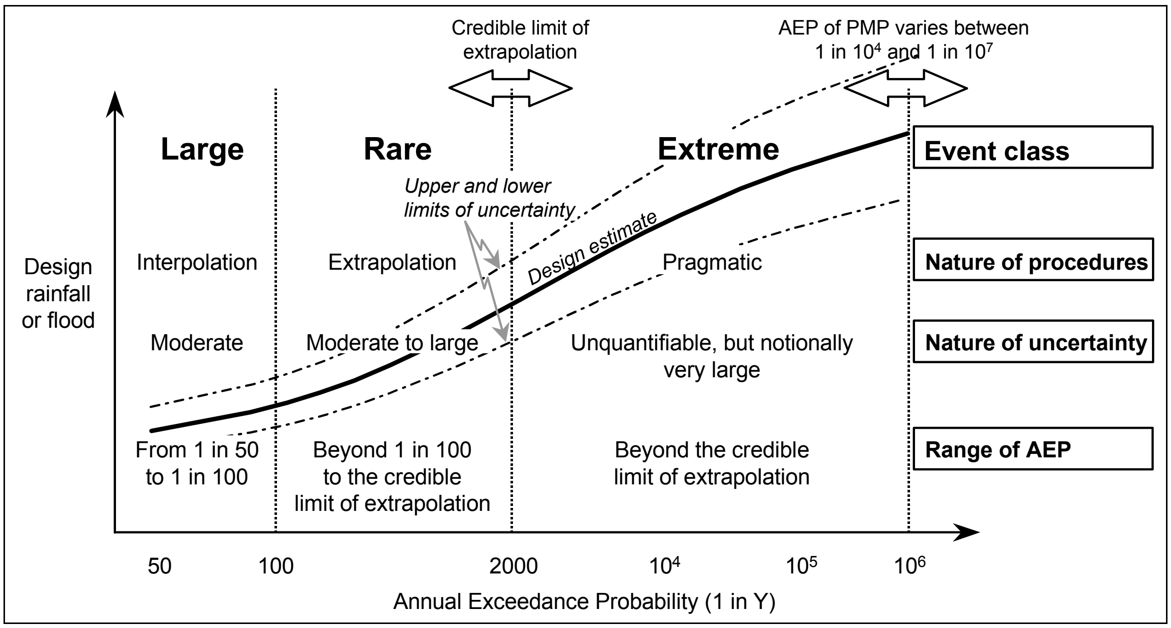

Figure 1: Design characteristics of notional design event classes.

Large Floods

Large floods are intended to represent those events for which direct observations relevant to the site of interest are available. The most common sources of information for this range of floods are the systematic records of rainfalls or streamflow (available either at the site of interest or else transposed from similar catchments), though they include historic information for notable events that occurred prior to the beginning of continuous gauged records. Accessible records in general only extend back to the past 100 years, and thus notionally the AEPs corresponding to this category are limited to events more frequent than 1 in 100.

Large flood estimates are derived by either at-site/regional flood frequency analyses of annual flood maxima, or else by rainfall-based flood event models. The current guidelines (Pilgrim and Doran, 1987) recommend that the annual flood maxima be fitted by the method of moments to the log-Pearson III distribution, though this is currently under review and is likely to be replaced by the use of LH-Moments fitted to the Generalised Extreme Value distribution (Wang, 1997).

The analyses are based on deriving design flood estimates that lie within the range of direct observations, and thus are essentially interpolative in nature. A large body of experience and a great variety of procedures are available to derive flood estimates within this range, and the associated degree of uncertainty in the estimates can be readily quantified.

Rare Floods

Rare floods represent the range of events between the largest direct observations and the "credible limit of extrapolation". With reference to the latter concept, it is worth noting that the term:

- "credible" is used to represent the limit of extrapolation that can be estimated without the use of other confirming information from an essentially independent source; and,
- "extrapolation" is used to denote estimates that are made outside the range of observations that are available at a single site.

The credible limit of extrapolation is dependent upon the nature of available data that can be obtained at and/or transposed to the site of interest. Procedures are often used which are based on the regional pooling of data, and the quality of the extrapolation depends on the strength of the assumptions made.

The notional credible limits of extrapolation for a range of data types in Australia are shown in Table 1. This table indicates the lower AEPs corresponding to both typical and the most optimistic situations, though in most cases the credible AEP limits are likely to be considerably closer to the typical estimates than the most optimistic bounds. At present in Australia using regional pooling techniques the credible limit of extrapolation (for rainfalls) is between 1 in 5000 and 1 in 10 000 AEP.

Table 1: Limit of credible extrapolation for different types of data in Australia (modified after USBR, 1999).

Type of data used for frequency analysis	Credible limit of extrapolation (AEP)	
	Typical	Most optimistic
At-site gauged flood data	1 in 50	1 in 200
At-site gauged rainfall data	1 in 100	1 in 200
At-site/regional gauged flood data	1 in 200	1 in 500
At-site gauged and paleoflood data	1 in 5 000	1 in 10 000
Regional rainfall data	1 in 2 000	1 in 10 000

Extreme Floods

Extreme floods, the third class, represent the range of floods where even a high level of expertise cannot reduce the level of uncertainty substantially, that is the region which borders on the “unknowable”. Estimates of such events lie beyond the credible limit of extrapolation, but are hopefully based on our broadest understanding of the physical limits of hydrometeorological processes. The procedures employ a consensus approach that provides consistent and reasonable values for pragmatic design. The procedures relating to this range of estimates are inherently prescriptive, as without empirical evidence or scientific justification there can be no rational basis for departing from the consensus approach.

Floods over this range can only be derived using rainfall-based flood models. The rainfalls used to input into the models are derived by interpolation between the credible limit of extrapolation and estimates of Probable Maximum Precipitation.

Rainfall-based Flood Event Models

In Australia, the most common method used to estimate a flood hydrograph is by runoff routing models. With this approach, a hydrograph is calculated by some form of routing of rainfall excess through a representation of the storage within the catchment. Runoff-routing models provide an alternative to unit hydrographs. They are not restricted to the assumption of linear behaviour, and in most applications non-linear behaviour is assumed. Most runoff routing models contain spatially-distributed conceptual storages to represent the catchment storage afforded by overland flow paths. Some models lump this overland storage together with the attenuation arising from channel storage, and some models simulate overland and channel storages separately. Probably the most common models used are RORB (Laurenson and Mein, 1997) and RAFTS (Willing and Partners, 1997).

The Book VI procedures are largely focused on the adoption of an *AEP-neutral approach*, in which it is assumed that the estimated design flood characteristic (e.g. peak flood) has the same AEP as its causative design rainfall. In order to satisfy this assumption it is necessary to incorporate representative design values of all inputs and parameters in such a way that they are AEP-neutral. In practice this commonly requires that a designer selects a single representative value from a wide range of all design inputs (such as losses, temporal and spatial patterns, and model parameters), though joint probability approaches are currently being explored to better achieve AEP-neutrality (e.g. Weinmann et al., 1998). With respect to achieving AEP-neutrality for outflow floods from reservoirs, explicit joint probability methods are commonly used (e.g. Laurenson, 1974) to take into account the likelihood that the reservoir may not be full prior to the onset of the flood.

Where suitable rainfall and runoff data are available, the flood event models are calibrated using observed floods on the catchment of interest and, where appropriate, the parameter values are adjusted to help reconcile differences between design values derived from flood frequency analysis and rainfall-based methods. In other cases, design values for the model parameters are estimated from calibration on adjacent gauged catchments, regional relationships, or other relevant information.

Design Rainfalls Inputs

Design rainfalls used as input to the flood event models are derived from a variety of sources (see Figure 2). For Large design rainfalls the depths are obtained from mapped information for durations ranging between 15 minutes and 72 hours. These rainfalls were derived by the subjective smoothing of rainfall quantiles derived from at-site frequency analyses of annual rainfall maxima. Rainfalls up to the credible limit are derived using a regional pooling procedure (Nandakumar et al, 1997) which takes into account the effect of correlation on the effective record length of the combined data sets.

Estimates of Probable Maximum Precipitation (PMP) are provided by a federal meteorology agency (the Bureau of Meteorology). These estimates are based generalised methods, as recommended by the World Meteorological Organisation (World Meteorological Organisation, 1986). These methods use data from a large region and make adjustments for moisture availability and topographic effects on extreme rainfall depths. Estimates of design rainfall depths between the credible limit of extrapolation and the PMP are based on interpolation procedures. These procedures are necessarily pragmatic as they attempts to link estimates based on conceptually different methods and different data sets; the interpolation procedures are not supported by scientific reasoning.

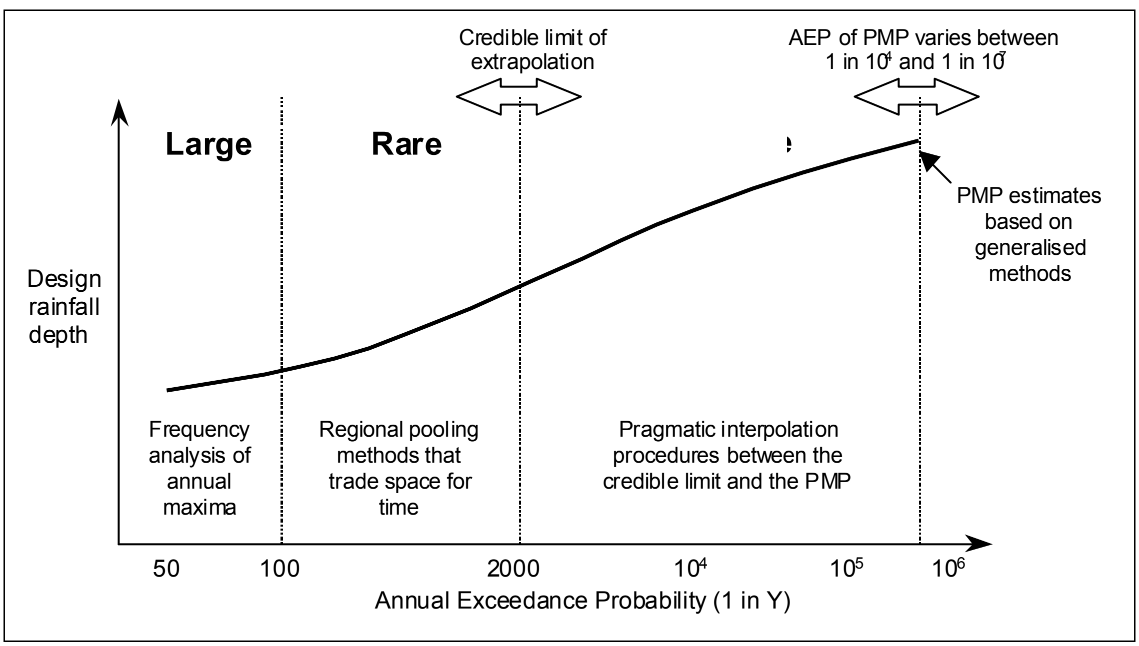

Figure 2: Summary of procedures used to derive design rainfall depths.

Temporal patterns used to distribute the rainfall depths in time are based on methods that were derived explicitly with the objective of AEP-neutrality (Pilgrim et al., 1969; Nathan, 1992). Importantly, “pre-burst” patterns are provided that allow intense bursts of design rainfalls to be converted to storm rainfalls (see next section). Procedures are also provided on how to spatially distribute the rainfalls across the catchment.

Estimation of Rainfall Excess

A loss model is needed to partition the design rainfall input into rainfall excess (runoff) and loss. The most common loss models used are the simple Initial Loss – Continuing Loss (IL-CL) model*,* and the Initial Loss – Proportional Loss (IL-PL) models. The initial loss is that which occurs prior to the commencement of surface runoff. The continuing loss is the average rate of loss, and the proportional loss the average fraction of loss, throughout the remainder of the storm. The continuing loss rate is often conceptualised as an average rate of potential infiltration over the catchment, while the proportional loss rate (equivalent to 1-C, where C is the runoff coefficient) can be understood to be the unsaturated proportion of the catchment which produces very little runoff.

One important distinction made in the application of loss rates is whether or not *design bursts* of rainfall are used or *complete storms*; a schematic diagram illustrating the difference between these two concepts is shown in Figure 3. Design bursts are generally preceded by some lower intensity rainfall (pre-burst rainfall), they do not represent complete storms. Accordingly the larger the rainfall the larger the expected cumulative depth of pre-burst rainfall. This expected variation means that if losses are used with design rainfall bursts then they are decreased in some fashion with increasing rainfall depths. On the other hand, if losses are used with design rainfall storms then the available empirical evidence (Hill et al, 1997) suggests that they may be held constant over the full range of rainfall depths considered.

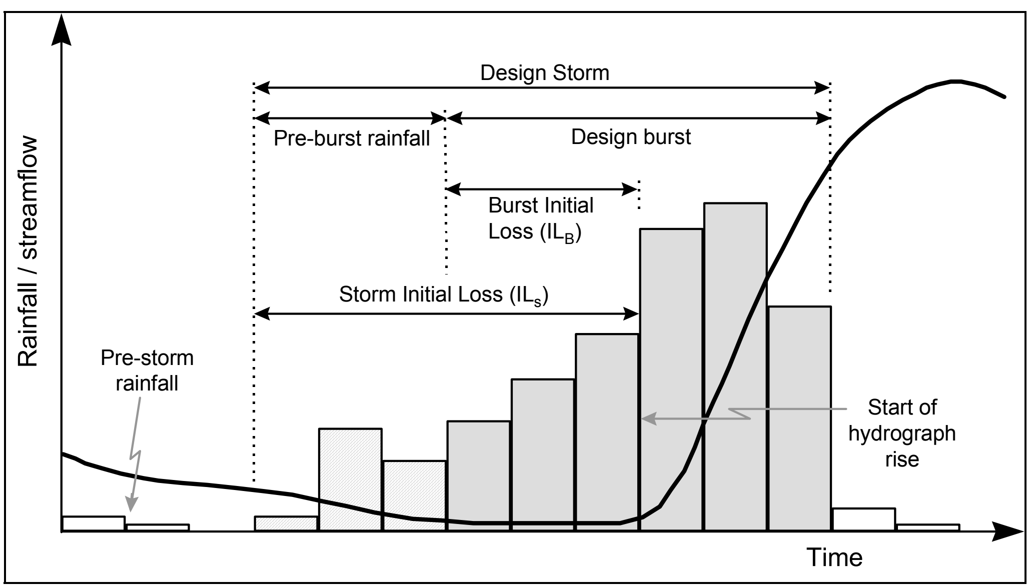

Figure 3: Schematic diagram illustrating concepts used in design loss formulation (adapted from Hill et al, 1997).

Estimation of the AEP of the PMP

Estimation of the AEP of the PMP (and hence the PMP DF) is needed to define the upper end of the frequency curve (Figures 1 and 2). While assigning an AEP to the PMP is inconsistent with the “upper limiting” concept of the PMP, it is recognised that *operational* estimates of PMP are estimates only, and their accuracy is crucially dependent on the validity of both the method and the data used to derive them. Thus operational estimates of PMP may conceivably be exceeded.

The method proposed to assign an AEP to the PMP is based on the review by Laurenson and Kuczera (1999) of a range of procedures developed both in Australia and overseas. The AEP of PMP estimates are considered to vary solely as a function of catchment area (Figure 4), and are consistent with the recommendations of Kennedy and Hart (1984), Pearse and Laurenson (1997) and Nathan et al. (1999). There is considerable uncertainty surrounding these recommendations as they are for events beyond the realm of experience and are based on methods whose conceptual foundations are unclear. It is not surprising that the notional 75% confidence and upper and lower limits are larger than is desirable, though they are regarded as a realistic assessment of the true uncertainty. A probability mass function is provided to allow the incorporation of uncertainty into risk analysis. Although the probabilities are subjective, they do reflect the considerable uncertainty in the AEP estimates.

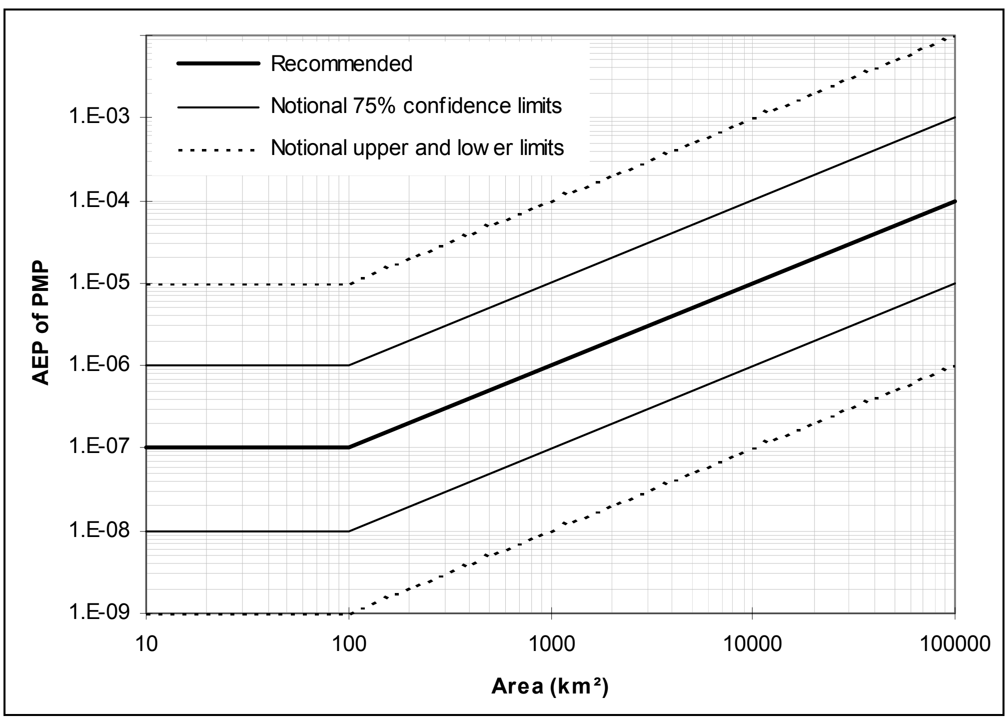

Figure 4 Recommended values of AEP of PMP.

Preliminary Estimates of Rainfall and Flood Frequency Curves

It is recognised that there are many design situations in which preliminary estimates of design floods are required. Accordingly the guidelines allow for the derivation of preliminary estimates using "quick" procedures based on regional information. Full flood frequency curves can be derived using the probabilistic rational method to estimate frequent floods (Pilgrim, 1987) and regional estimates of the Probable Maximum Flood (Nathan et al, 1994) to define the upper end of the curve. Regional prediction equations have also been derived to provide quick estimates of PMP depths (Nathan et al, 1999).

Research Priorities

There are two major areas of research that are considered to be a high priority to address in the short to medium term:

Annual Exceedance Probability of the Probable Maximum Precipitation

The AEP of the PMP defines the location of the upper tail of the rainfall (and hence flood) frequency distributions. The location of the upper tail influences estimates of risk beyond the credible limit of extrapolation, and this is a region of importance when assessing the risk of overtopping failure for many existing dams.

The problem of estimating the AEP of the PMP has been considered a problem for a long time – indeed it is viewed by some as being unsolvable. However, there is some research being undertaken currently in Australia at two different institutions that shows considerable promise: (i) use of joint probability approaches to estimate the likelihood of a PMP occurring anywhere in a homogeneous meteorological region, and (ii) the use of stochastic storm transposition concepts to estimate the conditional likelihood that if a PMP does occur in the region, that it occurs over the catchment of interest (Agho and Kuczera, 2000).

Techniques required to minimise bias in the AEP transformation between rainfall and floods.

If rainfalls are used in event-based models to estimate flood peaks, then in a risk-based context special attention needs to be given to ensuring that the AEP of the incident rainfall is preserved in the consequent flood, e.g. if an estimate of the 1:5000 AEP rainfalls is available from regional pooling, then what considerations are required to ensure that the AEP of the resulting flood peak is also 1:5000.

There are a number of ways of ensuring that this is achieved for frequent floods, but as the AEP of the flood decreases it becomes increasingly difficult to validate. The factors that influence this are many, though possibly the major factors are non-linearity of flood response in overland flowpaths and channels, rainfall losses, temporal patterns, and initial snowpack. Some of these issues can be solved, some are tractable research problems, and some are unlikely to be resolved in the near future. Physically-based models provide a vehicle to explore ways of using physical reasoning to condition extrapolations of flood response, and paleo-hydrological techniques provide another.

Conclusions

Australian guidelines have recently been revised to incorporate a shift towards a risk-based framework for characterising the likelihood of dam failure due to overtopping. They provide both a framework and design inputs for estimation of floods down to annual exceedance probabilities as rare as 1 in 10^4 to 1 in 10^7.

At present in Australia the credible limit of extrapolation of rainfalls is limited to exceedance probabilities of 1 in 5 000 and 1 in 10 000. Estimates of risk beyond this limit are subject to considerable uncertainty and are based on a mixture of engineering pragmatism and physical reasoning. While there is some justification for estimates of the magnitude of PMP depths (and to a lesser extent the resulting floods), the guidelines do provide a rational and consistent framework for characterising risks relevant to dam safety.

The most urgent needs for research are considered to be in the refinement of the annual exceedance probability of extreme rainfall depths, and in the further investigation of factors that influence the bias in AEP-transformation between rainfall and floods.

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CURRENT AND FUTURE HYDROLOGIC RESEARCH NEEDS FOR DAM SAFETY ANALYSIS IN MATURE DAM SAFETY PROGRAMS

By
D.N.D. Hartford[1]

Considerations for Dam Owners

Dam owners have a duty of care to protect the public, property and the environment from harm that might result from their operations. In this regard, the dam owner can be considered to be the creator of the risk and increasingly there are requirements in law for the dam owner to identify the hazards, assess the risks, prepare a safety case demonstrating how the risks will be prevented or otherwise controlled, and set out a safety management system showing how the safety case will be implemented and maintained.

Risk assessment, which provides a structured, systematic examination of the likelihood of harmful events and the associated consequences should the events occur, is the essential anticipatory element that underpins the safety case. Therefore, in the preparation of the safety case and in demonstrating due diligence in risk management and control the quality of the risk assessment is of paramount importance to the owner. **Therefore, research into the quality of the risk assessment process is of obvious interest to dam owners.**

A second very important consideration pertains to the context within which a dam safety decision is to be made. The modern view from the perspective of a risk regulator (HSE, 2001) is that *"the proper use of risk assessment would require inter alia that:*

- *more often than not, the results of a risk assessment should be expressed as a value judgement rather than a number;*
- *the risk problem should be properly framed*
- *the nature and limitations of the risk assessment are understood; and*
- *the results of the risk assessment are used to inform rather than to dictate decisions and are only one of the many factors taken into account in reaching a decision."*

Researching what all of this means and its implications are a second interest to dam owners.

The dam owners risk profile, characterized in large part by the consequences of dam failures for the portfolio, provides a third important consideration which must be accounted for in the risk assessment and decision-making processes. Societal catastrophic loss risk management is different to the other risks managed by dam owners. The rules for decision-making for catastrophic loss risks are also different, as are the representations of the risk. The decision and risk assessment processes used by an owner whose losses are limited or insurable can be expected to be different to those owners managing catastrophic loss risks.

[1] BC Hydro

Fourth, the degree of maturity of the owner's dam safety program will influence the approach to risk assessment and decision-making. Here the term "degree of maturity" is used in the sense of a long track record of demonstrably effective risk identification and risk control as opposed to simply being long established and/or having no track record of incidents yet which in itself does not demonstrate effectiveness in risk management.

It is clear that the actions that dam owners take with regard to dam safety management are governed by a number of complex, interacting and often opposing factors. The prevailing legal, regulatory and societal expectations, business considerations and the owner's values and principles govern dam owner's decision-making processes. Having determined these boundary conditions, the dam owner must establish a decision process that meets the needs of these boundary conditions and also ensures the viability of the operation (be it business or some level of government). The effectiveness, in the sense of assuring that dams are safe enough and legal defensibility of the decision process, where the term legal defensibility is used in its broadest sense, that lead to the conclusions concerning the safety of dams are primary considerations for dam owners.

Context of this Paper

The above suggests that owner's dam safety research needs are multifaceted and driven by the owner's decision process. Given the generally good track record (including economic efficiency - a debate for another forum) of established dam safety practice, it seems reasonable to hold the view that most dam owner's research needs relate to dealing with problems that are beyond conventional engineering wisdom (traditional dam safety practice). Some of the research needs that owners must address are of an engineering nature, others are not, making it necessary to understand where the balance changes from one of engineering dominance of the decision process to one of engineering support for the decision process.

Since the owner is responsible for both ensuring the safety of the dam and the decision process (to varying degrees depending on the regulatory environment) that determines the level of safety of the dam, one can infer that dam safety research needs are fundamentally determined by owner's needs. The regulator is the other principal stake holder and while the regulator's research needs may be the same as those of the owner in some respects, they can be expected to be different in others. Thus owners and regulators dam safety research needs govern the form, nature and future direction of research initiatives.

The need for research

In to-day's challenging business environment research funding is scarce and owners require demonstrable evidence that research is necessary prior to considering funding research work. Research can only be justified if it is necessary or beneficial to improve existing practices or create new practices because existing procedures are inadequate in some way. Therefore, prior to embarking on a research initiative, owners need to identify (or have identified for them) inadequacies (from the perspectives of improved economic efficiency or legal defensibility and due diligence) in the existing state of knowledge and procedures that require rectification.

The view that *"methodologies for estimating the chance of dam failure are poorly developed and, at the present time, do not provide a defensible basis for the conclusive sign off on the safety status of a dam"* (McDonald et al. 2000) provides a basis for concluding that there might be good reasons for owners to question current capability in dam safety risk assessment. The view is supported by recent data collected by BC Hydro, which although carried out to investigate potential dam safety deficiencies, also provided a basis for validating past risk assessments. The National Research Council's report Risk Analysis and Uncertainty in Flood Damage Reduction studies (NRC, 2000) provides further evidence of a need to improve risk assessment capability.

Focus of the paper

This paper, written from the perspective of a commercially focused owner of dams ranging in size and hazard potential from the very small (by any standards) to amongst the largest in the world, reflects the view that dam owner's research needs should be determined through analysis of the present state of affairs in a way that reveals the gaps in current capability, thereby revealing dam owner's research needs.

The need to understand the uncertainties in all important aspects of the inputs to the dam safety decision processes is central to the paper. The manner in which decisions are made under conditions of uncertainty and the underlying bases for these decisions provides direction for examining owner's research needs.

Decision Context

A conceptual form of a dam owner's decision context is illustrated in Figure 1 (Hartford and Stewart, 2001). This framework reflects established dam safety practice that has served dam owners and the public well thus far and permits the extension of this practice to incorporate the emerging realities of explicit consideration of risk issues in dam safety decision-making.

Figure 1 is conceptual in nature and the decision context in any particular case is broadly determined by utilizing the horizontal and vertical axes. Decisions that can be made in terms of building codes or standards established by Government would place in the upper left hand section whereas those decisions where no precedents or standards exist and which involve significant societal concern place towards the bottom right.

Category "A" can be considered applicable to "routine" risk management situations for dams where the application of codes and standards is appropriate. Category B relates to those situations that are less "cut and dried" but where there is general guidance concerning how to implement risk controls, with certain aspects of the risk being unique to the situation at hand. Category "C" can be related to the more complex safety decisions, where the public interest and/or the environment are of paramount importance but where it is necessary to make significant trade-offs between benefits and risks. The risk control measures can be expected to be novel and potentially extremely costly for the risk reduction benefits gained. Societal interest and involvement are potentially high requiring a participatory role for the public. Decisions in this context also include those where the complete spectrum of long-term implications are highly uncertain and potentially devastating. An example is retrofitting dams to meet new safety requirements that have not achieved the status of authoritative good practice, where the retrofit solution to meet a new standard is unique, where retrofit technology does not exist or is unproved, or where serious risk trading obfuscates the decision.

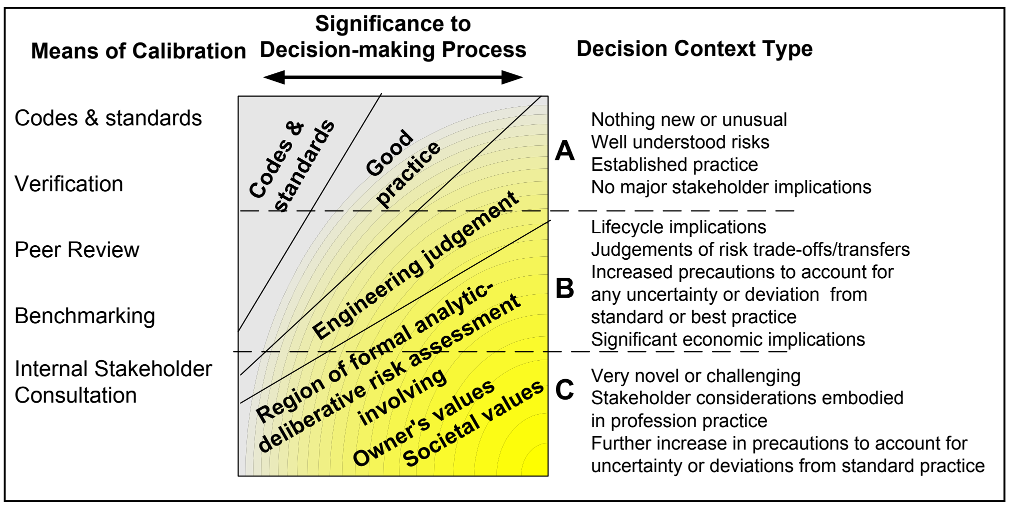


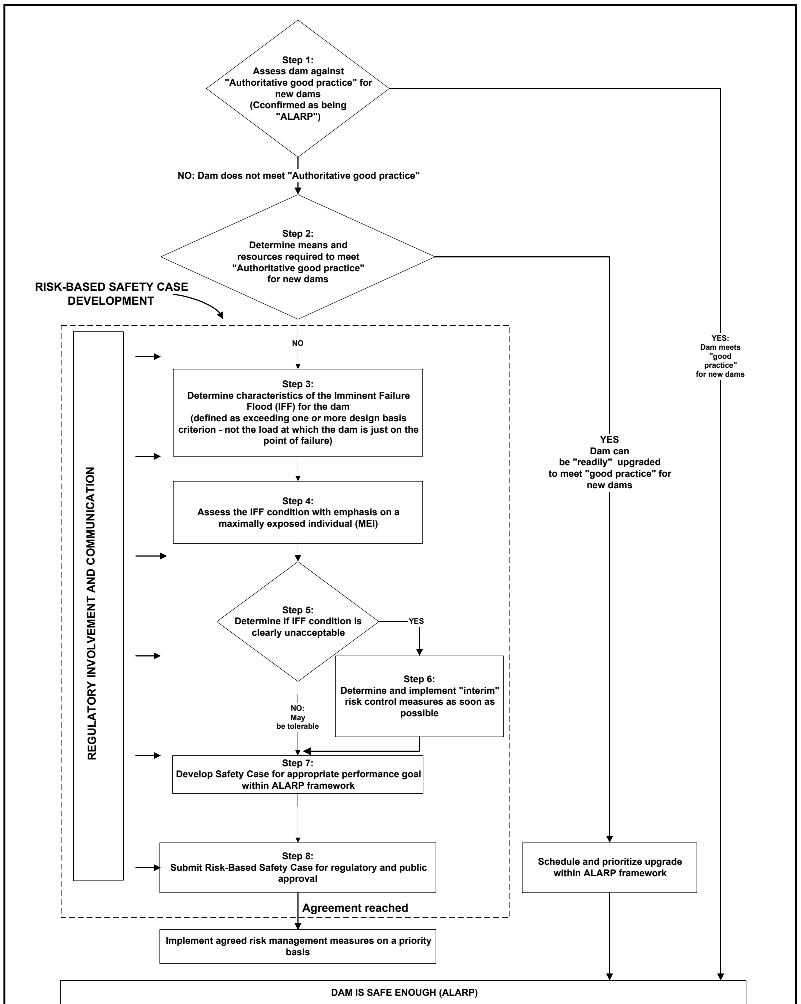
Figure 1. Proposed Decision Context Framework for Dam Safety Decision-Making (Hartford and Stewart (2001) based on UKOOA as reported by Brinded (2000))

Figure 1 provides general guidance for both the establishment and management of a dam safety program as well as the research needs of dam owners with mature dam safety programs. From the perspective of a commercially focused dam owner, there is little value in applying quantitative risk assessment to situations where the decision is to be made in terms of codes and standards and accepted good practice. The need for application of risk assessment increases as the decision context moves through categories B and C towards the bottom right hand corner. It is in this lower region that the research needs of dam owners lie.

Decision Process

The decision process is the second feature of a dam safety program that influences dam owner's research needs. A decision process suitable for decision-making in terms of the modern view of risk assessment is illustrated in Figure 2. The aspects of the process relevant hydrologic research needs are summarized as follows:

1. Use the Precautionary principle where the decision-making process and criteria adopted are such that the actions taken are inherently precautionary, commensurate with the level or risk to individuals, the societal concerns and the degree of uncertainty.
2. Ensure that at a minimum the Inflow Design Flood (IDF) implements authoritative good practice irrespective of situation-specific risk estimates.
3. If there is no reliable base of good practice for ensuring that risks are adequately controlled, a process of risk analysis, evaluation and assessment should be carried out to decide the extent of the risk control measures.
4. Implement risk controls until the residual risk is reduced to the extent that additional measures are likely grossly disproportionate to the risk reductions achieved.



OUTLINE OF PROCEDURE FOR SELECTING FLOOD PERFORMANCE GOALS FOR EXISTING DAMS
(a similar procedure can be followed for earthquakes)

Figure 2. Dam Safety Decision Process

Point 2 above suggests that there is little or no opportunity not to adhere strictly to established practice in selecting the Inflow Design Flood for a dam, with the PMF being the standard for all High Consequence dams. However, this is not the case for at least two reasons:

- What constitutes 'authoritative good practice' for selecting the IDF for a dam remains undefined (see Hartford and Stewart. ibid.); and, much more importantly,
- Accepted dam safety practice, including selection of the PMF as the IDF, has not been submitted to the rigorous tests of risk assessment to determine if they actually provide effective risk control in terms of the As Low As Reasonably Practicable (ALARP) principle.

This is not an argument against selection of the PMF as the IDF for High Consequence dams. Rather, if PMF protection can be achieved, if the associated risks are sufficiently low and if it passes the ALARP test, then there is little basis to argue against it. Thus, rather than assuming that PMF protection is adequate, the proposed approach requires that selection of the PMF be justified in terms of a broader, more comprehensive set of societal values. Conversely, if less than PMF protection results in a very low level of risk and if the incremental cost of achieving PMF protection is grossly disproportionate to the risk reduction benefits gained, then we propose that it is reasonable to expect owners to prepare safety cases aimed at demonstrating that less than PMF protection is appropriate, that society or individuals are not exposed to excessive risks, and that it is worth taking the risk to accrue the associated benefits.

When viewed in this way the decision process is clearly both an enhancement of traditional practice by subjecting traditional practice to the ALARP test, and an advance over traditional practice which provides a basis for decision-making in situations where there are clear difficulties in applying traditional practice. The process has two important features that sets it aside from some contemporary views of risk assessment:

1. By embodying traditional practice this risk assessment approach to decision-making is not presented as an alternative to traditional practice.
2. The decision process is not a technocratic one whereby the decision is made in some mechanical way by estimating the risk and comparing the estimate with a criterion (e.g. expected value or F-N curve).

Feature 1 means that the view that *"the immediate objective of many of those advocating risk assessment in current practice is to provide defensible design solutions as economic optima that are likely to be of lower cost than those that result from a traditional engineering standards approach to design"* (ANCOLD, 1994) does not apply. Feature 2 means that when applying risk assessment, it is necessary to go significantly beyond the view presented in guidelines in the early 1990's (e.g. ANCOLD, BC Hydro) as decisions concerning the tolerability of risk cannot be made in such a simple way.

Decision Basis

The third feature of the decision process that drives dam owner's research needs is the decision basis which includes the parameters required to make the decision. The risk to the maximally exposed individual is one such parameter. People who are exposed to risks are becoming increasingly interested in the nature and degree of the risk and often wish to be in the position to make choices concerning their exposure. To address this important public concern and for the purpose of simplicity at the moment, it can be assumed that the maximally exposed individual (MEI) has no means of escape and spends his/her entire life immediately downstream of the dam. Hence, it can be assumed that the risk to the MEI is equal to the probability of dam failure. Again this simplification is conceptually sound for the purposes of this proposal because it overestimates the risk to any individual downstream of the dam. Further, a more realistic characterization of the risk to individuals downstream of dams is now available (Assaf and Hartford 2001), and this more advanced approach can be used if required.

Other parameters include the various measures of societal risk, including the risk to the population downstream of the dam, property damage, environmental degradation, and broader socio-economic activity impacts.

To be meaningful for decision-making, it is important that the measure of risk to the individual include a full characterization of the uncertainty in the estimate of risk. The measure of uncertainty can be presented as a mean value with an associated probability distribution, or as a single value obtained by integrating over the probability distribution. This measure of uncertainty in the risk estimate (Figure 3) is something that is usually not found in contemporary applications of risk assessment, although some might argue that it is done in some cases where Monte Carlo simulation is used. The need to fully characterize the uncertainty on the risk estimate and the associated need to be able to demonstrate that the estimate of risk and associated uncertainties have been made in a scientifically valid and legally defensible way provide a basis for determining the research needs of dam owners.

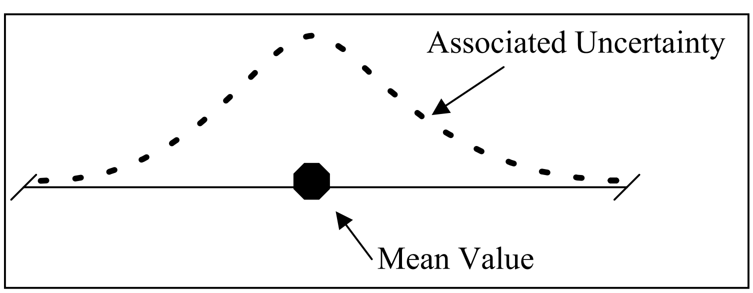


Figure 3 Full Characterization of the Risk

The risk estimate and associated uncertainty can then be incorporated in a decision framework such as that of the Health and Safety Executive approach to judging the tolerability of risk (HSE, ibid.) is of the form illustrated in Figure 4.

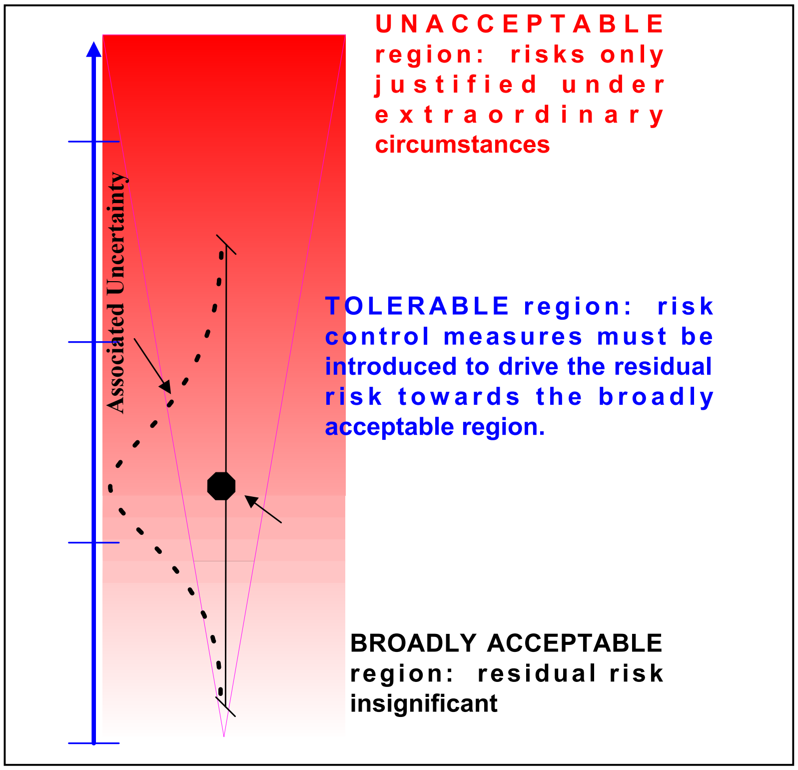


Figure 4. Tolerability of Risk (HSE, 2001)

A Basis for Determining Research Needs in Dam Safety Analysis

It is possible to determine the research needs by examining how well the inputs to and outputs from the decision process meet requirements for quality, scientific validity, verifiability and legal defensibility. The quality and validity of the risk estimates as illustrated in Figure 3 and the reliability and legal defensibility of the decisions based on these estimates as utilized in the decision process of Figures 2 and 4 are dependent on the quality and robustness of the procedures used to generate the risk information illustrated in Figure 3.

The determination of the quality and reliability of the risk estimates can be determined through analysis of the underlying procedures and the process used to integrate the outputs of the individual procedures. This entails decomposing the risk measure, including associated uncertainties into its fundamental parts and examining the robustness of each of the constituent procedures and the robustness of the integration process. Clearly, if each constituent procedure and the method of integration are robust and meet the accepted norms of broad professional acceptability established in terms of the time tested approach of open challenge, and have not been overtaken by modern scientific advances (cannot be improved upon at the moment) little in the way of research can be justified.

However, should it be revealed that the capability of characterizing the risk in a scientifically valid and legally defensible way, is somewhat questionable, or that recent scientific advances permit a marked improvement in the quality and economic efficiency of the dam safety assurance process while not reducing safety standards, then a basis for justifying research projects exists.

While risk analysis may be based on past experience, with an implicit assumption that the past is a good predictor of the future, the relatively small number of dam failures in the historic record together with the lack of homogeneity across the population of dam failures mean that statistical methods cannot be relied on as a basis for assessing the risks posed by individual dams. Therefore, the risk analysis process involves constructing a description of how events may develop from a given initial state. This description is termed a model of the behavior of the different elements of the system under the various conditions that can exist. Usually this modelling endeavor will require the construction of a number of sub-models for the different sub-systems and elements. Linking all of the sub-models together constitutes part of the overall analysis process.

One possible "process" model is illustrated in Figure 5 (Hartford et al. 2001).

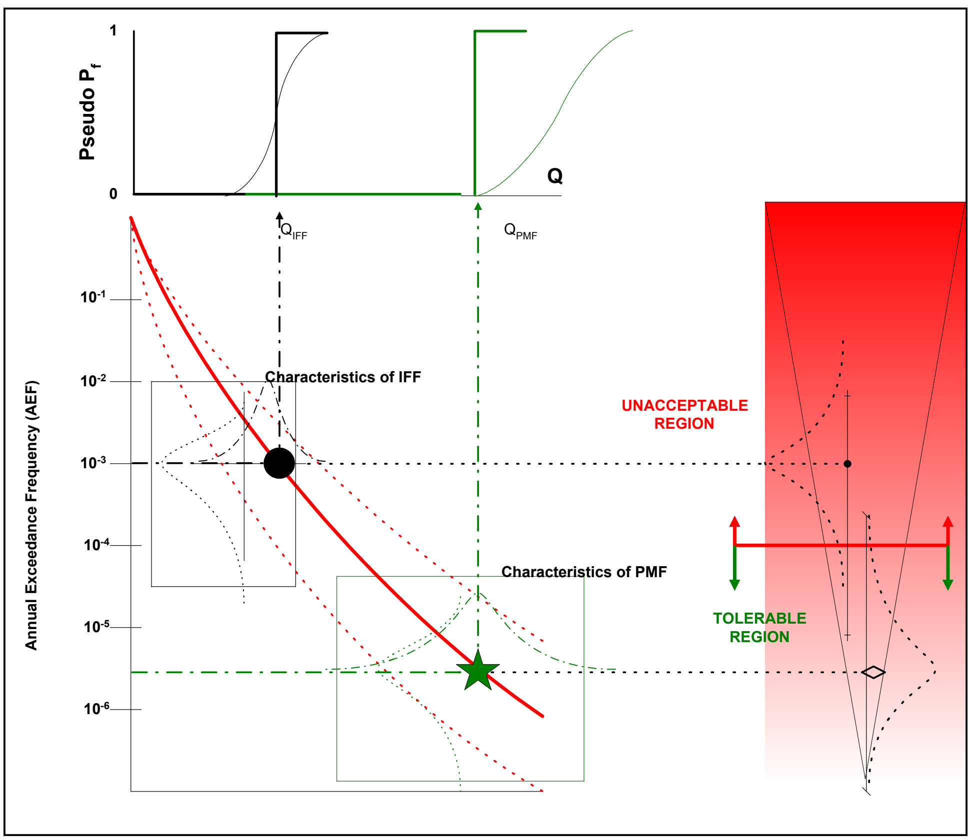


Figure 5. Process model for analyzing risk

Figure 5 which illustrates a model to make a conservative estimate of the risk to the individual, (it does not present all of the sub-models that are required to fully characterize all of the consequences of dam failure and associated uncertainties), provides insight into the form of the outputs of the sub models and provides a guide as to what attributes of these sub-models require verification.

The question as to how reliably existing procedures generate the outputs of the sub-models needs to be answered as does the question as to how reliably existing procedures integrate all of the sub-model outputs to generate the model outputs. These questions are important to owners who are responsible for risk control and to regulators who need to be satisfied that the owner's risk control measures are reliable and that the risk assessment process used is genuinely informing the decision process. These questions represent two topic of research of particular interest to owners who, for legal due diligence reasons need to have substantial indicia of reliability of all aspects of the processes that generate the risk information.

Fundamentally this requires demonstrating the scientific validity of the procedures where the term science refers to knowledge ascertained by observation and experiment, critically tested, systemized and brought under general principles. **In this regard, researching the scientific validity of risk analysis and risk assessment procedures is of paramount importance to owners concerned about legal defensibility.**

In its decomposed form, the overall model can be considered to comprise models that permit construction of the risk measure by means of a process of combinatorial logic that includes full characterization of all uncertainties in the models and the input parameters (Figure 6)

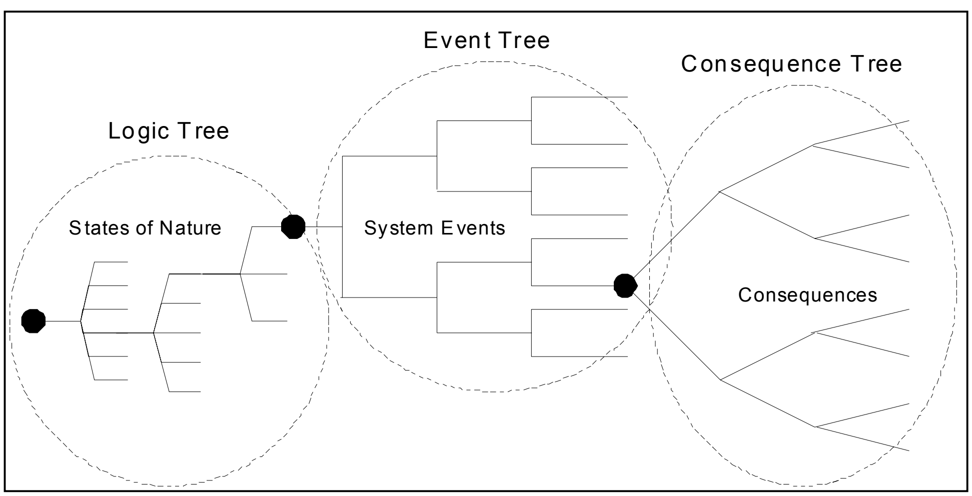


Figure 6. Conceptual form of the logic the fully decomposed form of the model

Investigations into the scientific validity of the overall risk assessment process necessarily requires investigation into the scientific validity and completeness of the supporting sub-processes. **Therefore there is a need to demonstrate, through research, the extent to which the all aspects of the hazard and the performance of the dam under the influence of the hazard are fully characterized.**

Full Characterization of the Hazard

Figure 7 illustrates the form of the fully characterized hazard in terms of the magnitude of the hazard and the associated uncertainties.

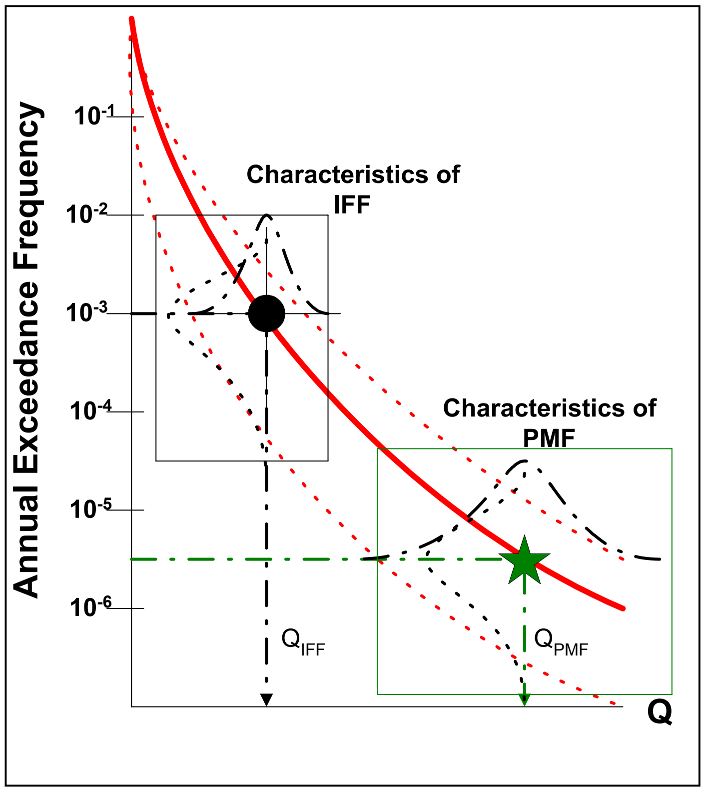


Figure 7. Fully characterization of the hydrologic hazard

Figure 7 provides an indication of the research needs for the hazard as in principle it is desirable to be able to reliably generate scientifically valid characterizations of the magnitude and probability of the hazard over the full range of physically possible realizations of the hazard. If the hazard cannot be fully characterized in this way then there may be a basis for owners supporting research aimed at completely (to the extend that is possible) characterizing the hazard.

Full Characterization of the Dam Response

The uncertainties in the response of the dam to the applied loading provides a second area of research interest to dam owners (Figure 8). From a safety management perspective and with reference to Figure 2, the magnitude of the "gap" between the existing design and the desirable situation is of paramount importance. Figure 8 also provides a perspective on the usefulness of researching the uncertainties in the response of the dam under the influence of the hazard. It appears from Figure 8, that the uncertainties in the dam response only represent a small part of the total uncertainty in the risk estimate. If this is the case, then research into the nature of the hazard is a more fruitful endeavor than research into the dam response.

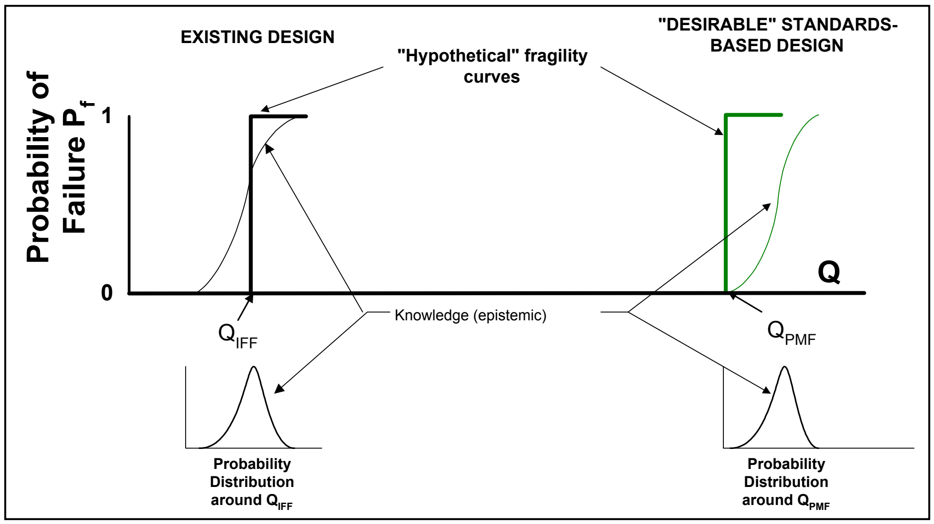


Figure 8. Characterization of Uncertainties in dam response

However, the fragility curves in Figure 8 may be somewhat deceptive as it appears that they mask the manner in which the probability of failure under static loading conditions might be represented in a risk analysis. Figure 8 appears to provide one "key" to estimating the probability of failure by piping, the second "key" being the logic and mathematics of the construction of epistemic probability distributions. In this regard, we can now propose that the fragility curves for the hydrologic hazard should be constructed over all loading conditions from the annual (normal) through to the very extreme as illustrated in Figure 9.

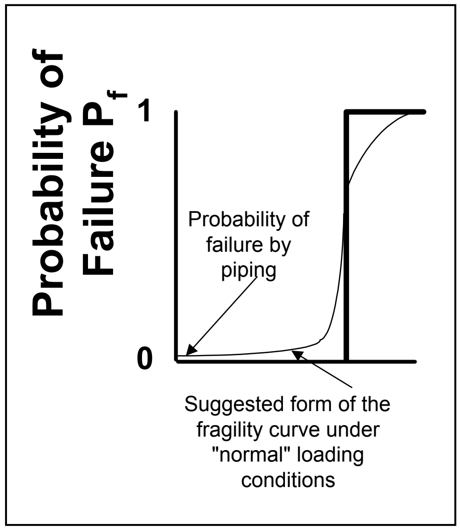


Figure 9. Suggested representation of the probability of failure under normal hydrologic loads

This said, the debate around this matter is one for the geotechnical engineers as the uncertainties in the hydrologic hazard under normal loading conditions are the least problematic from a characterization perspective.

Full characterization of the consequences of dam failure

There is significant scope for research into physically-based modelling of the consequences of dam failure. Two dimensional dam breach modelling, advances in artificial intelligence (AI), digital terrain mapping, GIS systems and virtual reality modelling provide powerful tools that are helpful in this endeavor.

Fundamentally it is desirable to that subjective 'engineering judgments' that usually constitute substantial proportions of dam breach consequence analyses be replaced by with a physically-based procedure that provides a transparent basis for making inferences concerning the range of possible outcomes. A key objective, consistent with the advice of the National Academies (NRC, 2000), is that *"the likelihoods of consequences* (risks) should be *estimated using scientific reasoning from data"*. Since loss of life data from dam failures is scarce, it is necessary to generate synthetic data from simulations that are based on realistic models of the situations that might evolve. Good practice in an endeavor of this nature is to ensure that it is possible for peers to review and if necessary reproduce all calculations. This requires that the basis for the models and the inherent calculation procedures be fully specified and the ingredient data made available (Cooke, 1991).

Outputs from a physically based model are of the form illustrated in Figure 10.

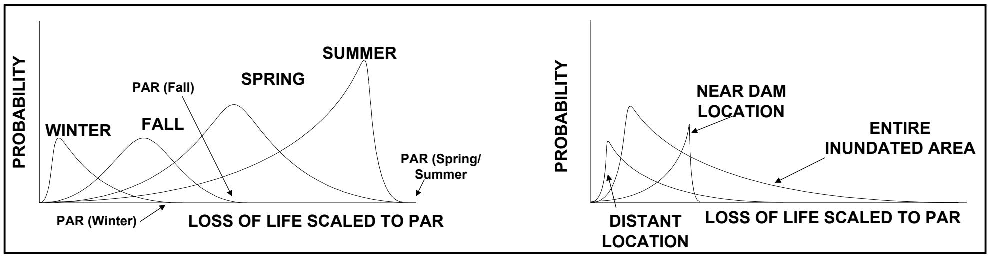


Figure 10. Probability distributions of loss of life from dam failure generated by physically-based models

The need for research in this area stem from three sources. First, from an emergency planning perspective these new modelling techniques can be used to simulate the various dam breach emergency scenarios that possibly unfold. Second, from the perspective of determining societal risk, statistical methods of estimating the loss of life from dam failures cannot be used to develop realistic probability distributions describing the full range of possible loss of life from dam failures because the historic record for each dam represents just one of a very large number (0 to the Population at Risk) of possible outcomes. Third, by accounting for the spatial and temporal variation of everyone in the vicinity of the dam breach and not just those in the inundated area, these models permit simulation of the risk to individuals making it possible to characterize the risk to individual members of population groups

In addition to physically-based modelling of life safety considerations, the technology now exists to rapidly and efficiently determine the property damage on a structure-by-structure basis. The computational capability now exists to maintain up-to-date inventories of everyone and everything that might be impacted by a dam failure.

“Detailed” (Rigorous) vs. “Simplified” Approaches to Risk Analysis

In recent years there has been some but not sufficient discussion on this potentially divisive matter, but unfortunately it has not received sufficient attention. There is a very significant possibility that this ongoing debate concerning ‘rigorous’ and ‘simplified’ approaches could degenerate into a serious dispute between the two ‘schools of thought’. This would be unfortunate and every effort should be made to prevent it from happening while at the same time fostering the difficult debate that is necessary to resolve any differences of opinion that might exist.

However, regardless of which view one holds, there is really no basis to argue against the view that both rigorous and simplified approaches to estimating risk should be validated, i.e. demonstrated as being a reasonable and realistic simplification of reality, before being relied upon in risk assessment.

Since any rigorous analysis is an inevitable simplification of reality, the reasonableness of the approximations and simplifications introduced to permit a less rigorous analysis of the same problem should be demonstrated. Therefore, any simplified approach to risk analysis must be based on a more complex analysis process. In cases where the 'simplified' approach is not based on a more complex approach, then the problem that is the subject of the analysis is a simple problem and the 'simplified' approach is 'de-facto' the complex approach. Here it becomes necessary for practitioners to be explicit about what they mean by 'simplified' or 'practical' approaches as well as the validity of any conclusions that might be drawn from the analysis.

The development of any simplified approach entails the following steps:

1. Develop a solid understanding of the physical processes involved.
2. Develop a robust, theoretically sound and scientifically verifiable theory or model of the physical process recognizing that it is a simplification of reality.
3. Introduce additional valid simplifications and approximations that do not compromise the theory or modelling process

Therefore, in principle, there are no grounds for divisive debates between advocates of 'rigorous' and 'simplified' approaches. In fact, the proponents of simplified approaches have even more work to do initially as it is not generally possible to arrive at 'stage 3' above without first completing stages 1 and 2, unless of course stages 1, 2 and 3 are one and the same. In practice, there may be grounds for debate if the simplified approaches are not demonstrated as being reasonable simplifications of the actual problem in hand. However, such a debate is not one of 'rigorous' vs. 'simplified' rather it is one of values which reflects the extent to which there are differences of opinion concerning the extent to which scientific correctness, validation and verification is necessary.

Obviously this position might be misinterpreted as opposition to "practical" approaches to risk analysis by advocating scientific correctness, validation and verification. If the so called "practical or pragmatic approach" involves not conforming to the principles of scientific inference and probabilistic reasoning, then it is difficult to demonstrate that such "practical" approaches would lead to legally defensible decisions and safety management actions. In this regard, a simplified approach developed in terms of the three steps outlined above remains faithful to these fundamental principles of risk analysis. Therefore, if the terms "practical" and "pragmatic" are used in the sense of "what is realistic" as opposed to "what is cheap and easy to perform", then "practical" approaches are in fact the 'simplified' approaches described above.

One desirable attribute of scientific defensibility of risk analysis is it entails the building of rational consensus, an approach that has evolved over the centuries to compensate for the fact that, "scientific proof" is notoriously fickle (Singh, 1997). These scientific principles also find application in subjective probability although traditional scientific method does not explicitly accommodate the use of "subjective probability" as scientific data. In principle, the differences between "simplified" and "rigorous" analyses should only relate to the extent to which uncertainty is described and the degree of defensibility required. How far one goes in characterizing uncertainty, and ensuring defensiblity is, in part, a value judgement, either the owner's values and/or the values of society and in part a professional matter where engineers are duty bound to comply to their codes of professional practice.

Risk analysis problems are very often complex and difficult. Their simplification, if done without thorough understanding can lead to false results and not approximate results. Importantly, the analysts might not even realize this. There is considerable danger that analysts are often ill equipped to distinguish between adequate and correct simplification and unacceptable trivialization.

A Comment on the Science of Risk Assessment

The science of risk assessment should not be confused with scientific research. The scientific approach to risk assessment involves the application of scientific principles of analysis in the gathering of data and in the synthesis of all facets of the existing knowledge of the dam including its expected performance under all existing and future conditions. It is through the application of scientific analysis principles that risk assessment derives its systematic features. Since risk pertains to uncertainty and since uncertainty pertains to the state of knowledge and since knowledge pertains to science, it seems reasonable to view the analysis of risk as fundamentally a matter of scientific inquiry. For engineered systems such as dams, the analysis of risk involves the application of scientific analysis principles to reveal the state of knowledge of the performance characteristics of the dam system.

In its deliberations on *"Understanding Risk"* the National Research Council (NRC, 1996) noted that: *"Structuring an effective analytic-deliberative process for informing a risk decision is not a matter for a recipe. Every step involves judgement, and the right choices are situation dependent. Still it is possible to identify objectives that also serve as criteria for success.* These objectives and criteria are: *Getting the science right; Getting the right science; Getting the right participation; Getting the participation right,* and *Developing an accurate, balanced and informative synthesis.*

This then raises two issues for dam owners, the research need to get the right science for the risk problem in hand and the need to get the science right.

The scientific approach to risk assessment does not exclude empirical data, personal experience of the phenomena involved and sound judgement. Rather, they are essential elements of the scientific approach, but they are not in themselves sufficient to construct the probability distributions. Certain branches of mathematics, logic and theories of the physical processes involved are also required to construct coherent, properly conditioned probability distributions which are determined through the process of scientific inference.

The probability distributions are logical constructs of the state of knowledge expressed in mathematical form, mathematics being the language of science. While the inputs may well, and usually do include subjective elements, it has been demonstrated (Howson and Urbach) that the process of constructing scientifically valid probability distribution is entirely objective. According to Howson and Urbach, *"there is nothing subjective in the Bayesian theory as a theory of inference: its canons of inductive reasoning are quite impartial and objective."* The Bayesian approach to scientific reasoning provides the fundamental rules for inferring probability distributions from elementary knowledge (e.g. data). They note that *"the probabilities might be personal, but the constraints imposed on them by the condition of consistency are certainly not."*

The importance of demonstrating the scientific validity or the results of a risk analysis should not be underestimated. If the results of a quantitative analysis are used as a basis for dam safety decisions, then the legal defensibility of these decisions will rest in part on the scientific validity of the analysis method. In this regard, it is valuable to reflect on the admissibility of expert testimony in US Federal Courts, because in March 1999, in the case Kumho Tire Co. v. Carmichael, the Supreme Court held that trial judges have a responsibility under Federal Rule of Evidence 702 (3) to ensure that all expert testimony must be based on reliable scientific theories - even if the expert witness is not a scientist (Ridenour, 1999).

The implications of this case are very significant. Previously in 1993, in the Daubert case, the Supreme Court found that that, *"in examining the admissibility of scientific testimony, trial judges may exclude expert testimony if the judge decides that an expert scientific witness' theory has not been or cannot be tested; if it has not been peer-reviewed or published; if the error rate of the theory or technique is unknown and if low-quality standards, or no standards, were in use during the testing or operation of the theory or technique in question.*

In other words, the Supreme Court cracked down on the use of junk science and crackpot theories by expert (often paid) witnesses in federal courtrooms, even when the expert witness claims only technical or other specialized, rather than purely scientific, knowledge."

According to Ridenour, *"in Kumho Tire, Justice Breyer noted that Rule 702 "makes no relevant distinction between 'scientific' knowledge and 'technical' or 'other specialized' knowledge" in expert testimony. Furthermore, said Breyer, it would prove difficult for judges to administer rules that "depended upon a distinction between 'scientific' knowledge and 'technical' or 'other specialized' knowledge." As a result, he said, Daubert's rules allowing judges to judge the reliability of scientific expert witnesses should also apply to expert witnesses claiming only technical or other specialized knowledge.*"

Clearly, there are grounds for dam owners (including those outside the United States) to determine the implications of the Daubert and Kumho Tire rulings in relation to the legal defensibility of dam safety decisions based on the results of risk analyses. It is worth noting that the debate about the process for generating probabilities is about as old as the discipline itself. The reason for the development of the probability calculus was to transform the early seventeenth century laws of probability from the intuition and experience of gamblers to a set of mathematical rules that more accurately describe the laws of chance. Even though Blaise Pascal was capable of developing an answer to the gambling problem posed to him by the professional Parisian gambler Antoine Gombaud, the Chevalier de Méré, he collaborated with the reclusive Pierre de Fermat to speed up the process of obtaining a rigorous solution to the problem. In doing so, they were led to the more subtle and sophisticated questions related to probability. Much was understood about the nature of these problems in the 17th Century, however their resolution provided immense challenges for philosophers until the end of the 20th Century.

One does not normally associate Fermat's name with the probability calculus but, according to Singh (p. 43), "*together, Fermat and Pascal founded the essential rules that govern all games of chance and that can be used by gamblers to define perfect playing and betting strategies. Furthermore, these laws of probability have found applications in a whole series of situations, ranging from speculating on the stock market to estimating the probability of a nuclear accident.*"

However, it is vitally important that the mathematics of probabilistic analysis be correct because, as described by Singh, *"probability problems are sometimes controversial because the mathematical answer, the true answer, is often contrary to what intuition might suggest. The failure of intuition is perhaps surprising because 'survival of the fittest' ought to provide a strong evolutionary pressure in favour of a brain naturally capable of analysing questions of probability. A talent for analysing probability should be part of our genetic make-up, and yet our intuition misleads us."* In short, the human brain is not equipped to construct probability distributions through some internal (subjective) cognitive process.

The issue of using correct logic in assigning probabilities can be outlined as follows: According to Cooke (ibid.), "*Arguments that are valid when the premises are known with certainty are not 'almost valid' when the premises are 'almost certain'. Premises that are equivalent when known with certainty are not 'almost equivalent' when the premises are 'almost certain'. Rather, discontinuities arise and just the slightest bit of uncertainty can change a valid argument into an invalid one or can make equivalent propositions inequivalent."* (See Cooke, Chapter 3 for an explanation as to why probabilistic reasoning is much more difficult than deterministic reasoning.)

The process of correctly handling uncertainty is notoriously difficult and there are numerous examples of relatively simple probability problems in everyday life where elementary errors in logic are made even by very knowledgeable people. It is also well known that uncertainty also plays tricks with one's intuition with the result that intuition can't be relied on in constructing probability distributions. The only way to guard against making these errors and avoiding the pitfalls inherent to reasoning under uncertainty is to ensure that the procedures used are mathematically sound. Legal defensibility follows directly.

Against this background, there is no reason, apart perhaps for reasons of cost, that the scientific validity of dam safety risk analyses cannot be revealed by explicitly describing the logic used in the process of constructing the probability distributions. There is nothing subjective about logic.

Conclusions

On the basis of the above, it can be concluded that dam owners research needs can be broadly grouped into two categories:

1. Research into the physical nature of the phenomena involved, the full characterization of all associated uncertainties and the development of new/better theoretical "Type A" predictive models (Lambe, 1973) to assist in the endeavor of risk characterization.
2. Research into the quality and the reliability the analytical processes and procedures used to inform dam safety decision-making, and,

Concerning point 1, hydrologic research initiatives should be carried out within the context of the "whole process" with proper consideration of the links between sub-processes and the procedures used to integrate the outputs of the various sub-models. The suggested method of characterizing the flood hazard is fully compatible with contemporary procedures for probabilistically characterizing earthquake hazards. In the light of Figure 9, **it may now be possible, at least in principle to estimate the risks for static failure modes, floods and earthquakes in the same fundamental way thereby permitting a unified way of estimating the total risk posed by a dam.**

Uncertainty in hydrologic hazards should be fully characterized over the full range of loads as, depending on the shape of the dam response fragility curve, the loading conditions substantially less than the PMF could be a significant contributor to the total risk.

Research into the manner in which all forms of probability distributions that enter the risk assessment should be conducted, with the view to ensuring that the practice of risk estimation is robust and scientifically valid.

The matter of the extent of the detail in a risk analysis requires considerable research to ensure that appropriate guidance is available concerning the level of rigor required in the analysis process for defensible decisions. However, provided the "less detailed" method is a valid simplification of the "fully detailed" method, then "less detailed methods can be used with some known confidence. The "science of simplification" of complex analysis problems is itself complex and worthy of research in its own right.

Concerning point 2, there is presently no basis for owners to hold the view that methods are available to fully and reliably quantify the risk for all hydrologic failure modes. In fact suggestions that methods are available to estimate the risks for dams for all failure modes have the potential to seriously hinder the funding of much needed research. Consequently proponents of risk assessment must be very careful in the way that they present their view of the current capability as there is no incentive for owners to invest in research if in fact sound methods are available to estimate the risks for dams for all failure modes. On the matter of quality and reliability of the risk assessments, owners need to know how well calibrated the process and the people using it actually are. Reliance on the "ipse dixit" of the proponent is simply inadequate, rather **substantial indicia of reliability and well designed quality procedures for verification and validation purposes will have to be developed to assure credibility and legal defensibility of the risk assessment and decision-making processes. Against this background there is good reason for research into how best to implement the scientific approach to estimating probability distributions for dam safety assessments.**

Returning to McDonald et al's observation (McDonald et al, ibid.) *"methodologies for estimating the chance of dam failure are poorly developed and, at the present time, do not provide a defensible basis for the conclusive sign off on the safety status of a dam"* it is necessary to debate whether the analysis process presented in this paper will ultimately provide the basis for conclusive sign-off on the safety status of a dam in terms of the modern view of risk assessment as outlined by HSE (HSE, ibid.). **Of course McDonald et al's observation creates another line of research that has not been discussed in this paper, specifically, if "methodologies are not adequate for the conclusive sign off on the safety status of a dam", then precisely what can the results of a contemporary risk analysis be used for and with what degree of confidence?** Perhaps this question alone is worthy of particular and urgent informed debate as the answer is not at all obvious and yet an answer must be found before risk assessment techniques can be used with any confidence in dam safety decision-making.

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New Developments and Needs in Site-Specific Probable Maximum Precipitation (PMP) Studies

By

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Current Procedures

Probable maximum (PMP) values are theoretical values that represent the maximum rainfall possible at particular geographic locations during a certain times of year assuming no change in climate. Historically it has been recognized that the technology needed to theoretically determine PMP values is not available. The procedures that have been developed rely on analyzing the largest observed storms and applying standard procedures to compute extreme rainfall values that provide the basis for estimating PMP values for the geographic region surround the historic storm location.

Extreme Rainfall Storm Identification and Analyses

This procedure is based on having a reliable inventory of all historic extreme storms that have occurred over the region that is "geographically and climatologically" similar to the location being evaluated. Historically the Corps of Engineers, Bureau of Reclamation and the Weather Bureau (currently National Weather Service(NWS)) have conducted extreme storm searches and storm studies for the largest storm identified. These are detailed analyses that provided extensive information on the storm meteorological characteristics and the resulting rainfall amounts, timing and spatial patterns. During the past several decades, these storm searches and storm studies have not been completed and site-specific PMP studies are required to perform storm searches and storm analyses to update the historic extreme storm rainfall data base for the geographic region around the drainage basin being studied. These storm searches and storm analyses are provided by the government agency or consultant performing the site-specific PMP study. The results provide a partial update to the historic storm analyses data base but are not systematically added to the publicly available storm studies archives at the NWS and the Bureau of Reclamation. For most geographic regions, extreme storm rainfall events are not systematically identified and the resulting rainfall characteristics are not evaluated.

Procedures and Analysis Technologies used in PMP Studies

The initial task in performing PMP studies is the identification of extreme storm events. During the first half of the last century, there appears to have been considerable effort expended on the identification of extreme storm events as soon as possible after they occurred. For the largest of these storms, teams were dispatched to the storm location to collect additional rainfall information to aid in storm analyses.
During more recent years, identification and study of extreme rainfall storm events has not accomplished as extensively. Where there is particular interest, storm studies have been completed, e.g. Tropical Storm Alberto in Georgia 1994 and Fort Collins, Colorado 1997.

Once extreme rainfall producing storms have been identified, the rainfall amounts and patterns need to be evaluated. Isoheytal analyses of the rainfall amounts are developed along with mass curves for rainfall at locations with the heaviest rainfall. Depth-area-duration analyses (D-A-Ds) are completed to quantify the amount of rainfall that fell over various areas sizes for various durations. These analyses become the basis for describing the rainfall that actually resulted from the historic storm as well as estimating the maximum rainfall that the storm could have produced.

Standard procedures have been developed to increase observed extreme rainfall amounts to estimate the maximum rainfall potential for each historic extreme rainfall storm. This procedure identifies dewpoint temperatures that are associated with the air mass that provided the atmospheric moisture to the storm that was converted to rain on the ground. A climatology of maximum dewpoint temperatures is used to determine the maximum dewpoint temperature that could have potentially have been associated with the storm and could have potentially contributed to an increase in the rainfall. The current climatology for maximum dewpoint temperatures for the US was published in 1965 and provides maximum observed dewpoint temperatures. It was developed from a limited data base using procedures that are not well documented. The most recent Hydrometeorological Reports (HMR 57 and HMR 59) as well as recent site-specific PMP studies have developed updated climatologies to provide values for maximum dewpoint temperatures. These updates provide regional climatologies and use various methods to compute the maximum dewpoint climatologies used in each study.

Historically 12-hour persisting dewpoint temperature values are used in the PMP procedure. This value provides the maximum dewpoint temperature that has persisted for 12 hours or in other words, the minimum dewpoint temperature that occurred during the 12 hour period. At least one regional PMP study has use average dewpoint temperatures averaged over time period consistent with the duration of the rainfall in an effort to more effectively represent the atmospheric moisture available to the storm for conversion to rainfall.

The procedure for identifying the location for where the dewpoint temperatures are selected is based on an analysis of the winds fields associated with the storm environment. For older storms (pre-1950), surface wind observations have been the primary data source for determining the inflow wind direction and magnitude. More recent storms have occurred when upper air wind analyses derived from weather balloon observations have been available and those wind fields have been used together with the surface winds to determine the storm winds. Particular difficulties arise when the storm moisture source is over ocean regions. Historically it has been very difficult to determine the appropriate winds to use and to determine a dewpoint one a location has been identified. Sea surface temperatures have been use as a substitute for dewpoint temperatures.

In an effort to increase the data base of extreme storms for a particular location, storms which have occurred over similar topography within the same climate region area considered. Under slightly different atmospheric conditions, those storms could have occurred over the location being studied while still maintained their basic characteristics. These storms are used in the PMP analysis after being modified for differences in atmospheric moisture availability between the actual storm occurrence location and the location being studied.

Extreme Storm Analysis Needs

Systemic identification of extreme rainfall events has not been a priority during the past several decades. Storms studies for a large number of storms were completed during the first half of the last century but identification and analyses of extreme rainfall events was not continued throughout the latter half of the century. The data base should be updated and catalog extreme rainfall events completed. Fortunately, extensive rainfall data from weather stations exist and can be efficiently used to search for the severe storms.

A program should be established where extreme rainfall events are identified in real time. Procedures should be in place to supplement standard observation with additional information immediately after the storm occurrence. This information can be extremely valuable for detailed storm analyses and quickly becomes unavailable with time.

Once a storm has been identified and supplemental information collected, the storm analysis should be completed using standard procedures and should provide standard products. Software has been developed, such has been used in the Maine Hydro site-specific study, to efficiently blend hourly with daily rainfall observation, produce hourly isoheytal analyses and produce depth-area-duration tables. The storm analysis can been completely in a timely manner and be made available to both the meteorology and hydrology communities for use in evaluating the impact of the storm and potential implication on existing design criteria such as PMP values.

For PMP applications, an update to the US maximum dewpoint climatology needs to be developed and made available to projects involved with site-specific PMP and hydrologic analyses. Evaluation of the exclusive use of 12 hour persisting dewpoint temperatures instead of average dewpoint temperatures for various durations needs to be evaluated. Maximum observed dewpoint temperature have been used and are still used to construct maximum dewpoint temperature climatologies. With over 50 years of dewpoint temperature observations digitally available for a large number of weather stations, return frequency climatologies should be developed to provide return frequency values for use in the PMP procedure.

Currently transposition limits for storms (determining the geographic region where an extreme storm could have occurred or a similar storm could potentially occur) are subjectively determined. More objective techniques have been developed using GIS to compare the topography of the historic site location with locations where a site-specific PMP study is being conducted. Use of these techniques in a standard procedure can provide increased reliability in transpositioning storms.

Recently the National Center for Environmental Prediction (NCEP) has developed a data base with modeled winds. Wind fields, along with temperature and other parameter fields, are available on a regular grid for various levels in the atmosphere four time a day or every six hours. This data base provides modeled data fields back to about 1950. Procedures should be developed to incorporate these data into the PMP analysis procedure.

Meteorological models development during the past decade has provides a significant increase in the reliability of these models to simulate storm behavior and rainfall amounts. The use of these models to provide maximum potential rainfall values should be investigated. Successful use of computer models will aid significantly in the understanding of extreme storms and in providing estimates of the maximum rainfall possible from these storms.

HYDROLOGIC RESEARCH NEEDS FOR DAM SAFETY ANALYSIS

by
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MGS Engineering Consultants, Inc.
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CURRENT PRACTICES IN ORGANIZATION

As a consulting firm, our hydrologic practices are based on meeting either the requirements of the governing regulatory authority or meeting the project-specific needs of the client. Inflow Design Floods (IDFs) are computed using standard rainfall-runoff watershed models via a variety of deterministic and probabilistic approaches. The watershed models may be event models with lumped inputs such as HEC-1[30] or HEC-HMS[31], or may be continuous models with distributed inputs such as WATFLOOD[11,12].

Conventional Deterministic Method

A conventional deterministic method is used in those cases where the regulatory authority utilizes a standards-based approach. This approach is typically used for computing Probable Maximum Floods (PMFs) or floods produced by a fixed percentage of the Probable Maximum Precipitation (PMP). Hydrometeorological inputs and watershed model parameters such as, antecedent watershed conditions, minimal infiltration rates, snowpack magnitude, etc. are primarily based on policy or guidelines set by the governing regulatory authority. The magnitude of the design precipitation and the storm temporal pattern are likewise set by policy or rule.

Mixed Deterministic-Probabilistic Method

A mixed deterministic-probabilistic method is used in those cases where the regulatory authority utilizes frequency-based standards. Hydrometeorological inputs and some watershed model parameters are selected based on probabilistic analyses of historical data. The goal is to produce a flood with the same Annual Exceedance Probability (AEP) as the design storm magnitude specified by the governing agency. This is what is commonly called an “AEP Neutral” approach and utilizes hydrometeorological inputs that are nearer typical values than extreme values. Accordingly, mean or median values of the hydrometeorological inputs are commonly used rather than conservative or worst-case values.

Stochastic Modeling of Extreme Floods

Stochastic modeling is utilized when information is needed on the magnitude-frequency and seasonal characteristics of flood peak discharge, runoff volume and maximum reservoir level. To address these needs we developed the Stochastic Event-based Flood Model (SEFM[29]) and also employ project-specific variations of that model. The basic concept of SEFM is to employ a deterministic flood computation model and treat the input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the hydrometeorological input parameters to vary in accordance with that observed in nature while preserving the natural dependencies that exist between many of the climatic and hydrologic parameters.

Multi-thousand computer simulations are conducted where each simulation contains a set of input parameters that were selected based on the historical record and collectively preserves the dependencies between parameters. The simulated floods constitute elements of an annual maxima flood series that can be analyzed by standard flood-frequency methods. The resultant flood magnitude-frequency estimates reflect the likelihood of occurrence of the various combinations of hydrometeorological factors that affect flood magnitude. The use of the stochastic approach allows the development of separate magnitude-frequency curves for flood peak discharge, flood runoff volume, and maximum reservoir level. Frequency information about maximum reservoir level is particularly important for use in hydrologic risk assessments because it accounts for flood peak discharge, runoff volume, hydrograph shape, initial reservoir level, and reservoir operations.

PROBLEMS FACED

Enormous sums of money have been spent in the past, and will be spent in the future, for upgrading of dams due to perceived spillway inadequacies. The decision to upgrade is often based largely on the findings of rainfall-runoff modeling for extreme floods. Currently, hydrologists use simplified conceptual and empirical models in conjunction with numerous policies, procedures, guidelines, and standards-of-practice in modeling extreme floods. This heavy reliance on institutionalized policies and procedures provides consistency of application, but does not necessarily provide accurate estimates of extreme floods.

If accuracy is defined as nearness to the truth, there are several factors that currently limit the ability of the engineering community to consistently achieve accurate results. First, in most applications, there is no benchmark for measuring accuracy. By the very nature of the problem, we are estimating extreme floods, events that are beyond, oftentimes well beyond, the historical data. Without a benchmark for accuracy, it is often difficult to make a compelling case that a given model, method, or procedure is superior to another. While models can be calibrated to past floods, there is almost always a need to extrapolate to obtain solutions for the extreme conditions of interest.

Second, while there may be a large set of models to choose amongst for modeling the hydrologic processes, we are typically woefully short of obtaining the field data necessary for properly applying any of those models on a watershed basis. This leads to the use of simplified physically-based models and conceptual models of the hydrologic processes and excessive lumping of inputs. Some of these models may not perform well beyond the limits for which they were originally developed or calibrated.

Given the life-safety and economic considerations involved in the decision to upgrade spillways, it is important that the rainfall-runoff modeling be conducted in a manner that truly emulates watershed flood response for extreme floods. Consideration of the discussion above indicates that greater research emphasis should be placed on analyses of extreme historical floods. The goal would be to improve the knowledge base and identify how modeling of extreme floods differs from modeling of floods of a magnitude commonly available for calibration. In addition, it is suggested that applied research be conducted in those aspects of rainfall-runoff modeling that can have the greatest affect on the magnitude of extreme floods and for which questions and knowledge gaps exist.

Example of a Specific Problem

Use of the linear unit-hydrograph theory and Hortonian overland flow concepts remain mainstays of current practice. These methods/concepts originated over 70-years ago and application of these approaches has changed little since their origin. Since that time, it has been learned that the runoff response can be very complicated in terms of the runoff pathways to a watercourse. While the runoff response is typically classified as surface runoff, interflow, and groundwater flow, the important distinction is the elapsed time in arriving at the receiving watercourse. It is now recognized that runoff during a flood includes elements of overland flow, saturated overland flow, throughflow, and the source area for these contributions varies during and following the storm event. In particular, interflow and throughflow[1,10] are primary contributors in forested watersheds and are common during long-duration general storms containing low to moderate rainfall intensities in the western US.

Nearly all of the project-specific unit-hydrographs and synthetic unit-hydrographs have been developed based on Hortonian overland flow concepts. Accordingly, there are valid questions about the utility of a one size fits all unit-hydrograph for a watershed when the runoff process includes various runoff mechanisms with differing response times. There is particular uncertainty when large extrapolation is required during modeling of truly extraordinary storms approaching PMP and for estimation of extraordinary floods approaching the magnitude of the PMF. Likewise, few studies have been conducted to identify the conditions for which linear unit-hydrograph theory is appropriate and when significant non-linearities occur. These are subject areas that warrant additional research.

NEW TECHNOLOGIES BEING EMPLOYED

We are currently using the following computer models and methods of data analysis that would be classified as new or recent technology.

Stochastic Modeling of Extreme Floods

The stochastic modeling of extreme floods is a relatively new hydrologic approach. In the past 3-years, we have employed the SEFM model, or variations of the model, on watersheds for five large dams in the western North America[18,19,20,26]. It has a promising future in that it offers the ability to compute magnitude-frequency relationships for a number of flood-related characteristics and can also provide seasonal characterizations. However, the model is data intensive and requires numerous probabilistic analyses of historical data to determine the frequencies of occurrence for the various hydrometeorological inputs. The methods of analysis are continuing to evolve as more is learned about the probabilistic and seasonal behavior of the various hydrometeorological inputs.

Use of Atmospheric Models in Rainfall-Runoff Modeling

An atmospheric model (Danard[6,7]) was used in stochastic modeling of extreme floods for Mica Dam on the Upper Columbia River[26] in British Columbia. The model provided distributed daily precipitation and temperature information for a historical 96-year period for the Upper Columbia watershed that was calibrated to precipitation and temperature gage measurements. This information was used to provide antecedent watershed conditions for WATFLOOD[11,12] a distributed hydrologic model. The temporal and spatial distributions of extreme storms in the historical period were also used in a resampling procedure for stochastic modeling of extreme floods.

Resampling Spatial and Temporal Patterns from Historical Storms

We are presently working with the Army Corps of Engineers in the analysis of the spatial and temporal patterns of historical storms on the American River in central California[21]. These patterns will be used in a resampling procedure for the stochastic modeling of floods for Folsom Dam on the American River. A procedure is currently under development that would allow combinations of spatial and temporal patterns from separate storms to be used in rainfall-runoff modeling. This would significantly increase the dataset of storms and include combinations both more severe and less severe than observed in the original sample of storms. The resampling approach replaces the conventional practice of using a synthetic design storm and can be used with either the conventional deterministic, mixed deterministic-probabilistic, or stochastic modeling approaches.

Spatial Mapping of Regional Precipitation-Frequency Information

Regional precipitation-frequency analysis[9] has been conducted at numerous locations around the globe since the late-1980's. Recent improvements to the spatial mapping of precipitation pioneered by Daly[4,5] and Oregon Climate Service[15] now allow high-resolution mapping of precipitation-frequency information. The spatial mapping of 100-year and 1000-year precipitation has recently been completed[27] for the 6-hour, 24-hour, and 72-hour durations for southwest British Columbia for use by BChydro in their dam safety program.

RESEARCH AND DEVELOPMENT NEEDS

Research about the hydrologic processes has been conducted for well over 70-years. Through past research, a sound scientific foundation now exists for describing nearly all of the hydrologic and hydraulic processes that are important for estimation of extreme floods. However, there continues to be a large chasm between the tools developed by the research community and the tools in common use by hydrologic engineers.

This chasm is primarily due to the practical problem of applying advanced models in situations where the necessary input data are either, unavailable, inadequate, or overly expensive to obtain on a watershed basis. Because of these constraints, it is difficult to take advantage of the capabilities of the advanced models. As a result, hydrologists continue to use simplified conceptual and empirical models in conjunction with numerous policies, procedures, guidelines, and standards-of-practice. In many cases, existing policies and procedures were developed decades ago based on information and experiences of past eras.

These same policies and procedures commonly receive reinforcement through requirements or guidelines set forth by regulatory agencies.

The continued use of these institutionalized policies and procedures has caused many engineers to become comfortable with fixed values, or ranges of values for hydrometeorological inputs and watershed model parameters. This heavy reliance on institutionalized policies, procedures, and guidelines has resulted in a false sense of confidence about the accuracy of our computations. It has also fostered the belief that there is a greater understanding of extreme storms and extreme floods than can be supported by the actual knowledge base.

The ability to incorporate new hydrologic tools from the research community will continue to be a problem due to the difficulties in obtaining the necessary input data on a watershed basis. Therefore, watershed models will continue to slowly evolve with some unavoidable reliance on policies, procedures and guidelines. While hydrology is considered a science, application of that science to practical problems on a watershed basis is as much art as science. Given the current situation, <u>application-based research</u> is the primary need in the dam safety area rather than pure or basic research.

As a practical matter, those topics/issues that have the greatest potential impact on flood magnitude, public/project safety, or rehabilitation cost should receive the higher priority. Considering all the background above, several specific research needs are listed below.

Short-Term R&D Needs

<u>Create a resource center for research findings and case-studies pertaining to historical extreme floods</u> – It would be very useful to have a resource center for research findings and case studies pertaining to historical extreme floods. This could start as a simple electronic bibliography of research articles and case studies for truly extreme floods. It could evolve into a University being a repository for information on extreme floods. It is likely that much information already exists in various research documents that could help address many of the questions and uncertainties about modeling of extreme floods.

Long-Term R&D Needs

<u>Non-linearity of the hydraulic response of watersheds</u> - Conduct research and examine case studies to identify the physical conditions for which the time-lag and peaking characteristics of the hydraulic response of a watershed can be considered linear. Likewise, identify the physical conditions for which the hydraulic response of a watershed should be considered non-linear. Develop recommendations and procedures for hydrologic modeling of the non-linear cases. Current policies on this issue vary greatly amongst agencies.

<u>Surface runoff versus interflow runoff for unit hydrographs</u> - Most unit-hydrographs in the western US were developed at a time when runoff was considered to be Hortonian surface runoff. More recent experience indicates that interflow runoff can be a major component of the runoff volume in western US

mountain watersheds in response to low to moderate intensities in long-duration general storms[1,10]. Misapplication of hydrologic models can result in large errors for situations where both surface runoff and interflow are both significant contributors to the runoff volume. Depending on the method of analysis and the choice of the unit-hydrograph, situations can arise to produce either significant under-estimation or over-estimation of flood peak discharge. Past studies for development of synthetic unit-hydrographs should be revisited to determine if interflow was a major component. Where applicable, unit-hydrographs should be revised and policy changes implemented to better model the situation where both surface runoff and interflow are present.

Updating and Improve Depth-Area-Duration Storm Analyses for Mountainous Areas
Update the current method for conducting depth-area-duration analyses for storms in mountainous areas. Review the current procedures for conducting storm analyses for opportunities to incorporate recent technological improvements such as NEXRAD radar and satellite imagery. Conduct research to improve procedures for interpolation of precipitation in mountainous terrain. Conduct research to improve procedures for transposition of storm-related characteristics such as spatial patterns from one site to another in mountainous terrain.

POLICY NEEDS

Review of Hydrologic/Flood Safety Criteria - A review of hydrologic criteria for design of new dams and safety evaluation of existing dams is needed for those State Dam Safety Programs that employ flood safety criteria expressed as some percentage of Probable Maximum Precipitation (PMP) or Probable Maximum Flood (PMF). The level of safety afforded by these types of criteria varies dramatically across the United States (Schaefer[17]). This review may be conducted by examination of the frequency of occurrence of extreme storms in the state (Riedel and Schreiner[16]) and comparison with the results of regional precipitation-frequency analyses (Hosking and Wallis[9,23]). This information will allow an assessment if the current flood safety criteria is providing the desired level of protection.

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Draft
Simplified Dam Failure Analysis for Inundation Mapping Using HEC-1

By
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Introduction

This paper describes a simplified approach to dam failure analysis using HEC-1 to provide input hydrographs for the hydrodynamic model Mike 21. Mike 21 was used in combination with digital elevation models (DEM) to analyze the dambreak flood and produce inundation maps.

The California Office of Emergency Services (CA OES) was directed by the Governor of the State of California to develop dam failure inundation maps for all non-federal dams in the state. The flood mapping was done using a 2-D hydrodynamic model (Mike 21) using existing topographic information available from the USGS. Nearly 500 dam failure inundation maps were produced in a four-month period. The purpose of this study was not to produce detailed dam-failure flood maps, but to reveal those dams for which detailed mapping studies are required. This was a screening study and not a study to provide the final detailed inundation maps for individual dams.

The modeling tools were chosen on the basis of convenience of use and the ability to link the generation of flood maps to the inundation process. CA OES selected two models: a modified version of NWS DAMBRK and the Danish Hydraulic Institute Mike 21 model for the dambreak flood analyses. However, nearly all of the maps were based on the 2-D Mike 21 modeling.

Mike 21 requires an input hydrograph since the program does not simulate a dam failure or provide reservoir routing to compute the outflow hydrograph through the breach as it develops with time. HEC-1 has these features so it was used to simulate the dam failures. HEC-1 also has an option for writing the calculated hydrograph data to user-formatted files. A utility program was used to reformat the HEC-1 output as Mike 21 input.

The database for dam and reservoir characteristics for the State of California is maintained by the Division of Dam Safety of the California Department of Water Resources for dams under their jurisdiction. The information includes the height of the dam, crest elevation and length, reservoir storage capacity, and reservoir area.

To simulate a dam failure HEC-1 requires breach characteristics, including total failure time, and an elevation-capacity curve for the reservoir. These were developed from the published values of crest elevation, crest length, dam height, and reservoir storage capacity.

Background

The California Office of Emergency Services dam failure inundation mapping and emergency procedure program applies to dams meeting specific size requirements making them subject to the jurisdiction of the State of California. Dams owned by agencies of the United States government are not under the jurisdiction of this program. The legislative intent of the original CA OES seismic safety of dams legislation was to establish emergency procedures for the evacuation and control of populated areas below

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dams which could be used to save lives and reduce injury in the event of a dam failure. Dam owners submit inundation maps to CA OES for review and approval in accordance with guidance issued by CA OES. Inundation maps represent the best estimate of where water would flow if a dam failed completely and suddenly with a full reservoir. Based upon approved inundation maps, or the delineated areas, cities and counties with territory in the mapped areas are required to adopt emergency procedures for the evacuation and control of populated areas below the dams.

HEC-1 dam failure analysis

Breach analysis—Because a large number of dams had to be analyzed, it was not possible to define specific characteristics for each dam am and reservoir. Dams were classified as either an earth or rockfill dam or a concrete dam. The following table shows the parameters for the two types of dams.

Assumptions concerning dam failure:

- "Sunny-day" failure
- Reservoir is full
- Failure is rapid

  Earth dam: 15 minutes for full failure

  Concrete dam: 9 minutes for full failure
- Failure is for full height of dam
- The maximum expected breach width occurs

Table 1. Dam breach parameters:

Parameter	Earth/rockfill Dams	Concrete Dams
Side slope of breach	**1.0**	**0.2**
Time until breach reaches its maximum size (hr)	**0.25**	**0.15**
Bottom width of breach (ft)	**5 * H**	**1 * H**
Discharge through turbines(cfs)	**10, 100, 1000**	**Value kept as small as possible.**
Elevation of water surface in reservoir at failure	**Weir Crest Elevation**	**Weir Crest Elevation**
Inflow at upstream end of reservoir	**Small dams : 10 cfs Medium dams: 100 cfs Large dams : 1000 cfs**	**Inflow to reservoir = discharge through turbines**

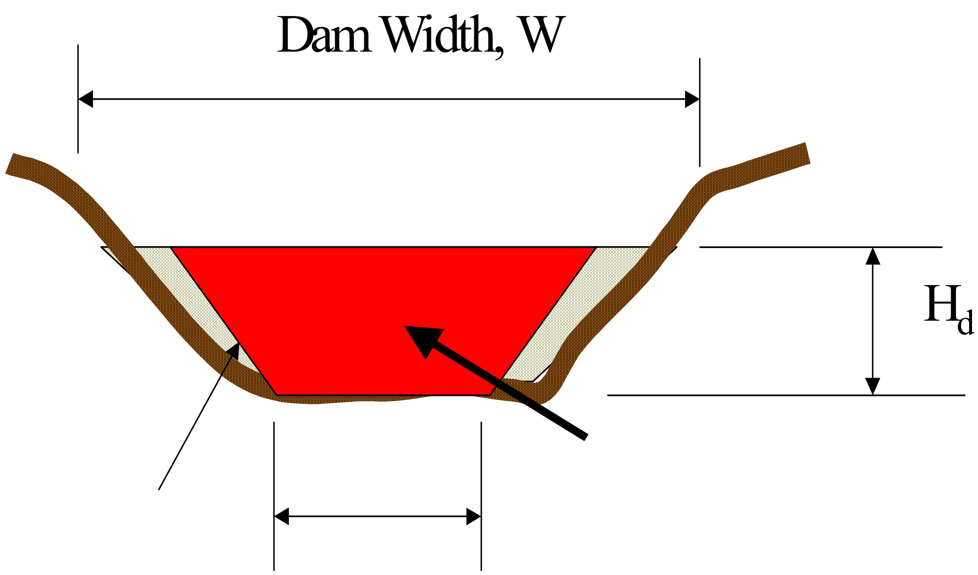

Figure 1. Breach geometry for earthen dams

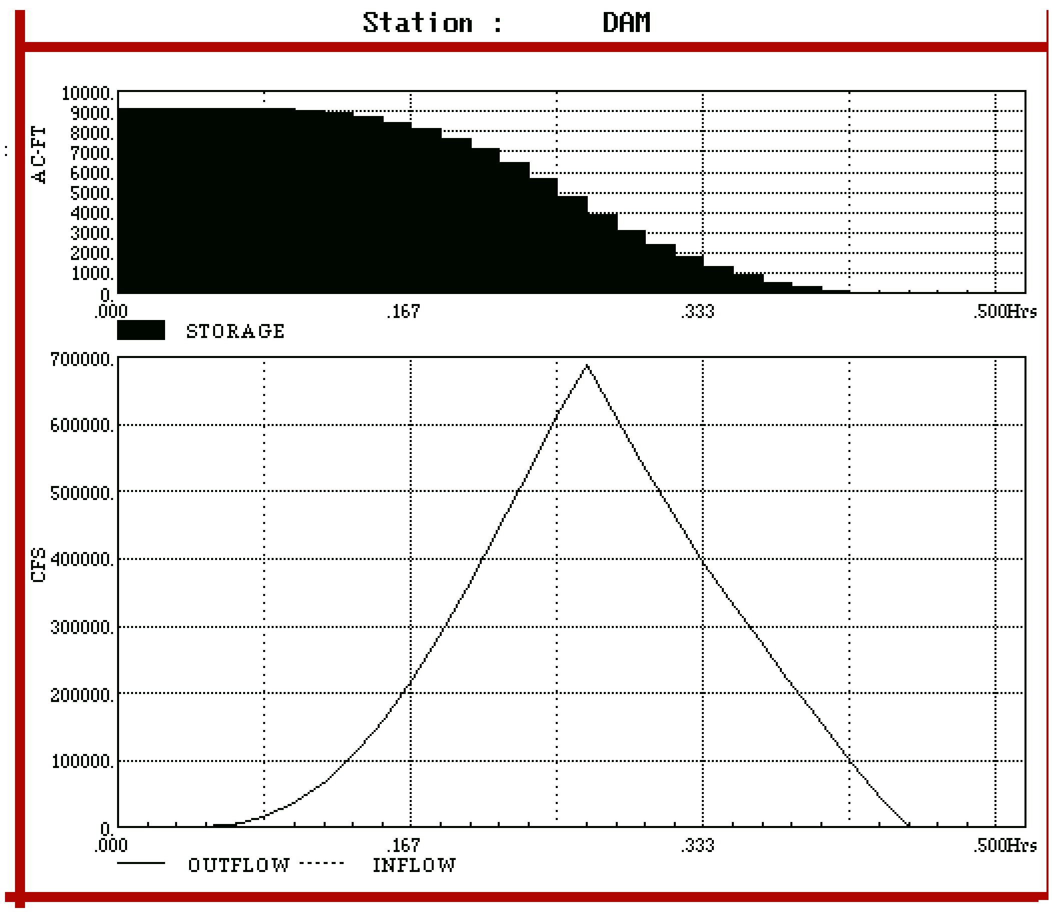

Figure 2: Dam failure hydrograph generated by HEC-1

Hydrodynamic model

MIKE 21 BACKGROUND

The version of Mike 21 used in this study simulates water level variations and flows in response to a variety of forcing functions in water bodies. The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry, bed resistance coefficients, wind field, hydrographic boundary conditions, etc. The system solves the full time-dependent non-linear equations of continuity and conservation of momentum. The solution is obtained using an implicit ADI finite difference scheme of second-order accuracy.

Mike 21 parameters:

The only changes to the modeling parameters used for all individual inundation models were to the Manning's n values used for boundary resistance. Higher values were used in canyon areas than in the floodplains. A single value was used for the entire model. No effort was made to vary Manning's n by land use. Each 30-meter grid cell was represented by a single elevation value and a single roughness coefficient. The dam failure hydrograph generated by HEC-1 had an initial steady flow and a constant base flow added at the end of the hydrograph. Model stability problems occurred without adding these to the hydrograph.

Table 2. Parameters used in Mike 21.

Parameter	Value used
Eddy Viscosity	**5 m^2/s**
Wind Conditions	**No wind**
Dry Depth	**0.04 m**
Flood Depth	**0.10 m**
Manning's n - Canyons	**0.06 to 0.08**
Manning's n - Floodplain	**0.04 to 0.05**

Results

The assumptions used produced conservatively large flows from the simulated dam failure; the Manning's n-values were considered conservatively low; and many of the detailed features of the surface geometry were not represented in the 30-m DEMs. It was concluded that the inundation maps developed using these data typically over-predict expected inundation areas that could occur as a result of a dam failure.

A primary purpose of this study was to identify dams for which flooding due to dam failure could cause major risk to people and property. It is the dam owner's responsibility to submit inundation maps to CA OES for review and approval in accordance with guidance issued by CA OES. Based on the results of this study various dam owners were directed to have dam failure inundation studies made.

Several maps developed in this study were compared with inundation maps prepared by engineering firms for dam owners. None of the previous comparison studies used two-dimensional flood models. In general the tools used for dambreak flood analysis have been the one-dimensional unsteady-flow DAMBRK model or steady flow one-dimensional models (HEC-RAS or HEC-2). For the latter, dambreak flood hydrographs were generated by HEC-1 or the National Weather Service model BREACH.

Maps developed in this study showed good agreement with maps produced in previous studies, especially in steeper areas and areas with well-defined channelizing features. The results differed in flatter floodplain areas, especially where flow could split around small hills and other topographic forms.

More accurate definition of potential inundation areas could be obtained using two-dimensional hydrodynamic models. However, accurate topographic information is required. The widely available 30-m DEMs do not provide very accurate information on topography, and more detailed topographic data should be obtained.

Conclusions

This study was conducted to establish emergency procedures for the evacuation and control of populated areas below dams that could be used to save lives and reduce injury in case of a dam failure. Inundation maps represent the best estimate of where water would flow if a dam failed completely and suddenly with a full reservoir. Based upon approved inundation maps, or the delineated areas, cities and counties with territory in the mapped areas are required to adopt emergency procedures for the evacuation and control of populated areas below the dams.

More detailed investigations of individual dams would produce more accurate definition of potential inundation areas, and these are expected to be done in the future. The results from this study were judged to be appropriate in the light of the purpose of the study, and on the basis of comparisons of inundation maps submitted by dam owners appeared to provide approximately the same level of accuracy as obtained by commonly used inundation mapping methods.

A FRAMEWORK FOR CHARACTERIZATION OF EXTREME FLOODS FOR DAM SAFETY RISK ASSESSMENTS

Robert E. Swain[5], David Bowles[6], and Dean Ostenaa[7]

Abstract

Risk-based decisions require different types of information than standards-based decisions. Traditional sources of information used for estimating probabilities of extreme floods include gaged streamflow records, indirect discharge measurements, and precipitation records. Generally these data sources have records that are less than 100 years in length. This framework for flood characterization for risk assessments uses the length of the data record and other characteristics of the data to determine the credible extrapolation limits used in the flood frequency analysis. Because risk assessments require estimation of floods with annual exceedance probabilities of 1 in 10,000, or less, emphasis is placed on developing probabilistic estimates using regional hydrometeorological data and paleoflood information. The uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute to convey into the risk assessment.

No single approach is capable of providing estimates of extreme floods over the full range of annual exceedance probabilities required for risk assessment. Therefore, results from a number of approaches need to be combined to yield a composite flood characterization; this means several methods and sources of data are needed. The application of several independent methods applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.

Introduction

The U.S. Bureau of Reclamation is now making extensive use of quantitative risk assessment in support of dam safety decision making (Von Thun and Smart, 1996). An important input to Dam Safety Risk Assessment is the development of probabilistic extreme flood estimates. This shifts the focus for dam safety flood evaluation from routing a single “maximum” event (i.e. the probable maximum flood, PMF) to consideration of the entire range of plausible inflow flood events, and ultimately to the magnitude-frequency relationship of maximum reservoir stages.

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For floods, the risk assessment process involves selecting a spillway evaluation flood (SEF) based on the probability of dam failure and the severity of the incremental consequences of dam failure. Past practice also examined consequences, but without formal consideration of probability of failure; if consequences were judged to be large, the SEF was chosen as the PMF.

Reclamation has identified the need for a review of its present procedures for developing probabilistic extreme flood estimates and their associated uncertainties for use in dam safety risk assessment. Where practical, Reclamation would like to develop improved procedures. The overall objective is to develop a practical, robust, consistent, and credible framework for developing probabilistic extreme flood estimates for Dam Safety Risk Assessment. The desired outcome is a robust framework in which components can be improved in the future as the state-of-the-art develops.

The framework was developed by inviting a group of approximately 20 professionals with extensive experience in the theoretical and practical aspects of physical, paleo-, and statistical flood hydrology and hydrometeorology to participate in a one-week workshop held at Utah State University in June 1997. Participants from North America, Australia, and the United Kingdom reviewed current Reclamation practice, and evaluated various advances in developing probabilistic extreme flood estimates for their potential role in the needed framework. A smaller group met in Denver to develop the details of the framework. This paper summarizes the findings of these groups.

Risk Assessment Stages

Present Reclamation risk assessment practice uses a staged approach for conducting risk assessments (USBR, 1997a). Project schedule and budget constraints are considered in determining the type of flood assessment prepared at each stage. While each risk assessment is unique, the following stages are generally used in Reclamation risk assessments:

a) **Screening Level Risk Assessment**: An evaluation of risk that includes definition of load probabilities and consequences for all load classes (flood, earthquake, and static). Structure failure probabilities and associated uncertainties are also considered in a global sense, but detailed event trees are not usually prepared. An emphasis at this stage is to maximize the use of available information, without conducting new analyses or collecting additional data. The intent is to identify areas where risks are potentially high and to determine the need for further evaluations and data collection. Results of these evaluations are used to determine Reclamation's risk profile and to "screen" out dam safety issues where additional funding and effort appears to have little potential for reducing dam safety risks.

b) **Scoping Level Risk Assessment**: A more detailed evaluation of risks is performed for the dam safety issues identified in a screening level risk assessment. This level of risk assessment typically involves more detailed treatment of event trees, load probabilities, structural response, and consequences. The intent is to invest sufficient effort so that the risk assessment team understands the major contributors to risk to enable formulation of risk reduction strategies and to determine the need for additional analyses and investigations.

c) **Decision Level Risk Assessment**: At this level, more detailed evaluation of risks is performed to provide decision makers with the information necessary to reach a dam safety decision for a structure. The decision may be related to continuing project operations, correcting dam safety deficiencies, selecting among risk reduction alternatives, or determining the need for interim actions to reduce risk while long term plans are developed. The intent is to provide decision makers with sufficient pertinent risk information such that the risk reduction objective can be effectively considered along with other Reclamation objectives. At this level of risk assessment, detailed loading information, structural response analyses, and consequence evaluations are developed for all significant issues. This type of risk assessment focuses on reducing uncertainties in the risk estimates and evaluating risk reduction actions.

Data Sources

The proposed framework for developing probabilistic extreme flood estimates for risk assessment uses the length of record and other characteristics of the data to determine the extrapolation limits for flood frequency analysis. Traditional sources of information used for flood hazard analyses include streamflow and precipitation records. Generally, these data sources have records that are less than 100 years in length, although in some cases these records can be extended to about 150 years using historical information. Regional precipitation and streamflow data can create pooled data sets from short periods of observation, and paleoflood data can extend records of floods to periods of up to several thousand years.

Streamflow Data

Many different types of streamflow information are used in developing probabilistic extreme flood estimates for risk assessment. Streamflow data are used in flood hazard assessment as input for frequency studies or as the basis for developing flood hydrographs. The usual source of these data is the streamflow records collected and maintained by the U.S. Geological Survey. However, similar data are collected and archived by many other Federal and State government agencies and some non-government organizations. Streamflow records consist of data collected at established gaging stations and indirect measurements of streamflow at other sites. Streamflow data can include estimates of peak discharge, as well as average or mean discharge for various time periods. Most streamflow measurements on U.S. streams began after 1900 with only a few records dating back that far. Most often, streamflow records at a single site range in length from about 20 to 60 years. Completeness of the data set may vary from station to station.

Climate Data

Precipitation and weather data used in hydrologic models can include rainfall, snowfall, snow water equivalent, temperature, solar radiation, and wind speed and direction from individual weather stations, as well as remote sensing information and radar information for broader regions. Data types available from various sources vary greatly in record length and quality throughout the United States. Some of these types of data (i.e., snowfall, snow water equivalent, solar radiation, and wind) are limited to record lengths of less than about 30 years; basic rainfall and temperature data are available for some stations for up to 150 years, but in most cases are limited to less than 100 years.

Historical Data

Historical data can provide a means for extending the length of record for many types of data, in particular for observations of the most extreme events. These data are most commonly used to extend streamflow records of peak discharge prior to organized stream gaging. Historical observations can provide information for other types of data such as weather patterns and the frequency of extreme storm events, or changes in land use or vegetation that may be significant to runoff modeling calculations. However, as with any type of historical data, the accuracy and validity of the observations must be carefully assessed and compared to the other types of data used in the analysis.

Paleoflood Data

Paleoflood hydrology is the study of past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrological procedures (Baker, 1987). Unlike historical data, paleoflood data do not involve direct human observation of the flood events. Instead, the paleoflood investigator studies geomorphic and stratigraphic records (various indicators) of past floods, as well as the evidence of past floods and streamflow derived from historical, archeological, dendrochronologic, or other sources. The advantage of paleoflood data is that it is often possible to develop records that are 10 to 100 times longer than conventional or historical records from other data sources in the western United States. In addition, the paleoflood record is a long-term measure of the tendency of a river to produce large floods. In many cases, paleoflood studies can provide a long-term perspective, which can put exceptional annual peak discharge estimates in context and assist in reconciliation of conflicting historical records.

Paleoflood data generally include records of the largest floods, or commonly the limits on the stages of the largest floods over long time periods. This information can be converted to peak discharges using a hydraulic flow model. Generally, paleoflood data consist of two independent components. One component is a peak discharge estimate; the second is a time period or age over which the peak discharge estimate applies. Paleoflood studies can provide estimates of peak discharge for specific floods in the past, or they can provide exceedance and non-exceedance bounds for extended time periods. Each of these differing types of paleoflood data must be appropriately treated in flood frequency analyses.

Extrapolation Limits for Different Data Types

The primary basis for a limit on credible extrapolation of extreme flood estimates derives from the characteristics of the data and the record length used in the analysis. The data used in the analysis provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. Different risk assessments require flood estimates for different ranges of annual exceedance probability (AEP), and therefore analysis procedures and data sources should be selected to meet project requirements. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation, regional streamflow, and regional paleoflood sources should provide the highest assurance of credible characterization of low AEP floods.

For many Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10,000 and ranging down to 1 in 100,000, or even lower. Developing credible estimates at these low AEPs generally require combining data from multiple sources and a regional approach. Table 1 lists the different types of data which can be used as a basis for flood frequency estimates, and the typical and optimal limits of credible extrapolation for AEP, based on workshop discussions or subsequent communications. The limits presented in the table represent a general group consensus; however, opinions differed amongst workshop participants. In general, the optimal limits are based on the best combination(s) of data envisioned in the western U.S. in the foreseeable future. Typical limits are based on the combination(s) of data which would be commonly available and analyzed for most sites.

Many factors can affect the equivalent independent record length for the optimal case. For example, gaged streamflow records in the western United States only rarely exceed 100 years in length, and extrapolation beyond twice the length of record, or to about 1 in 200 AEP, is generally not recommended (IACWD, 1982). Likewise, for regional streamflow data the optimal limit of credible extrapolation is established at 1 in 1,000 AEP by considering the number of stations in the region, lengths of record, and degree of independence of these data (Hosking and Wallis, 1997). For paleoflood data, only in the Holocene epoch, or the past 10,000 years, is climate judged to be sufficiently like that of the present climate, for these types of records to have meaning in estimates of extreme floods for dam safety risk assessment. This climatic constraint indicates that an optimal limit for extrapolation from paleoflood data, when combined with at-site gaged data, for a single stream should be about 1 in 10,000 AEP. For regional precipitation data, a similar limit is imposed because of the difficulty in collecting sufficient station-years of clearly independent precipitation records in the orographically complex regions of the western United States. Combined data sets of regional gaged and regional paleoflood data can be extended to smaller AEPs, perhaps to about 1 in 40,000, in regions with abundant paleoflood data. Analysis approaches that combine all types of data are judged to be capable of providing credible estimates to an AEP limit of about 1 in 100,000 under optimal conditions.

In many situations, credible extrapolation limits may be less than optimal. Typical limits would need to reflect the practical constraints on the equivalent independent record length that apply for a particular location. For example, many at-site streamflow record lengths are shorter than 100 years. If in a typical situation the record length is only 50 years, then the limit of credible extrapolation might be an AEP of about 1 in 100. Similarly, many paleoflood records do not extend to 10,000 years, and extensive regional paleoflood data sets do not currently exist. Using a record length of about 4,000 years, a typical limit of credible extrapolation might be an AEP of 1 in 15,000 based on regional streamflow and regional paleoflood data.

The information presented in Table 1 is intended as a guide; each situation is different and should be assessed individually. The limits of extrapolation should be determined by evaluating the length of record, number of stations in a hydrologically homogeneous region, degree of correlation between stations, and other data characteristics which may affect the accuracy of the data.

Ideally, one would like to construct the flood frequency distribution for all floods that could conceivably occur. However, the limits of data and flood experience for any site or region place practical limits on the range of the floods to which AEPs can be assigned. There does not appear to be sufficient data to justify computation of AEPs less than 1 in 100,000. In general, the scientific limit to which the flood frequency relationship can be credibly extended, based upon any characteristics of the data and the record length, will fall short of the probable maximum flood (PMF) for a site. PMF estimates provide a useful reference to past practice and can be compared with extreme floods characterized for risk assessment. However, the workshop participants concluded that there is limited scientific basis for assigning an AEP to the PMF. For precipitation data, similar limitations apply to extrapolations that approach values described by probable maximum precipitation.

Table 1. Hydrometeorological Data Types and Extrapolation Limits for Flood Frequency Analysis

Type of Data Used for Flood Frequency Analysis	Limit of Credible Extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 750	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

Methods of Analysis

At Site Flood Frequency Analysis

Frequency analysis is an information problem: if one had a sufficiently long record of flood flows, or perhaps rainfall for a basin, then a frequency distribution for a site could be determined with good precision, so long as change over time due to anthropogenic or natural processes did not alter the distribution of floods. In most situations available data are insufficient to precisely define the annual exceedance probability of large floods. This forces hydrologists to use practical knowledge of the physical processes involved, and efficient and robust statistical techniques, to develop their estimates (Stedinger et al., 1993).

Fitting a distribution to data sets allows both a compact and smoothed representation of the frequency distribution revealed by the available data, and a systematic procedure for extrapolation to frequencies beyond the range of the data set. Given a family of distributions, one can estimate the parameters of that distribution so that required quantiles and expectations can be calculated with the "fitted" model. Appropriate choices for distribution functions can be based upon examination of the data using probability plots, the physical origins of the data, previous experience, or prescriptive guidelines.

Several general approaches are available for estimating the parameters of a distribution. A simple approach is the *method of moments,* which uses the available sample to compute estimators of the distribution's parameters. The Federal guidelines published in Bulletin 17B (IACWD, 1982) recommend fitting a Pearson type 3 distribution to the common base 10 logarithms of the peak discharges. It uses at-site data to estimate the sample mean and variance of the logarithms of the flood flows, and a combination of at-site and regional information to estimate skewness.

Another method that may be used to estimate the parameters of a distribution for at-site frequency analysis is the Expected Moments Algorithm (EMA). EMA (Cohn et al., 1997) is a moments-based estimation procedure and is identical to the existing Bulletin 17B (IAWCD, 1982) approach when no high or low outliers are present. The EMA method was developed to utilize historical and paleoflood information in a censored data framework. This approach explicitly acknowledges the number of known and unknown values above and below a threshold, similar to a maximum-likelihood approach. Three types of at-site flood information are used: systematic stream gage records; information about the magnitudes of historical floods; and knowledge of the number of years in the historical period when no large flood occurred.

Still another method, which has strong statistical motivation, is the *method of maximum likelihood*. Maximum likelihood estimators (MLEs) have very good statistical properties in large samples, and experience has shown that they generally do well with records available in hydrology. In many cases MLEs cannot be reduced to simple formulas, so estimates must be calculated using numerical methods (Stedinger et al., 1988; O'Connell, 1997).

L-moments are another way to summarize the statistical properties of hydrologic data. Sample estimators of L-moments are linear combinations (and hence the name L-moments) of the ranked observations, and thus do not involve squaring or cubing the observed values as do the product-moment estimators. As a result L-moment estimators of the dimensionless coefficients of variation and skewness are almost unbiased and have very nearly a normal distribution (Hosking and Wallis, 1997).

Regional Flood Frequency Analysis

In hydrology, sufficient information is seldom available at a site to adequately determine the frequency of rare events using frequency analysis. This is certainly the case for the extremely rare events which are of interest in dam safety risk assessment. The National Research Council (1988) has proposed several general strategies, including substituting space for time for estimating extreme floods. One substitutes space for time by using hydrologic information at different locations in a region to compensate for short records at a single site.

Three approaches (Cudworth, 1989) have been considered for regional flood frequency analysis: (1) average parameter approach; (2) index flood approach; and (3) specific frequency approach. With the average parameter approach, some parameters are assigned average values based upon regional analyses, such as the log-space skew or standard deviation. Other parameters are estimated using at-site data, or regression on physiographic basin characteristics, perhaps the real or log-space mean. The index flood method is a special case of the average parameter approach. The specific frequency approach employs regression relationships between drainage basin characteristics and particular quantiles of a flood frequency distribution.

Index Flood Method. The index flood procedure is a simple regionalization technique with a long history in hydrology and flood frequency analysis (Dalrymple, 1960). It uses data sets from several sites in an effort to construct more reliable flood-quantile estimators. A similar regionalization approach in precipitation frequency analysis is the station-year method, which combines precipitation data from several sites without adjustment to obtain a large composite record to support frequency analyses. The concept underlying the index flood method is that the distributions of floods at different sites in a "region" are the same except for a scale or index-flood parameter which reflects the size, rainfall and runoff characteristics of each watershed. Generally the mean is employed as the index flood (Hosking and Wallis, 1997).

Average Shape Parameter. As at-site records increase in length, procedures that estimate two parameters, with at-site data to be used with a regional shape parameter, have been shown to perform better that index flood methods in many cases (Stedinger and Lu, 1995). For record lengths of even 100 years, 2-parameter estimators with a good estimate of the third shape parameter, are generally more accurate than are 3-parameter estimators (Lu and Stedinger, 1992; Stedinger and Lu, 1995). However, whether or not it is better to also regionalize the coefficient of variation depends upon the heterogeneity of the regions and the coefficients of variability of the flows. In regions with high coefficients of variation (and high coefficients of skewness) index flood methods are more attractive.

Regional Regression. Regional analysis can be used to derive equations to predict the values of various hydrologic statistics (including means, standard deviations, quantiles, and normalized regional flood quantiles) as a function of physiographic characteristics and other parameters. Stedinger and Tasker (1985, 1986a, 1986b) developed a specialized Generalized Least Squares (GLS) regression methodology to address the regionalization of hydrologic statistics. Advantages of the GLS procedure include more efficient parameter estimates when some sites have short records, an unbiased model-error estimator, and a better description of the relationship between hydrologic data and information for hydrologic network analysis and design.

Design Event-Based Precipitation-Runoff Modeling

Precipitation-runoff modeling is typically used as an event-based method for determining extreme floods. A single set of hydrometeorological parameters and watershed characteristics are used to simulate a design flood event. The major inputs to a design event-based precipitation-runoff model are: (1) climate data (rainfall, snowfall, and other variables needed to predict snowmelt); (2) losses (infiltration/interception); (3) physical watershed characteristics for runoff and routing simulations (drainage areas, watershed and channel slopes, lag times, antecedent moisture, etc.); (4) precipitation-runoff transformation function; and (5) runoff conveyance/routing mechanisms. Model output includes runoff hydrographs at user-specified locations, maximum peak discharges, and total runoff volumes. Examples of this type of model include HEC-1 (USACE, 1990) and RORB (Laurenson and Mein, 1995).

Stochastic Event-Based Precipitation-Runoff Modeling

In the stochastic approach, hydrologic model inputs are treated as random variables. Monte Carlo sampling procedures are used to allow the input variables to vary in accordance with their observed distributions, including the observed dependencies among some climatic and hydrologic parameters. The use of the stochastic approach with regional precipitation information allows the estimation of flood magnitude-frequency curves for flood peak discharge, flood runoff volume, and reservoir level. An example of this type of model is discussed by Barker et al. (1997).

Atmospheric Storm Modeling and Continuous Precipitation-Runoff Modeling

This method combines the work of atmospheric modelers and regional precipitation analysis to derive a precipitation magnitude-frequency curve (Chin et al., 1997). The atmospheric model is used to generate storms over the watershed, and the findings from the regional analysis are used to estimate the annual exceedance probability of point and areal precipitation generated by the model. Using distributed precipitation-runoff modeling, snowpack and other antecedent conditions can be combined to estimate a simulated flood frequency curve using a Monte Carlo approach.

Data Generation and Continuous Simulation Modeling

The data generation and continuous simulation modeling approach is based on Monte Carlo generation of long and detailed sequences of hydrometeorological variables, including precipitation, air temperature, and wind speed and direction. In order to represent spatial differences across the watershed adequately, it is necessary to generate hydrometeorological variables for several sites concurrently. Hydrological models of watershed behavior and hydraulic models of confluences, wave effects and reservoir outlets are used to simulate the reservoir water level continuously. An estimated magnitude-frequency relationship of maximum reservoir stages is input to the risk assessment (Calver and Lamb, 1996).

Combining Methods and Data Types

No single approach is capable of providing the needed characterization of extreme floods over the full range of annual exceedance probabilities that may be required for risk assessment. In particular, characterization of floods with AEPs less than 1 in 10,000 can be expected to require that results from a number of approaches, based on multiple data sources, need to be combined to yield a composite flood frequency description. The application of several independent methods and types of data applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.

Table 2 lists various methodologies that were considered for characterizing extreme floods to support dam safety risk assessment. A flood frequency analysis must be combined with each of these methodologies to assign annual exceedance probabilities to the floods.

The framework developed for Reclamation does not propose a specific methodology for rigorously combining information from these differing data sources and methodologies in an overall statistical framework. In some cases the information may be combined statistically, and in other cases one set of results may be used as a bound on the frequency distribution obtained by analysis of other data. Clearly, this process will require a measure of judgement. Regardless of the approach taken for combining results, it should incorporate sound physical and scientific reasoning for weighting or combining results.

All floods characterized for the risk assessment process should display the uncertainties resulting from the analysis. As the risk assessment moves from the screening and scoping levels to the decision level, uncertainty should be reduced and better quantified so that appropriate information is included in the dam safety decision-making process.

Table 2. Applicability of Hydrologic Methods of Analysis to Various Risk Assessment Levels

Method of Analysis	Risk Assessment Level		
	Screening	Scoping	Decision
Flood frequency analysis	Yes	Yes	Yes
Design event-based precipitation-runoff modeling	No	Yes	Yes
Stochastic event-based precipitation-runoff modeling	No	Yes	Yes
Distributed simulation modeling	No	No	Yes
Atmospheric modeling and distributed precipitation-runoff modeling	No	No	Yes

Evaluation of Uncertainty

Uncertainty can be evaluated by applying Monte Carlo analysis to the overall risk assessment calculations. For example, consider the estimation of threat to life consequences and probability of failure associated with an existing dam and various risk reduction alternatives. One is concerned with uncertainty due to such risk assessment inputs as flood frequency distribution parameters, system response estimates, population at risk, warning time, and estimated loss of life. Then in each iteration of Monte Carlo analysis, one could generate likely values of each of these inputs and evaluate the threat to life and probability of failure. The expected annual life loss and the annual exceedance probability of failure, which are both used as Reclamation Public Protection Guidelines (USBR, 1997b), could be computed for each iteration. By generating many replicates, one obtains samples that describe the possible values of these risk measures (performance metrics).

Averaging over the replicates provides “expected” values of the quantities reflecting both the modeled probability distributions of the phenomena (risk assessment inputs) that are considered to be random variables, and the uncertainty in the parameters describing those distributions. The sample standard deviations describe the variability of the performance metrics. Replicates can be used to estimate frequency distributions which can be used for describing and evaluating the decision implications of uncertainty in the risk assessment inputs.

Calibration to Flood Frequency Quantiles

The ability of a flood event model to reproduce historic events certainly gives some confidence to the validity of subsequent estimates. However, even in a well gaged watershed the annual exceedance probabilities of the calibration floods are likely to range between 1 in 5 to 1 in 20, and only occasionally up to 1 in 100. While it would be expected that floods of these magnitudes will activate some floodplain storage, the non-linear nature of drainage basin flood response is such that the routing characteristics of larger events may be considerably different. Thus, while calibration of a model provides valuable information on the flood response of a drainage basin, caution is needed when using the calibrated model to estimate floods of much larger magnitudes (Pilgrim and Cordery, 1993).

Calibration to flood frequency quantiles using design rainfall inputs can provide important information on flood response characteristics for extreme design events (Nathan and Bowles, 1997; Nathan, 1992). With this approach, design rainfall information is prepared for a specified AEP, and then used with a given set of model parameters and input assumptions to derive a design hydrograph. The peak (or volume) of the design hydrograph can then be compared to the corresponding quantile obtained from a combined at-site/regional flood frequency analysis. The model inputs associated with the greatest uncertainty can be varied within appropriate limits to ensure agreement with the selected flood quantile. Model calibration should be undertaken for a range of AEPs to ensure a consistent variation of parameters with flood magnitude or AEP.

For risk-based studies based on a “design storm concept”, it is necessary to adopt an AEP-neutral approach, where the objective is to derive a flood with an AEP equivalent to its concomitant precipitation (Nathan and Bowles, 1997). The factors that influence the transfer between precipitation and runoff can be characterized by probability distributions, and ideally the design hydrograph should be determined by considering the joint probabilities of all the input factors. Monte-Carlo methods are ideally suited to the AEP-neutral objective, as they accommodate the observed variability of the inputs while still preserving the interdependencies between parameters. Simpler approaches may be appropriate, where the decrease in rigor is offset by the computational convenience and the transparency of the adopted functional relationships. For the least important parameters it may be appropriate to adopt a single representative (mean) value instead of the full distribution. However, the relationship between rainfall and runoff is non-linear, and adoption of a single representative value for the major inputs will introduce bias into the transformation. Accordingly, for more important inputs it is necessary to adopt a joint probability approach. The nature of the method can be tailored to suit the relative importance of the parameter concerned.

Conclusions

A framework has been developed for characterizing extreme floods for the purposes of dam safety risk assessment. By incorporating regional information on precipitation, floods, and paleofloods with good at-site records, it is possible to provide scientifically credible flood estimates to annual exceedance probabilities as low as 1 in 100,000, although higher AEP limits may exist in many cases. In general, the scientific limit to which the flood frequency relationship can be extended based upon available data will fall short of the PMF for a site. PMF estimates provide a useful reference to past practice and can be compared with floods characterized for risk assessment; however, there is limited scientific basis for assigning an annual exceedance probability to the PMF.

No single approach is capable of providing the needed characterization of extreme floods over the full range of AEPs required for risk assessment. Therefore, the results from several methods and sources of data should be combined to yield a composite characterization. The application of several independent methods applicable to the same range of AEPs will increase the credibility and resulting confidence of the results.

Uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute for the characterization of extreme floods. Flood characterization should include a "best estimate" of the annual exceedance probability of floods of different magnitudes and a description of the uncertainty in such results. Such uncertainties need to be honestly represented and considered throughout the risk assessment process.

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HYDROLOGIC RESEARCH NEEDS FOR DAM SAFETY
Experience Learned from Alamo Dam Risk Assessment Study

By

James Chieh[1] and Joseph B. Evelyn[2]

Introduction

Hydrologic dam safety evaluation is moving from a deterministic design standard basis to a probabilistic (risk based) approach. Because of this trend, the U.S. Army Corps of Engineers is in the process of developing risk assessment guidance for its Dam Safety Assurance Program. As part of this effort the Los Angeles District participated in a demonstration project, the Alamo Dam Risk Assessment Study, using one of its reservoir projects. Some specific outcomes of the demonstration risk assessment study were the following:

- An understanding of potential failure modes
- An evaluation of the risk posed by the existing dam against various risk-based criteria.
- An assessment of risk reduction and the cost effectiveness of risk reduction expected for various structural and non-structural measures.

A hydrologic analysis was conducted to support the study to achieve the above expected project outcomes. To perform the analysis from the hydrologic aspect required the determination of reservoir inflow volume-frequency relationships, reservoir elevation-frequency relationships, reservoir elevation-duration relations for flood loading conditions, and the "Threshhold Flood". The hydrology results were then used for the hydraulic analysis to develop dam break flood hydrographs, and downstream overflow area information (floodplain depths, flood wave velocities, and travel times) for consequence analysis. The hydrology results were also used for economic analysis and other risk assessment, such as potential loss of life downstream.

This paper briefly describes the hydrologic analysis performed on the Alamo Dam Risk Assessment Study, and summarizes the hydrologic research needs identified for dam safety.

Alamo Dam

Alamo Dam was completed in 1968 as a multipurpose project for flood control, water conservation and supply, and recreation. Alamo Dam is located on the Bill Williams River, 39 miles upstream from its confluence with the Colorado River in Havasu Lake near Parker, Arizona. The dam is on the border of Yuma and Mohave Counties, Arizona, about 2.5 miles downstream from Alamo Crossing. The drainage area above Alamo Dam is 4770 square miles, and is generally mountainous,

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in west central Arizona. The drainage area is bounded on the north by the Cottonwood Cliffs; on the east by the Juniper and Santa Maria Mountains; on the south by the Date Creek and Harcuvar Mountains; and on the west by the Hualpai Mountains. Figure 1 is a picture of Alamo Dam; some physical characteristics and hydrologic information regarding the dam and spillway is presented below the figure.

Hydrologic Analysis for Alamo Dam Risk Assessment Study

Brief descriptions of the hydrologic analysis conducted for the Alamo Dam Risk Assessment including volume frequency analysis, balanced hydrographs, design flood routings, filling frequency analysis, and elevation duration analysis are presented in this section.

(a) Volume Frequency Analysis

An analysis was performed on the Alamo reservoir inflow record to establish 1-, 2-, 3-, 5-, 10-, 20-, and 30-day volume frequency curves. The inflow records were from October 1928 to December 1993, a total of 65 years records. The volume frequency relationships were extrapolated to a recurrence interval of 10^{-6} using judgment, comparison with the volume duration characteristics of the SPF and PMF, and the shapes of the filling frequency curves relative to each other. The PMF exceedance frequency was assumed to be 10^{-6} based on engineering judgment. Likewise, median plotting positions and a logarithmic scale were applied for graphical frequency analysis. For the risk assessment flood loading analysis it was necessary to extrapolate the volume frequency curves beyond 10^{-6} to plot the results of Corps spillway design practice calling for SPF plus PMF as the inflow design flood. Figure 2 presents the inflow volume frequency curves for the Alamo reservoir.

(b) Balanced Hydrographs

Balanced hydrographs (50-; 100-; 200-; 500-; 1000-; 5000-; 10,000-; 50,000-; 100,000-; and 1,000,000- year) were constructed for reservoir inflow based on the volume frequency relationships described above. The historical flood hydrograph from the February- March 1978 event, and the PMF hydrograph were used to determine an appropriate pattern hydrograph. The reasonableness of balanced hydrographs was verified by visual inspection of graphical plots of hydrographs, and comparison of 50-year and 100-year balanced hydrograph routing results with the statistical estimate of 2 percent and 1 percent exceedance water surface elevations.

(c) Design Flood Routings

To be consistent with standard practice in the evaluation of design flood routing of Standard Project Flood (SPF) and Probable Maximum Flood (PMF), the starting reservoir water surface elevation for routings was assumed to be the target objective elevation (1125 feet) at the current reservoir operation plan, and the maximum reservoir release is 7,000 cfs. Routings assumed the 7,000 cfs release was continued throughout spill events.

In order to address issues concerning the capability of the existing project and risk reduction alternatives to handle design floods (SPF and PMF) at different starting water surface elevations, flood routings were performed through Alamo reservoir using the net storage capacity curve for the following cases.

Case 1. Starting water surface elevation of 1125 feet, then SPF.
Case 2. Starting water surface elevation of 1125 feet, then PMF.
Case 3. Starting water surface elevation of 1125 feet, then SPF, followed 23 days later by PMF. This routing results in a starting WSE corresponding to about 50 percent of flood control pool filled at start of PMF.
Case 4. Starting water surface elevation of 1125 feet, then SPF, followed immediately by PMF

(d) Filling Frequency Analysis

Alamo Dam filling frequency relationships up to and including SPF plus PMF were determined for the existing dam configuration and all flood risk reduction alternatives.

An HEC5 reservoir operation simulation of the historical daily inflow record (1929 to 1998) for Alamo Dam was performed using the adopted reservoir operation plan to determine maximum annual water surface elevation. The HEC-FFA computer program was used to plot the annual maximum values using median plotting positions and log cycle scale for probability. Since the highest reservoir pool elevation was well below the spillway crest for any risk reduction alternatives, the results of this analysis were used as the starting portion of the filling frequency curve estimated for all alternatives.

The balanced hydrographs were routed through the reservoir for existing conditions with overtopping of the existing embankment (no failure). Reservoir routings were made using the current reservoir operation plan modified to limit the maximum release to 5000 cfs (instead of 7000 cfs) until spillway crest is reached to account for the likelihood of release reductions required by lower Colorado River system reservoir operation for flood control. The filling frequency curve was extended to the maximum water surface elevation attained during each routing (i.e., the filling frequency curve was not truncated due to probable dam failure at this point of the analysis).

Routings of the balanced hydrographs were made for each risk reduction alternative dealing with hydrologic deficiency. Results from the routing of the balanced hydrographs were plotted along with the simulation results from the historical records (the starting portion of the filling frequency curve) to generate filling frequency relationships for each risk reduction alternative. In graphically drawing the filling frequency curve, the influence of the spillway discharge relation on the slope of the filling frequency curve was considered in each case. Results of maximum surcharge water surface elevation and maximum outflow from the dam were tabulated and plotted on Excel spreadsheets. Figure 3 shows the Excel spreadsheet for the existing condition.

Trial and error reservoir routings were made to determine the Threshold Flood as about 83 percent of PMF (largest flood event safely handled by dam and spillway without failure using Corps freeboard criteria). The starting water surface elevation for the Threshold Flood determination was 1125 feet.

(e) Elevation Duration Analysis

For the existing condition dam (with net storage curve) the reservoir pool elevation versus total duration relationship was computed using the available 70 years of simulated daily WSE values. This total duration curve helped in determining the probability of geotechnically related failures (seepage, piping, seismic, etc.) because the relationship of number of days at any given elevation is given.

Hydrologic Research Needs for Dam Safety

During 1982 through 1997, the Corps of Engineers Los Angeles District conducted several Alamo Dam safety studies based a deterministic approach. The district accomplished a lengthy and costly Corps reporting and evaluation process based on spillway design flood standard that was ultimately unsuccessful in upgrading spillway capacity due to legitimate cost vs. benefit concerns.

Our experience with the Alamo Dam Demonstration Risk Assessment (1998-1999) was:

a. Holistic approach covering all dam safety aspects
b. Hydrologic risk put into perspective of total project risk
c. Risk reduction benefit vs. cost of alternatives displayed.

As presented in the above section, the risk based approach to dam safety analysis required:

a. N-year volume frequency relationships
b. Flood hydrograph shape
c. Entire range of frequencies from 2-year to PMF and beyond
d. Elevation-duration frequency relationship.

During the demonstration dam safety study, the characteristics of hydrologic procedures needed were identified as:

a. Quick & dirty (cheap) methods for reconnaissance and "portfolio" studies
b. More comprehensive (expensive) methods for in-depth analysis
c. Procedures applicable nationwide
d. Procedures based on available hydrologic/meteorologic/geologic data
e. Confidence limits/reliability of estimates.

Through these dam safety analyses some hydrologic research needs were identified:

b. Method for assigning a reasonable estimate to the probability of PMF
c. Procedure for filling the large gap between observed hydrologic data and PMF estimates
d. Hydrologic methods consistent over large areas due to need to assess multiple dam failures in same watershed

e. A practical approach to uncertainty analysis to enable better (more meaningful) evaluations than sensitivity analysis.

Specific research items were also identified:

a. Case studies of observed extreme flood events as compared with PMF and discharge and volume frequency estimates
b. Reconstitution of rainfall-runoff relationships for extreme events
    a. Antecedent precipitation and soil moisture
    b. Unit hydrograph characteristics (efficiency of runoff or time of concentration findings)
c. Compilation of paleo-hydrologic information nationwide and integration with PMF & discharge-frequency estimates; generalize findings if possible.

Conclusion

We need hydrologic tools that enable advancing from strictly deterministic (design flood) evaluations to performing risk based (probabilistic) dam safety assessments.

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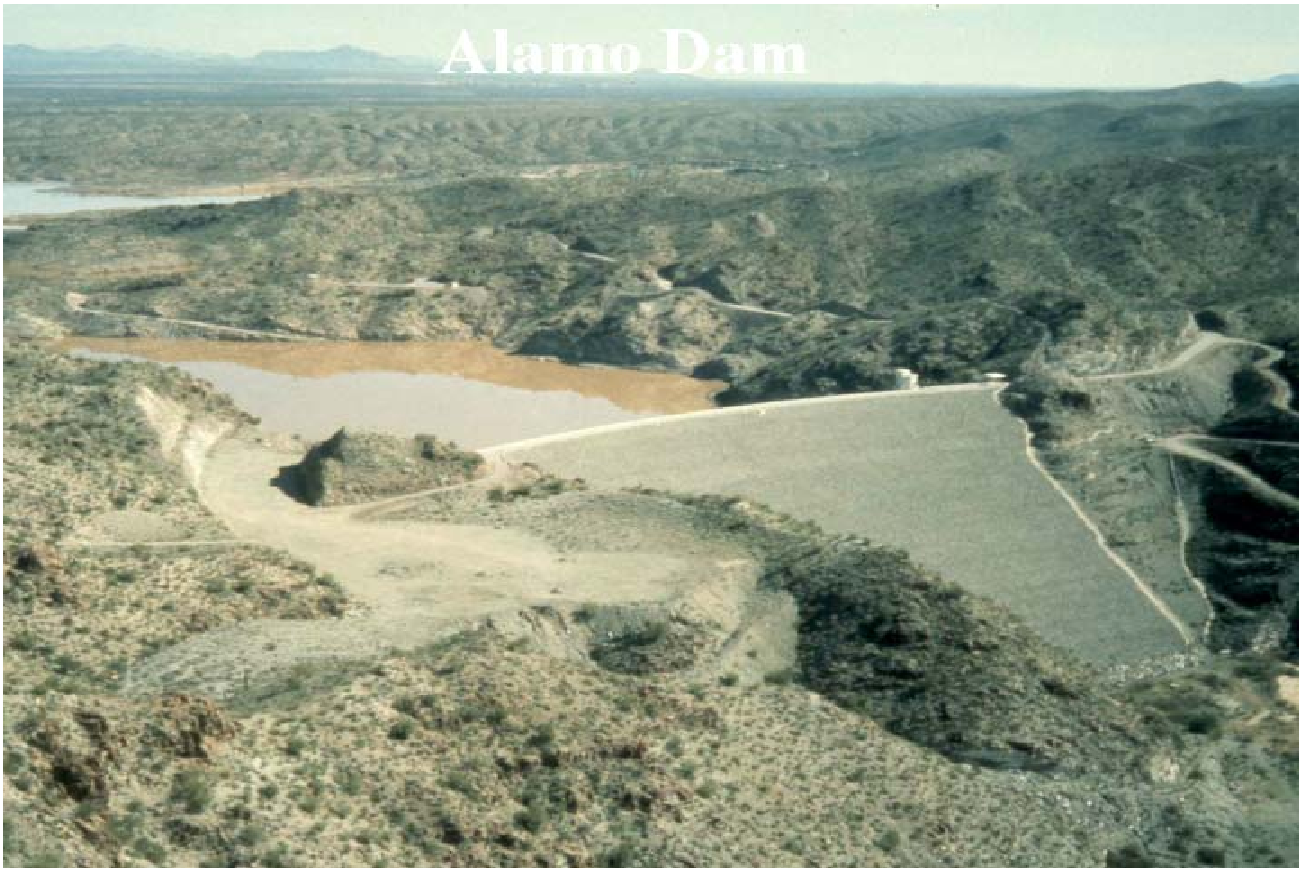


Figure 1 Alamo Dam

Alamo Dam and Spillway

Drainage area = 4,770 square miles
Dam embankment height = 283 feet
Reservoir storage at spillway crest = 1 million acre-feet
Reservoir storage at TOD = 1.3 million acre-feet
Existing spillway capacity = 41,500 cfs
PMF inflow = 820,000 cfs and 1.39 million acre-feet
PMF overtops existing dam by 20 feet
Threshold Flood = 83% of PMF
PMF Peak Outflow
    With dam failure = 2.9 million cfs
    Without dam failure = 362,000 cfs

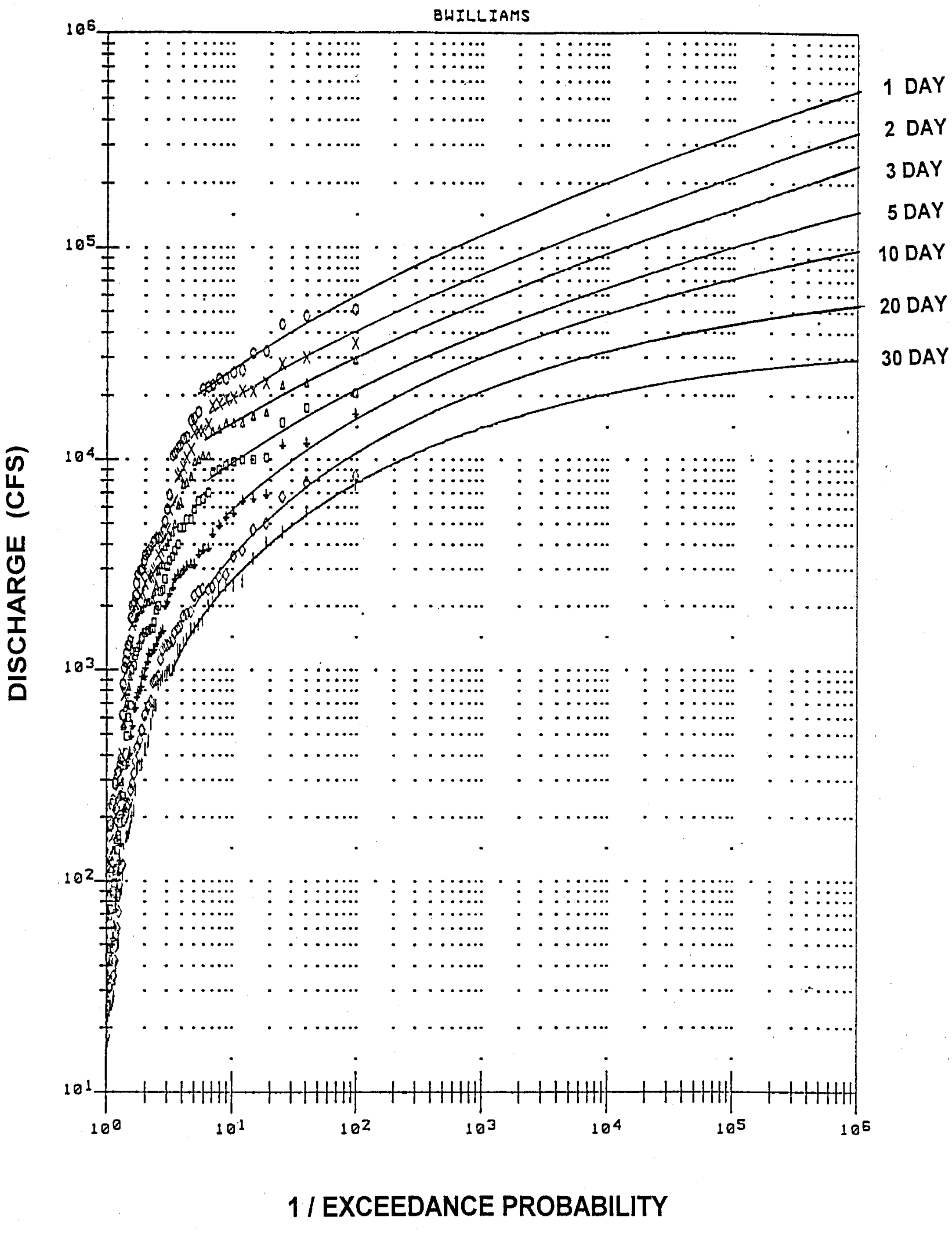


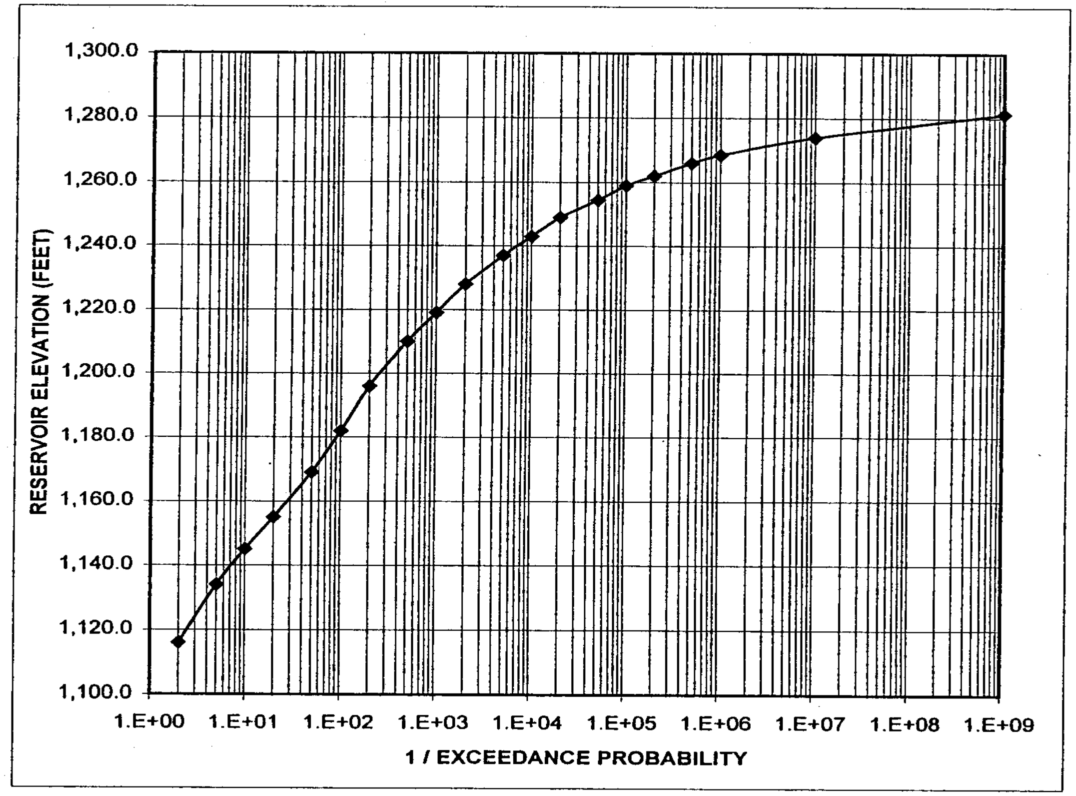
Figure 2 Alamo Dam Risk Assessment Inflow Volume Frequency Curves

Alamo Dam Risk Assessment Demostration Study - 1998

Reservoir Stage-Frequency and Outflow-Frequency Relationships for Existing Conditions

Existing Dam w/o Modification (Code FR-0)

Average Return Interval ARI (yr)	Annual Exceedance Probability AEP (%)	Maximum Reservoir Stage (feet)	Maximum Reservoir Outflow (cfs)
2	50	1,116.0	5,000
5	20	1,134.0	5,000
10	10	1,145.0	5,000
20	5	1,155.0	5,000
50	2	1,169.0	5,000
100	1	1,182.0	5,000
200	0.5	1,196.0	5,000
500	0.2	1,210.0	5,000
1000	0.1	1,219.0	5,000
2000	0.05	1,228.0	5,000
5000	0.02	1,237.0	7,000
10000	0.01	1,243.0	12,526
20000	0.005	1,249.0	21,311
50000	0.002	1,254.5	33,391
100000	0.001	1,259.0	45,510
200000	0.0005	1,262.0	53,560
500000	0.0002	1,266.0	68,188
1000000	0.0001	1,268.5	85,596
10000000	0.00001	1,274.0	157,107
1000000000	0.0000001	1,281.3	282,142



Note: Maximum reservoir outflow is a combination of discharge through the dam outlet works, spillway, and over or through the embankment (in the case of dambreak)

Note: Values assume no embankment failure regardless of extent of overtopping

Figure 3 Reservoir Stage-Frequency and Outflow-Frequency Relationships for Existing Conditions

Paleoflood Hydrology, Dam Safety, and Floodplain Management

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Abstract

In the past decade, there has been a growing interest by dam-safety officials to incorporate a risk-based analysis for design-flood hydrology. Extreme or rare floods, with annual exceedance probabilities (AEPs) in the range of about 10^{-2} to 10^{-7} chance of occurrence per year, are of continuing interest to the hydrologic and engineering communities for purposes of planning, design, and maintenance of structures such as dams [National Research Council, 1988]. Flood-frequency analysis is synonymous with flood-risk assessment. Flood-frequency relations also are difficult to estimate when using short gage record lengths typical of streamflow-gaging stations in the United States. Reliable flood-frequency estimates is needed as input to risk assessments for determining appropriate levels of public safety, prioritizing projects, and allocating limited resources in a wide range of water-resources investigations such as flood-plain management, flood forecasting, and related environmental studies. The NRC stresses that as much information as possible about floods needs to be used for evaluation of the risk and consequences of any decision. Paleoflood hydrology provides useful information to assist dam-safety officials and flood-plain managers in their assessments of the risk of large floods. Documenting maximum paleofloods combined with regional analyses of contemporary extreme rainfall and flood data help provide reliable flood estimates with very small AEPs. This paper provides an overview of contributions in paleoflood hydrology by the U.S. Geological Survey research project "Paleohydrology and Climate Change," recent research findings, an example applied of an paleoflood study, and suggestions for future directions in hydrologic research needs for improving hydrologic estimates for dam safety, and flood-plain management.

Introduction

Worldwide, floods are among the most destructive events related to meteorological processes. In the United States, the average annual death toll of 125 is accompanied by about $2.4 billion in damages from floods (Federal Emergency Management Agency, FEMA, 1997a). In 2001, natural disasters caused at least 25,000 deaths and total economic losses were $36 billion worldwide (Environmental News Network, ENN, 2001). Storms and floods dominated these statistics, contributing more than two thirds to the 700 major disasters and causing 91 percent of all insured natural disaster losses. The worst weather-related disaster in 2001 was tropical storm Allison that produced record flooding in parts of Texas, which caused losses of about $6 billion, making it "the most expensive tropical storm in history" (ENN, 2001). Although large expenditures of resources are made to mitigate flood losses, damages from floods continue to rise at an alarming rate, and thus, better approaches are needed to reverse this trend.

Effective planning, design, and maintenance of flood-risk management projects require accurate estimates of flood risk (National Research Council, NRC, 1999). Poor understanding of flood frequency contributes to unnecessary loss of life and increased flood damages in some cases, and conversely, leads to costly overdesign of hydraulic structures located on floodplains and questionable hydrology in flood-plain management for other situations (Jarrett and Tomlinson, 2000). In an evaluation of extreme floods and the use of the probable maximum flood (PMF) methodology to estimate design floods, the Interagency Advisory Committee on Water Data (IACWD, 1986) raised a major concern about PMF's being either dangerously small or wastefully large, and they emphasized the importance of accurately estimating the risk of extreme flooding. Thus, the objective of a flood study should be to generate as much information as practicable about the flood potential at a site (NRC, 1988), which should be the basis for evaluation of the risk and consequences of any decision.

For about the past 50 years, the design criteria for construction of structures such as dams has included an estimate of the Probable Maximum Flood (PMF) (Cudworth, 1989). The PMF is an estimate of the maximum flood potential for a given drainage basin and is derived from an analysis of the Probable Maximum Precipitation (PMP) (Cudworth, 1989). The NRC (1988, 1994) recognized the: 1.) limited hydroclimatic data available to estimate PMP/PMF values for mountain basins less than about 1,050 km^2; 2.) subjectivity and variation of PMP estimates among experienced meteorologists; 3.) critical need for regional analyses of extreme precipitation and flooding; 4.) the need to better use historic and paleoflood data; and 5.) potential use of probability-based methods for providing an alternative to the PMP/PMF approach. Greater emphasis is needed to better understand processes that generate floods to improve methods for estimating flood risk, mitigating flood impacts, and designing infrastructure in floodplains.

Other countries have made major investments in updating their procedures for determining flood flow frequency. For example, the United Kingdom updated their procedures in 1999 in the *Flood Estimation Handbook* (Reed et al., 1999). This handbook replaced the 1975 *Flood Studies Report* by the Natural Environment Research Council. Australia has also updated their flood frequency approach in *Australian Rainfall and Runoff – a guide to flood estimation* (Nathan and Weinmann, 1998).

Although there is substantial research on improving flood-frequency methods in the United States, progress in integrating this research into standard hydrologic engineering practice generally has been slow. One exception is Reclamation where significant resources have been committed for risk-assessments for dam safety in about the past ten years. Reclamation has been using quantitative risk assessment for dam safety decision making for several years (U.S. Bureau of Reclamation, 1999; Levish, 2001).

There also is substantial interest and need for improving methods to estimate flood frequency in floodplain management, flood inundation mapping, water resources management, and many related environmental disciplines (e.g., NRC, 1988, 1999; Swain and Jarrett, 2000; Vecchia, 2001; Jones et al., 2001; Levish, 2001). Floodplain management is an issue of national concern (Vogel et al., 2001), and there is increasing research to address effects of climatic variability on flooding (NRC, 1999; Lins and Slack, 1999; Jarrett and Tomlinson, 2000). Climatic variability and other nonstationarity issues (e.g., land-use changes and regulated flow streams) require more robust flood-frequency analysis and add another level of complexity in flood-hazard assessments.

FEMA, which administers the National Flood Insurance Program, and other federal agencies rely on the procedures for estimating flood flow frequency presented in Bulletin 17B *Guidelines for Determining Flood Flow Frequency*, Interagency Committee on Water Data (IACWD, 1982), to map flood-plain hazards throughout the United States. However, Bulletin 17B guidelines were developed in the late-1960s and last revised in 1982 (IACWD, 1982). Many of the effective flood maps were created in the late 1970's and early 1980's, and suffer from a number of well recognized deficiencies such as out-of-date or inaccurate flood-frequency estimates, changes in basin characteristics, and have additional flood data since the frequency studies were originally done (Jarrett and Tomlinson, 2000; Jones et al., 2001). Forty-five percent of effective maps are over 10 years old and many communities do not have effective flood mapping. The National Flood Insurance Reform Act of 1994 mandates that the Nation's flood maps be revised in the near term and subsequently reviewed every 5 years. FEMA estimates that updates to existing flood insurance studies and creating new maps for communities without mapping will cost between $800 and $1,000 million. FEMA's Map Modernization Plan also emphasizes that more cost-effective methods to produce flood maps are essential (FEMA, 1997a, 1997b, 1998).

USGS Paleohydrology and Climate Change Project

To help support efforts of the Bureau of Reclamation, Corps of Engineers, Federal Emergency Management Agency, and other federal, state and regional water resources agencies, U.S. Geological Survey (USGS) Paleohydrology and Climate Change (PCC) project scientists and engineers are conducting research on the hydraulics, hydrometeorology, and paleoflood hydrology to help assess the frequency of extreme or rare floods, with AEPs in the range of about 10^{-2} to 10^{-4} or smaller. A primary focus of this interdisciplinary research is to develop cost-effective paleoflood techniques that can be used to complement meteorologic, hydrologic, and engineering methods to improve estimation of the magnitude, frequency, and risk of floods. This objective is achieved through basic and applied research that includes improving methods for estimating flood discharge, hydrometeorologic processes of floods, flood-frequency analysis, better use of historic and paleoflood data at gaged sites, ungaged sites, and in regional settings, and quantifying the effects of natural and anthropogenic climatic variability on flooding. For about the past decade, the USGS has worked closely with Reclamation on technical consultation for paleoflood hydrology related to dam safety. The U.S. Army Corps of Engineers (COE) also is implementing a risk-assessment method to evaluate potential safety problems for its more than 550 dams to aid decision-makers in prioritizing investment decisions (Foster, 1999). Two PCC projects in progress focus on incorporating paleoflood data into flood-frequency analyses for two COE projects. The COE requested that the flood hydrology for the American River in California be reanalyzed to better include historical and paleoflood data to better extrapolate frequency relations for AEPs less than 0.01. In a complementary PCC study for the COE, paleoflood data are being incorporated in a regional flood-frequency study to be used to revise the hydrology for a revised FEMA flood-insurance study for Fountain Creek basin, Colorado.

A Role for Paleoflood Hydrology in Water-Resources Investigations

Paleoflood hydrology is the science of reconstructing the magnitude and frequency of large floods using geological evidence and a variety of interdisciplinary techniques (House et al., 2001). Although most studies involve prehistoric floods, the methodology is applicable to historic or modern floods at gaged and ungaged sites (Baker et al., 1988). Floods leave distinctive sedimentary deposits (Webb et al., 2001, House et al., 2001; Jarrett and England, 2001), botanical evidence (Yanosky and Jarrett, 2001), erosional features on channel margins (O'Connor et al., 1993), and modifications of geomorphic surfaces by floodwaters (Levish, 2001) in channels and on floodplains. These features, termed paleostage indicators (PSIs), can be used to infer the maximum stage of past floods (Figure 1). In paleoflood studies, the most commonly used PSIs are slackwater deposits (SWDs) of silt and sand rapidly deposited from suspension in sediment-laden waters where velocities are minimal during the time that inundation occurs. Other types of PSIs used in paleoflood studies include flood bars (FBs) of sand, gravel, cobble, and boulder deposits. Estimating paleoflood discharge using PSIs (which can be viewed as old high-water marks, HWMs) is similar to estimating peak discharge using recent HWMs with step-backwater analysis, the slope-area, critical-depth, and slope-conveyance methods (Webb and Jarrett, 2001).

There has been a misunderstanding that paleoflood techniques are only used for estimating very old and extreme floods. Paleoflood studies to obtain data for contemporary floods (recent to about 500 years) also are used to complement short gage records and can be used to estimate magnitude-frequency relations at sites with minimal or no gage data. Paleoflood studies provide important information that can be used in risk assessments and in the assessment of "nonstationarity" flood

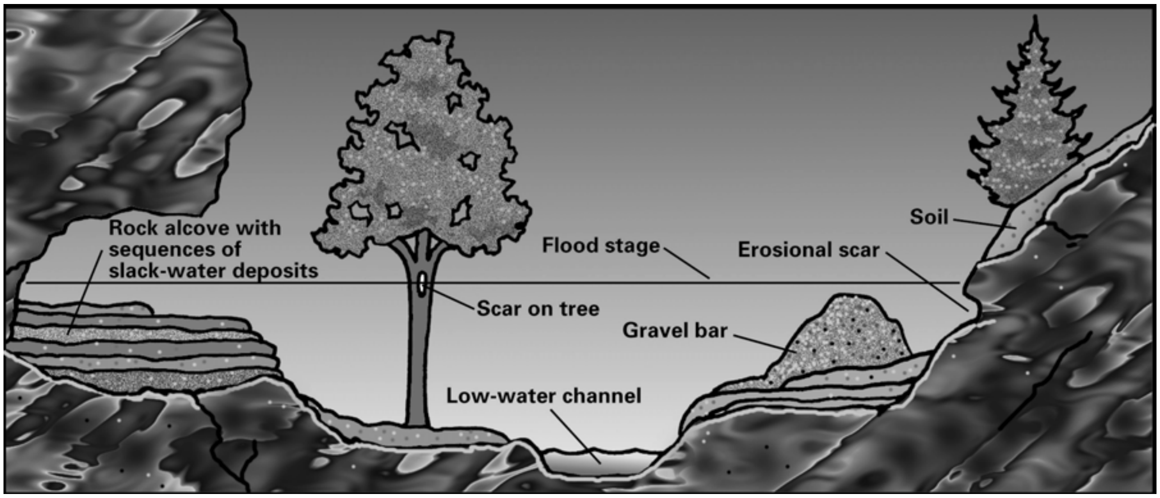

Figure 1. Diagramatic section across a stream channel showing a peak flood stage and various paleoflood features used as paleostage indicators (PSIs) such as slackwater deposits, gravel, cobble and boulder bars, trees scars, and erosional scars (Source: Jarrett and England, 2001).

at various temporal and spatial scales (NRC, 1999; Jarrett and Tomlinson, 2000; Vecchia, 2001). Non-stationarity typically includes effects of natural and anthropogenic climatic variability, but also effects of land-use changes such as urbanization, detention storage, and wildfire. Paleoflood data are particularly useful in providing upper limits of the largest floods that have occurred in long time spans (Enzel et al., 1993; Jarrett and Tomlinson, 2000). The extreme upper tail of a flood frequency distribution is most important for design of high-risk structures (Vecchia, 2001). Paleoflood data can provide unique insight for estimating the upper tails of frequency distributions.

Because of the important role of paleoflood hydrology is increasingly being used in a range of water-resources investigations, the American Geophysical Union (House et al., 2001) published a book *Ancient Floods, Modern Hazards, Principles and Applications of Paleoflood Hydrology* that provides a state-of-the-art review of paleoflood hydrology. In 1999, the American Society of Civil Engineers began a task committee on paleoflood hydrology as it relates to dam safety and risk-based assessments as well as better use of historical data and paleoflood data in water-resources investigations. The task committee on Paleoflood Hydrology also is preparing a monograph entitled *Use of Paleoflood and Historical Data in Water Resources Applications* (Swain and Jarrett, 2000), which will emphasize using paleoflood techniques and applications by practicing hydrologists, engineers, and scientists in related fields.

Recent Paleoflood Research Results

This section summarizes two recent research studies of the PCC project. A main source of uncertainty in paleoflood reconstructions is maximum flood stage inferred from PSIs.

Typically, the elevation of the top of the PSI is used as the minimum elevation of the flood that deposited the sediments (Figure 1), but little evidence has been provided to support this assumption. Jarrett and England (2001) documented the first systematic assessment for one aspect of paleoflood data: the relation between paleostage indicators (PSIs) and the peak stage of floods responsible for their emplacement. Recent flood-transported sediments (fresh PSIs) deposited as flood bars (FBs) and/or slack-water deposits (SWDs) from recent large floods can be directly related to flood high-water marks (HWMs) at the same location. A flood-chasing approach was developed to visit as many extreme flood sites as possible after a flood, and obtained PSI-HWM data from recent large floods at 192 sites. This systematic documentation and analysis of recently emplaced flood-deposited sediments (new PSIs) provided a unique opportunity to study the physical evidence of floods in the United States. Data were obtained from 13 states, including: Alaska (4), Arizona (1), California (23), Colorado (126), Hawaii (1), Idaho (3), Montana (2), Nebraska (1), New Mexico (6), Oregon (16), Utah (2), Wyoming (5), and Washington (4).

Data from recent large floods (median recurrence interval of 75 years), primarily in the western and west-central United States, were used for a comprehensive evaluation of the relation between flood-transported sediments deposited as flood bars and/or slack-water deposits and flood high-water marks (HWMs). Surveys of flood-deposited sediments, HWMs, and channel geometry were made for 192 sites, primarily streams with gradients larger than 0.002 m/m and depths less than about 4.5 m. Analysis of the data indicates that the elevation at the top of the flood sediments (PSIs) is on average 15 mm higher than the HWMs (Figure 2) with a range of –914 mm to +2,347 mm; results slightly vary with type of deposit and location. No statistically significant relation was identified with channel gradient, particle size, discharge, recurrence interval, expansion or contraction ratios, width, or depth variables. The main result from this study is that use of the elevation at the top of flood-deposited sediments (new PSIs), preferably deposits nearest to channel margins, provide a reliable and accurate (±5 percent) indication of the maximum height of the flood.

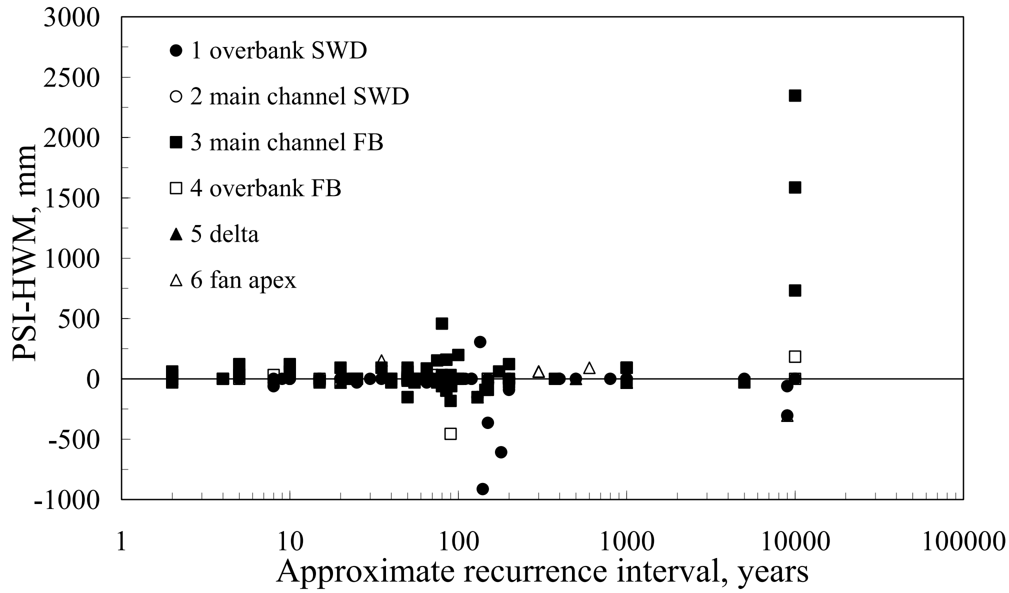

Figure 2. Graph of difference between the elevation of new PSIs and HWMs stratified by deposit type with approximate recurrence interval for recent floods (Source: Jarrett and England, 2001).

In a similar study, Yanosky and Jarrett (2001) studied the height of scars formed by an extraordinary flood in 1996 along Buffalo Creek, a high gradient stream in the Colorado Rocky Mountains southwest of Denver, Colorado. A rainstorm on July 12, 1996, of over 130 mm of rain in about one hour over the rugged mountains that had been severely burned by wildfire on May 18, 1996. The wildfire exacerbated flooding producing unit discharges (peak discharge divided by drainage area) of up to 60 $m^3/s/km^2$; adjacent unburned basins had little to no runoff. Along the reach of Buffalo Creek that tree scars were studied, peak discharges ranged from about 85 m^3/s at the upstream study reach to 500 m^3/s at the downstream end of the reach. The study was conducted along an 8-km reach with bed gradients ranging from 0.01 to 0.04 m/m, thus extending the range of hydraulic conditions for documented tree scar data available for lower gradient rivers (Gottesfeld, 1996). The streambed contains small gravel and boulders up to several meters in diameter. Riparian trees include ponderosa pine, lodgepole pine, Douglas fir, and cottonwood. Scar data were collected from 102 riparian trees along the reach of Buffalo Creek. The elevation of each HWM along the streambank was extended to the top of the highest scar on each tree. The heights of all scars ranged from –60 cm to +150 cm relative to 1996 HWMs (mean +21 cm); 64 scars (63 percent) were within 20 cm (Figure 3). Scar heights relative to HWMs were slightly greater along the upper study reach, possibly owing to increased flow depths, velocity, and flow turbulence. The mean height of scars relative to measured crest elevation along Buffalo Creek was about 40 cm greater than determined along the lower gradient Skeena River in British Columbia (Figure 3) in a comprehensive study by Gottesfeld (1996). Gottesfeld studied scar height of 48 trees along a 170-m reach of river produced by a snowmelt flood in 1990 having a recurrence interval of about 9 years. The height of scars ranged from +9 cm to –80 cm relative to the flood crest (mean was –20 cm). It is possible that extraordinary floods on low-gradient streams might possess sufficient energy to produce a tree-scar distribution similar to that of the high-gradient Buffalo Creek. Although additional tree-scar data are needed from a wider range of hydraulic and botanical conditions, the few studies conducted to date (see Yanosky and Jarrett, 2001) suggest that maximum scar heights provide acceptable estimates of paleoflood stage along both low- and high-gradient streams.

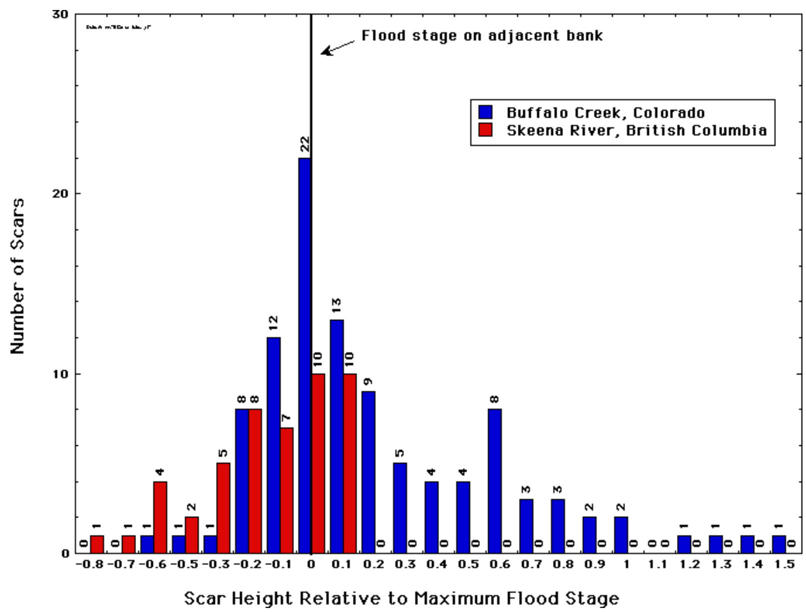

Figure 3. Maximum heights of scars on riparian trees relative to peak flood crest on Buffalo Creek, Colorado (N=102 trees), and on the Skeena River, British, Columbia, (N=48 trees) (Gottesfeld, 1996) (Source: Yanosky and Jarrett, 2001).

A second research summary is provided concerning indirect methods used to estimate peak discharge. Indirectly determining the peak discharge of floods, particularly extraordinarily large floods in higher gradient (~0.01 m/m or larger) rivers, typically has produced overestimated discharges by about 60 percent (Jarrett, 1987). Thus, it is essential that validation of methods and results be used in investigations where possible. Jarrett and England (2001) obtained forty-six peak discharges (Q_{site}) using the critical-depth (35 sites) and slope-conveyance (11 sites) methods for comparison with peak discharges obtained from gage records (Q_{gage}) at or near streamflow-gaging stations by others (Figure 4). Of these Q_{gage} floods, 22 peak discharges were determined using current-meter measurements, and 12 were estimated by using modest rating-curve extensions. Peak discharges also were derived using flow through a flume or over a diversion dam (6 sites), which are believed to be more reliable than the critical-depth and slope-conveyance methods. In addition, Q_{gage} peak discharges were estimated using the slope-area method at six sites for comparison with the critical-depth discharge estimates. The range in the difference of the peak discharge using the critical-depth and slope-conveyance methods is –45 to +43 percent with an average difference of +1 percent. They found 42 of the 46 estimates were within ±25 percent of the gage peak discharge measurements (Figure 4). These results have larger uncertainty in critical-depth and slope-conveyance method estimates compared with Q_{gage} peak discharges of ±12 percent for streams in northwestern Colorado noted by Jarrett and Tomlinson (2000). The floods documented in northwestern Colorado rivers were from relatively small magnitude, snowmelt peak discharges (AEPs of ~0.04). These results for peak-discharge estimation are encouraging because of their ease of use when resources and time preclude use of 1-D (step-backwater modelling) and/or 2-D hydraulic models commonly used in flood and paleoflood studies. The validation with gage data indicates the critical-depth and slope-conveyance methods, when applied in hydraulically good channel reaches, provide reasonable flood estimates.

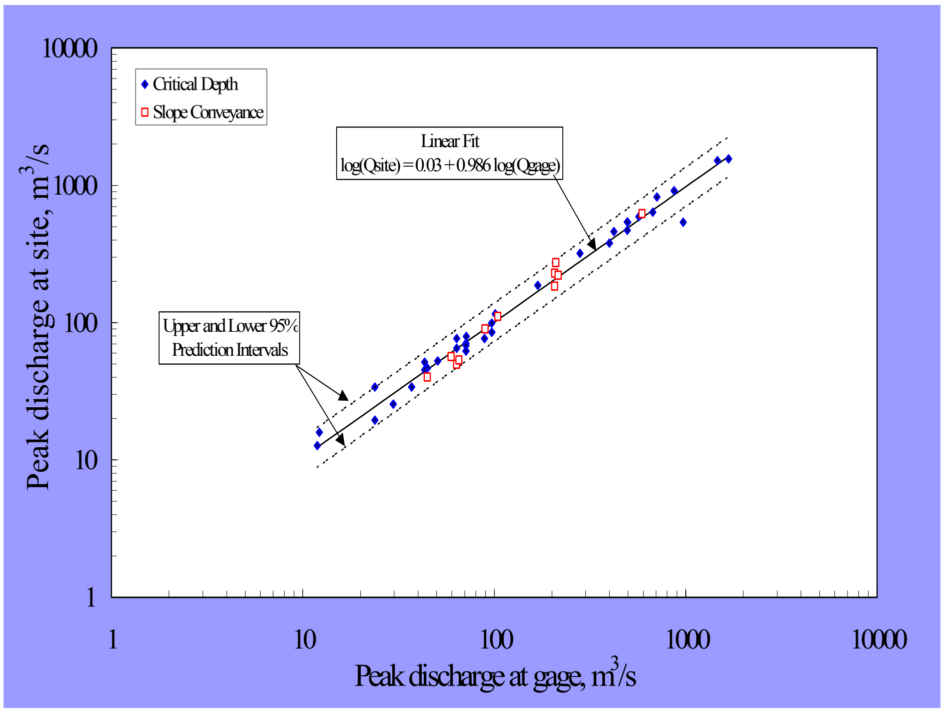

Figure 4. Relation of peak discharge between streamflow-gaging station values and peak discharge computed with the critical-depth and slope-conveyance methods (Source: Jarrett and England, 2001).

Paleoflood techniques have inherent assumptions and limitations that produce uncertain flood estimates. Although paleoflood estimates also involve uncertainties, the estimates are based on interpretations of physical data preserved in channels and on floodplains spanning thousands of years. Paleoflood uncertainties primarily are related to possible post-flood changes in channel geometry and flood heights interpreted from PSIs. Where possible, paleoflood estimates are obtained in bedrock controlled channels that minimize changes in channel geometry. The HWM-PSI relations developed from recent floods in the western United States (Jarrett and England, 2001; Yanosky and Jarrett, 2001; House et al., 2001) help to improve the reliability of paleodischarge estimates. Validation of the critical-depth and slope-conveyance methods to estimate peak discharge is encouraging and provides a cost-effective framework for additional validation (Jarrett and England, 2001).

A Recent Applied Paleoflood Study: Elkhead Reservoir, Colorado

This section provides a summary of an applied paleoflood study for Elkhead Reservoir on Elkhead Creek near Craig in the Colorado Rocky Mountains (Jarrett and Tomlinson, 2000). The cost-effective approach, which can be used in many other hydrometeorologic settings, was applied to Elkhead Creek basin (531 km^2) in northwestern Colorado; the regional study area was 10,900 km^2. A regional, interdisciplinary paleoflood approach provides a more thorough assessment of flooding and with site-specific PMP/PMF studies provide dam safety official with new information to assess extreme flood potential. The study was conducted for the Colorado River Water Conservation District to complement a site-specific PMP by Tomlinson and Solak (1997) and a PMF study by Ayres Associates Inc. in Fort Collins, Colorado, for Elkhead Reservoir. Elkhead Reservoir was being recertified for hydrology safety by the Colorado State Engineer. PMP estimates are considered of lesser reliability along the Continental Divide, which includes the upper Yampa River basin. Therefore, a site-specific PMP study was conducted to address issues raised by the NRC (1988, 1994) pertaining to the hydrometeorology for the basin and the surrounding geographical and climatologically similar region. Inherent in a site-specific PMP study are analyses of extreme storms that have occurred in the region since the generalized hydrometeorology report was published. Site-specific hydrometeorologic studies are being conducted because dam-safety officials recognize the difficult problems inherent in PMP estimates in the Rocky Mountains. Utilization of an interdisciplinary regional paleoflood study provides additional supporting information for understanding the magnitude of the largest contemporary floods and paleofloods with estimates of the PMF potential for a particular basin. Interdisciplinary components included documenting maximum paleofloods, and analyses of contemporary extreme rainfall and flood data in a basin and in a broader regional setting. Site-specific PMP studies were conducted to better understand extreme rainfall processes by analyzing the rainstorms with similar hydroclimatic conditions (Tomlinson and Solak, 1997). The approach provides scientific information to help determine the delicate balance between cost of infrastructure and public safety.

Paleoflood data using bouldery flood deposits and non-inundation surfaces for 88 streams were used to document maximum flood discharges that have occurred during the Holocene. A variety of relative dating techniques (degree of soil development, surface-rock weathering, surface morphology, lichenometry, and boulder burial) were used to determine the paleoflood record length for paleoflood deposits and non-inundation surfaces. Peak discharge for a paleoflood deposit was obtained primarily using the critical-depth and slope-conveyance methods. Maximum paleofloods provide physical evidence of an upper bound on maximum peak discharge for any combination of rainfall-or snowmelt-runoff in northwestern Colorado in at least the last 5,000 to 10,000 years (since deglaciation).

No evidence of substantial flooding was found in the study area. The maximum paleoflood of 135 m^3/s for Elkhead Creek is about 13 percent of the site-specific PMF of 1,020 m^3/s. Envelope curves encompassing maximum flood at 218 sites (Figure 5) and rainfall at 181 sites were developed for northwestern Colorado to help define maximum contemporary and Holocene flooding in Elkhead Creek and in a regional frequency context. Paleoflood estimates incorporate the effects of climatic changes on hydrology during the period of the paleoflood record. Certainly, moderate climate changes (or other changes such as wildfire effects on flooding or vegetation changes) have occurred during the Holocene; however, these effects are reflected in the maximum flood preserved at a site. Paleoflood data where the maximum age during which the flood occurred is at least 5,000 years are denoted with large, solid triangles and as small, solid triangles for less than 5,000 years (Figure 5). The envelope curve of maximum flooding incorporating the paleoflood data (Figure 5) is about 20 to 25 percent larger than contemporary maximum flooding in about the past 100 years since streamflow monitoring began. This modest increase likely is due to the large spatial extent of the data and relatively low-magnitude flooding in northwestern Colorado. Variability in climate and basin conditions during the Holocene does not appear to have had a large impact of flood magnitude, and that the assumption of stationarity may be valid for the upper end of the flood-frequency curves in the study area. Thus, the envelope curve probably reflects an upper bound of flooding during the Holocene in northwestern Colorado, which includes the effects of climate change and other factors (wildfire and vegetation changes) during the Holocene.

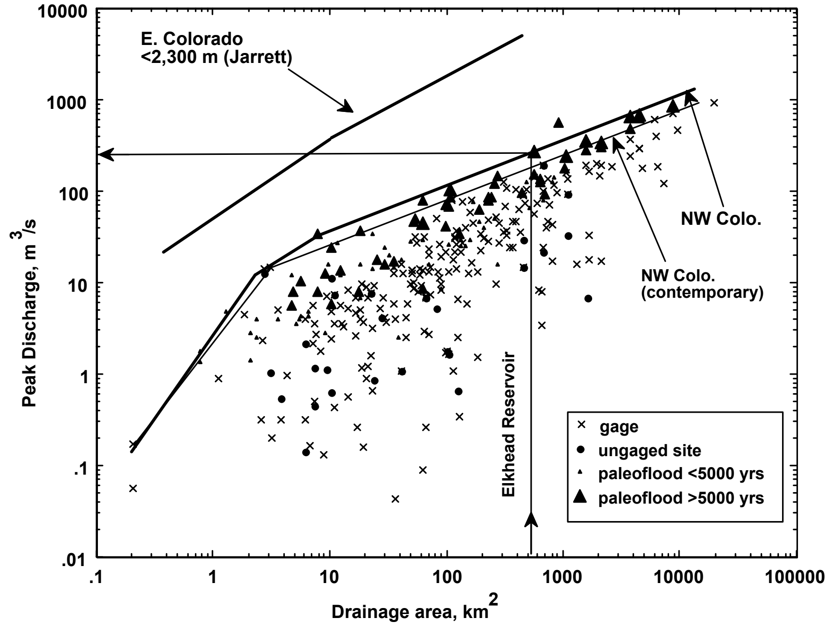

Figure 5. Relation between contemporary and paleoflood peak discharge and drainage area with envelope curves for northwestern Colorado. The envelope curve of maximum flooding for eastern Colorado is shown for comparison (Source: modified from Jarrett and Tomlinson, 2000).

Maximum observed 24-hr rainfall is about 150 mm in about the past 100 years for northwestern Colorado (see Jarrett and Tomlinson, 2000), which provides additional support for the lack of flood and paleoflood evidence. Maximum rainfall and flooding in northwestern Colorado is substantial less than in eastern Colorado, which is subject to some of the most extreme rainfall flooding in the United States where maximum 6-hour observed rainfall has approached 610 mm. Large floods, if as hypothesized by transposition of such large rainstorms into northwestern Colorado and PMF magnitude floods, would have left recognizable paleoflood evidence in at least one of the 88 streams studied, but no substantial out-of-bank flooding was identified.

A critical assumption for calculation of synthetic rainfall-runoff modelling approach, including PMP estimates, is geographic transposition of storm events from geographically and climatologically similar locations to watershed of interest. However, the NRC (1994) cautions that storm transposition and moisture maximization needs to be for a slightly different location in the same hydroclimatic region. Regional analyses of rainfall, streamflow, and paleoflood data in the present study provide information to evaluate the assumptions about large rainstorms in northwestern Colorado. The assumption that large rainstorms or rain-on-snow produce large floods in the Rocky Mountains (FEMA, 1976; Hansen et al., 1977; Hansen, et al., 1988) has implications for dam safety and floodplain management. Although a number of streamflow-gaging stations in the northwestern Colorado had over 75 years of record, but no large rainfall floods, these long-term gage data were assumed not to be representative of extreme flood potential from rainfall by FEMA (1976). Thus, the flood hydrology for some studies was based on transposing distant, large rainstorms from Arizona, New Mexico, and southwestern Colorado into northwestern Colorado and using rainfall-runoff modelling to adjust the upper end of the gage flood-frequency relation (FEMA, 1976).

Flood-frequency relations using the Expected Moments Algorithm (England, 1998), which better incorporates paleoflood data, were developed to assess the risk of extreme floods. Flood-frequency analyses were made for eight streamflow-gaging stations. The flood-frequency relations for Elkhead Creek basin are shown in Figure 6. The relations were developed at a gage site upstream from Elkhead Reservoir and using regional regression relations to estimate magnitude frequency at the reservoir. The flood-frequency relation for Elkhead Creek at Elkhead Reservoir developed by Ayres Associates, Inc. (written commun., 1996) (Figure 6) essentially is the same as the flood-frequency relations from this study up to about the 20-year flood. The Ayres relation sharply increases above the 20-year flood due to rainfall-runoff modelling, falls outside the confidence limits of the regional flood-frequency relations above the 50-year flood, exceeds the maximum paleoflood for the basin at a recurrence interval of about 150 years, and exceeds the envelope curve value of 250 m^3/s, which is not reasonable hydrometeorologically. Similar results were noted for other streams in northwestern Colorado. The difference for larger recurrence intervals primarily results from transposition of distant rainstorms over basins in northwestern Colorado and then using rainfall-runoff modelling to estimate the upper end of flood-frequency relation as well as the PMF. The gage and paleoflood data based on the evaluation of physical evidence in channels provide information that can be used to refine assumptions used to estimate extreme flooding using storm transposition and rainfall-runoff modelling to at least a recurrence interval of 5,000 years. The paleoflood data provide no support for sharp upward slope increase of the frequency curve. The lack of substantial rainstorms and flood evidence in northwestern Colorado probably is explained by high mountain barriers, which substantially reduce the available atmospheric moisture from the Pacific Ocean or Gulf of Mexico.

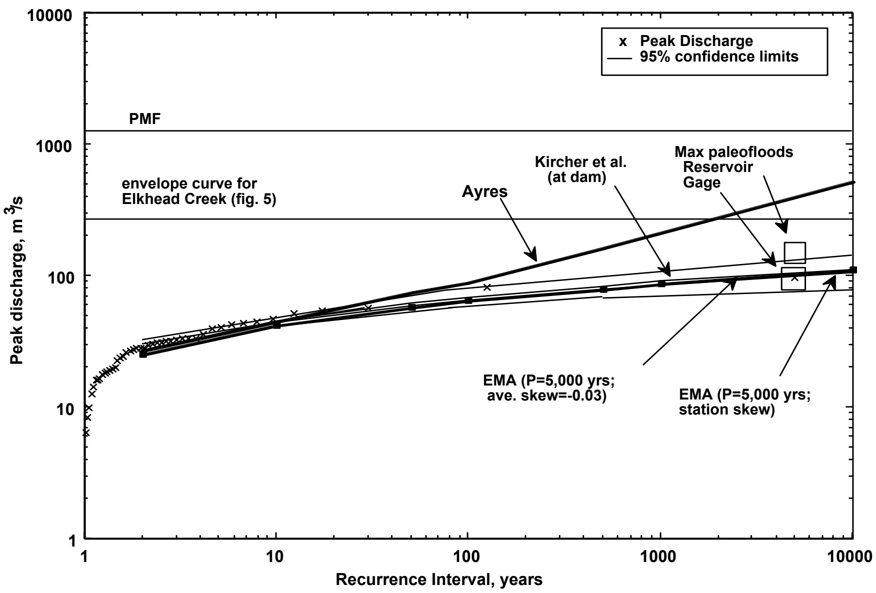

Figure 6. Flood-frequency relations for Elkhead Creek at Elkhead Reservoir using regional regression equations with paleoflood data (shown as a rectangle) at the reservoir; near Elkhead gage (0924500) with paleoflood data (shown as a rectangle) using at-site and average skew with 95 percent confidence limits. P denotes the paleoflood length of record. The envelope curve value (Figure 5) for maximum flooding in the Holocene is also shown. The flood-frequency relation and probably maximum flood for Elkhead Reservoir (Ayres Associates, Inc., Fort Collins, Colorado, unpublished data) are shown for comparison (Source: Jarrett and Tomlinson, 2000).

The site-specific PMP study conducted for the Elkhead Creek drainage basin west of the Continental Divide in northwestern Colorado revisited various issues related to the PMP under the explicit conditions which exist at Elkhead Reservoir and other reservoirs in northern Colorado (Tomlinson and Solak, 1997). These issues included a physical accounting of the effect of topography on storm transpositioning, downslope wind flows under PMP storm conditions and high altitude moisture depletion.
The combined results of the site-specific PMP/PMF study and the regional interdisciplinary paleoflood study showed that Elkhead Dam would not be overtopped from the site-specific PMP. These results were accepted by the Colorado State Engineer for dam-safety certification with no modifications to the existing structure.

Changnon and McKee (1986) estimated the cost for modifying just the 162 high-risk dams in Colorado to the PMP standards (Hansen et al., 1988) was approximately $184 million. This modification cost appears low as the estimated modification cost for proposed modifications of the Cherry Creek dam are as high as $250 million for Cherry Creek dam near Denver, Colorado (U.S. Army Corps of Engineers, written commun., 1997). There are over 10,000 dams in the Rocky Mountain region that may need to be modified for current PMP criteria during dam safety recertification. Thus, given the large differences in maximum paleoflood and PMF values in the Rocky Mountains, it seems prudent to conduct additional hydrometeorologic and paleoflood research to help reduce the uncertainty in estimates of maximum flood potential. This regional interdisciplinary paleoflood approach, which is cost-effective, can be used in other hydrometeorologic settings to improve flood-frequency relations and provide information for a risk-based approach for hydrologic aspects of dam safety.

Considerations for Future Research

The IACWD (1982, p. ii) indicated that the Nation's flood frequency guidelines are a continuing effort and that much additional study is needed to achieve correct and consistent guidelines. Many alternative approaches for flood-frequency analysis have been developed since 1982. Updated, consistent, reliable, and uniform guidelines/approaches are needed to determine flood flow frequencies in order to have an effective flood damage abatement and related environmental assessment programs within Reclamation, the COE, the USGS, and other water agencies. Increasing flood losses, increasing emphasis on risk assessments for dam safety, improved floodplain management, and numerous related needs emphasize the need to improve methods to estimate the magnitude-frequency relations of flooding. Credible flood estimates, particularly with very small AEPs, are needed as input to risk assessments for determining appropriate levels of public safety, prioritizing projects, and allocating limited resources.

The need to develop more efficient and robust flood-frequency estimates for a wide array of water resources applications as quickly as feasible are widely recognized. The Bureau of Reclamation and U.S. Geological Survey recently proposed a $5 million, 5-year study to update and improve the Nation's guidelines of flood frequency and related issues. The goals of the proposed study "Improvements to Flood Frequency Analysis Techniques" are to develop new guidelines for flood frequency analysis and to demonstrate the viability of using emerging technologies in applied flood frequency analyses.

Initially, Bulletin 17B guidelines (log-Pearson 3, LP3), expected moments algorithm (EMA), maximum likelihood estimators (MLE), and L-moments (LMOM), and other flood frequency estimation techniques, including regional approaches will be evaluated. A compilation and comparison of flood frequency estimates using EMA, MLE, and other new methods is then planned. A comprehensive model validation with field data is the critical component to the success of the new guidelines. Input on future directions and needs in flood frequency will be obtained from other agencies, universities, and consulting engineers and scientists. Five representative hydrologic regions in the United States will be used to evaluate proposed new flood-frequency methods and guidelines. Recommendations will be proposed for changing the flood frequency analysis guidelines for consideration by the IACWD and other water management agencies.

An integrated science approach will be used to involve participation of Reclamation and USGS engineers and scientists as well as full IACWD participation to help meet the needs of the water-resources community. Probabilistic hazard-estimation requires extrapolation well beyond the limits of gage and historical data. Thus, extrapolation requires improved understanding of physical processes and extending the observational record with paleoflood data. Though not a direct component of this proposal, a strong interagency commitment is needed to enhance detailed storm and flood documentation, long-term basic and applied research, applied flood-hazard assessment, and improved model interfaces for model users. The following tasks will be addressed; tasks are prioritized by need but may change depending on needs of funding agencies.

Extrapolation techniques for probabilistic risk assessment. Extrapolation of flood-frequency relations for return periods exceeding the 50-year flood (AEPs <0.02), which are most important to flood-plain managers and dam-safety officials. This analysis will focus on floods for AEPs ranging from 0.02 to 0.0001 (50- to 10,000-year range), though reliability of the entire frequency curve will be emphasized. Determining the amount and types of data needed to credibly extend flood frequency relations to small AEPs are a primary focus of this element. Various regional approaches for flood-frequency analysis for probabilistic risk assessments will be evaluated.

Improve methods to evaluate the effects of land-use changes on flood hydrology. These changes include hydrologic effects of wildfire, urbanization, and changes in vegetation patterns on flood magnitude and frequency (forms of non-stationarity issues). Separate, regional flood data sets for recent flooding, which document the effect of wildfire and urbanization, derived using paleohydrologic techniques, are available and proposed for study. The flood data and associated detailed rainfall data will be evaluated with rainfall-runoff modelling and geospatial (GIS-based) statistical methods. Generally, few data are available to properly assess non-stationarity issues. Thus, flood-hazard assessments can conducted using precipitation modelling and hydraulic modelling practices (Leavesley et al., 1996; Vecchia, 2001; Smith et al., 2000). These analytical tools will be used to develop and evaluate viable methods to quantify the effects of land-use changes on flood hydrology.

Flood frequency for regulated-flow streams. Develop a procedure for estimating flood-flow frequency downstream from flood regulating structures. Members of the IACWD Subcommittee on Hydrology have begun collecting approaches used by various agencies. However, the information should be evaluated and assembled in a fashion usable to practicing engineers, hydrologists, and scientists in related fields.

Climatic variability, non-stationarity issues. Evaluate the effects of natural and anthropogenic climate change on flood frequency. Paleoflood, historical, and gage data would be examined to evaluate non-stationarity of the flood record over varying time scales and the impact on the resulting flood-frequency relations. Regional paleoflood data available for five diverse hydrologic regions in the west-central

United States will be used to assess the effects of climate change on flood magnitude. [Currently there are no regional paleoflood data for the eastern United States, however, if they become available, they will incorporate them into the analyses.] These data then will be used to test and evaluate various assumptions of hydrologic modeling scenarios of climate change effects on flood magnitude and frequency.

Products include several reports and supporting journal articles summarizing unified, state-of-the-art techniques for flood-frequency estimation that have general application for water-resources investigations. Recommendations will be proposed for changing the flood frequency analysis guidelines for consideration by the IACWD and other water management agencies. Benefits of the proposed study will include improve guidelines for flood hazard assessments, flood inundation mapping and as input to risk assessments for determining appropriate levels of public safety, prioritizing projects, and allocating limited resources. A major benefit of the proposed study supports the National Flood Insurance Reform Act of 1994 mandates that the Nation's flood maps be revised in the near term and subsequently reviewed every 5 years. The FEMA estimates that updates to existing flood insurance studies and creating new maps for communities without mapping will cost between $800 million and $1,000 million. FEMA's Map Modernization Plan also emphasizes that more cost-effective methods to produce flood maps are essential.

Concluding Remarks

We hope to stimulate discussion of research needs, including optimizing a balance of "flood chasing" and detailed modeling approaches of paleoflood investigations. Our results indicate further research is needed that better accounts for physical processes of flooding, for sediment transport and deposition during flood conditions, and the need to improve methods for estimating peak discharge of floods and paleoflood. There is much work to be done to improve our understanding of the distribution and location of sediment deposits and erosion thresholds of surfaces from extreme floods. A better understanding of the physics of large flood response and better predictive capabilities than those documented here is needed. Research is needed to identify other types of PSIs, if they exist, and to better understand geomorphic effectiveness of floods. More quantification (e.g., using 1-D or 2-D hydraulic modelling to calculate paleoflood discharges, using absolute-age dating of flood deposits and validation of relative-age dating methods, particularly developing guidelines for more robust flood-frequency parameter estimation procedures, regional flood-frequency analysis with paleoflood data, etc.) are essential for dam safety risk assessments, flood-inundation mapping, flood-plain management, and related environmental investigations. While use of complex procedures provide slightly more precise quantitative description of the data, discharge and frequency estimates of extreme floods in a basin may be readily estimated by the cost-effective approach paleoflood techniques described above, the ability to have multiple approaches that fits the needs and resources specific to a specific water-resources application are needed.

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Current Hydrologic Practices, Problems, and Needs
Within California's Dam Safety Program

By
Melissa Collord

Introduction

There are over 1,200 dams within the jurisdiction of the California Department of Water Resources (DWR), Division of Safety of Dams (DSOD). The dams are located throughout the state and have drainage basins that vary in size from portions of an acre to thousands of square miles. DSOD requires that all dams within its jurisdiction be capable of adequately passing a selected design flood. A method was developed by DSOD to estimate flood hydrographs for ungaged or poorly gaged watersheds for use in spillway evaluation.

Methodology

The procedure devised by DSOD in 1981 to determine the hydrologic adequacy of any spillway in California consists of eight parts:

1. Assessment of the potential downstream hazard
2. Determination of appropriate storm return period
3. Development of precipitation
4. Development of synthetic unit hydrograph parameters
5. Development of loss rate parameters
6. Computation of the flood hydrograph
7. Routing of the flood hydrograph through the reservoir
8. Evaluation of the spillway adequacy

The following discussion will focus on parts 4 thru 6, their basic concepts and shortcomings.

Unit Hydrograph

DSOD utilizes Clark's method to develop a synthetic unit hydrograph. Clark's unitgraph parameters are obtained from a generalized study, conducted in 1971, of observed rainfall and runoff events, which related these parameters to drainage basin characteristics by regression analysis. The study is applicable to the State of California except the area south of the Tehachapi Mountain Divide and the area east of the Sierra Nevada Divide. The regression equations relate the drainage basin characteristics of stream length, area, elevation, and ground cover to the time of concentration (t_c) and Clark's storage coefficient (R) for development of a basin-specific unit hydrograph. The study also presents guidelines for estimating loss rate parameters.

Flood Hydrograph

The flood hydrograph is developed using the computer program HEC-1 (Hydrologic Engineering Center, 1981). The program obtains the flood hydrograph by convolution of the effective rainfall increments with Clark's unitgraph. Losses due to surface retention and infiltration are estimated by the exponential loss rate function within HEC-1. The general criteria is that the percent runoff should not be less than 70 when the mean annual precipitation (MAP) at the basin is greater than 25 inches and should not be less than 60 when the MAP is 25 inches or less.

If applicable, allowances for snowmelt, base flow in the basin, runoff from prior storms, import of water, etc., are added to the storm runoff hydrograph to obtain the design flood hydrograph for the watershed.

Problems Faced

The regression equations provide a rational, consistent and simplistic method to developing a basin-specific synthetic unit hydrograph. However, with the advent of faster and more sophisticated computers and programs, such as HEC-HMS, calibration of basin models has become easier and a more widely used approach. The optimization feature in HEC-HMS estimates unit hydrograph and loss rate parameters with observed rainfall and flow data. Unfortunately, there still exists the problem of a lack of basic hydrologic data in most small drainage basins. This makes it impossible to calibrate a basin's unitgraph and loss rate or to check the reasonableness of a synthetic unit hydrograph. Therefore, we highly recommend that more research be conducted into developing unit hydrographs and determining loss rates for small ungaged basins.

Modeling large ungaged drainage basins that range in size from 100 to 1000 square miles present an even more difficult task. In addition to determining the unit hydrograph parameters for each subbasin, channel routing or lag time must now be included in the analysis. The methods that are available in determining routing parameters (DSOD typically uses the Muskingum routing method) are imprecise and our level of confidence in accurately defining the routing conditions is low.

Utilization of HEC-HMS as our primary tool to perform our hydrology and reservoir routing calculations will occur in a very gradual process as more staff members are exposed or are given training to operate the program. Several staff members have already received some training on HEC-HMS, but are unable to use the program since the exponential loss rate function is no longer available and in some cases snowmelt calculation is needed. DSOD can certainly modify loss rate assumptions to be compatible with HEC-HMS, but we do encourage HEC to incorporate snowmelt calculations into HMS as soon as practical.

Bureau of Reclamation Hydrologic Research

Presented at the FEMA Workshop on Hydrologic Research Needs for Dam Safety
By
Robert E. Swain, Louis C. Schreiner, and Daniel R. Levish

Introduction

The U.S. Bureau of Reclamation is now making extensive use of quantitative risk assessment in support of dam safety decision-making (Von Thun and Smart, 1996). An important input to Dam Safety Risk Assessment is the development of probabilistic extreme flood estimates. The focus has shifted from routing a single "maximum" event (i.e. the probable maximum flood, PMF) to consideration of the entire range of plausible inflow flood events, and ultimately to the magnitude-frequency relationship of maximum reservoir stages.

Reclamation has identified the need for a review of its present procedures for developing probabilistic extreme flood estimates and their associated uncertainties for use in dam safety risk assessment. Where practical, Reclamation would like to develop improved procedures. The following sections of this paper describe ongoing hydrologic research activities for use in dam safety analysis.

Flood Hydrology Database

A variety of hydrologic data are used as input in flood frequency analyses, probabilistic hydrographs, stochastic rainfall-runoff models and other hydrology studies aimed at making flood hazard probability statements for use in risk analyses. The physical understanding and modeling of extreme flood events requires collection and review of a variety of flood hydrology data including peak discharge and mean daily stream flow records, precipitation (rainfall and snowfall) and temperature data, soil data, paleoflood information, extreme rainfall data, and many other sources of information. A searchable database that includes organized and connected lists of available data, visual selection capability, and links to the data would allow faster and more thorough assessment.

The purpose of this research is to continue development of a hydrology database that will include a variety of hydrology data such as peak discharge estimates, paleoflood data, precipitation and temperature data, as well as potential sources of infiltration characteristics and other geologic properties of drainage basins. These data would be used as input into flood frequency analyses, probabilistic hydrograph development, and prediction of basin response in stochastic modeling of extreme flooding. This project focuses on the development of a flood hydrology database that identifies, summarizes, and links hydrologic data that is needed for developing flood frequency analyses and probabilistic hydrographs, as input for stochastic rainfall-runoff models, and other hydrology studies. The eventual goal of this project is to provide spatial and temporal data for use in probabilistic flood hazard studies in the 17 western states.

A variety of data including information on extreme peak discharge have been gathered for the Sierra Nevada region of northern California. Paleoflood data have been gathered throughout the western U.S., as well as in a database at the University of Arizona, tree.ltrr.arizona.edu/~katie/paleofld.html. Currently, Reclamation has a paleoflood database in Microsoft Access and hydrology database in Arcview exist as separate databases. These databases need to be integrated into one database in order to efficiently store and access information for flood-related studies. In addition, computer code and a user interface have been developed for the hydrology database that will allow the user to access records by graphically selecting an area. By the end of 2002, a preliminary user-friendly database is scheduled for completion. This data information system will require updating and continual maintenance.

Revision and Update of Precipitation-Frequency Studies for the United States and Its Possessions

Since the mid 90's, meteorologists in both Reclamation's Flood Hydrology Group and River Systems & Meteorology Group have been addressing the need to revise and update precipitation-frequency estimates for the United States. The demand for this work is obvious in that precipitation-frequency atlases presently used by Reclamation are woefully outdated, with the far majority of the previous studies dating back 30 to 40 years ago, and lack extensions to important meteorological parameters (duration, area, return period, etc.). This information is used in establishing hydrologic design criteria for the safety evaluation of water control structures (dams, canals, levees, culverts, etc.), design of other types of construction (roads, bridges, flood warning systems, etc.), and for establishing project operational criteria. Results of this work will provide consistent precipitation-frequency information that can be incorporated in risk assessments that are used in current/future flood hydrology studies.

The project is a cooperative effort among several federal, state, and local agencies involved in water resource management. The National Weather Service (NWS), Hydrometeorological Design Studies Center (HDSC) is the lead agency for accomplishing the work with participation from other agencies (financial, in-kind-services) dependent on their interest/needs to provide support for the particular region under investigation. Because of the large amounts of data to process and the need to test new meteorological and statistical analysis techniques, the United States and its Possessions were broken into nine separate zones. Presently, four of these zones are under development in varying degrees. These zones include: Semiarid Southwest, the Ohio River Basin and Surrounding States, Hawaii, and Puerto Rico and the Virgin Islands. Work on a fifth study region, the Upper Midwest, has been started by Reclamation to assemble maximum daily precipitation (prior to 1949) data. For the next couple of years, Reclamation expects to continue with data set development for the Upper Midwest, but concentrate its effort on development of Depth-Area (DA) relationships used to adjust point precipitation-frequency values to representative areal average precipitation-frequency estimates.

The Semiarid Southwest, Ohio River Basin and Surrounding States, and Puerto Rico and the Virgin Islands zones are scheduled for completion in 2002. Hawaii is scheduled for completion in 2003. Current updates/progress reports concerning all work underway is available at: http://www.nws.noaa.gov/oh/hdsc. The precipitation-frequency work as completed will be published as NOAA Atlas 14, Volume (#). It is expected that the entire Atlas will be completed by 2006.

Probabilistic Flood Hydrographs

Flood runoff hydrographs integrate the drainage basin and channel response to precipitation and snowmelt, given some initial, variable state of moisture throughout the watershed. Probabilistic flood hydrographs are developed to assess the adequacy of the spillway and reservoir flood/surcharge space to temporarily store a portion of the flood volume, and to attenuate or pass the hydrograph peak without overtopping the dam. Flood hydrographs are needed for situations where: the reservoir inflow peak discharge is greater than the maximum spillway capacity; the reservoir has a large, carry-over storage; and/or the reservoir has dedicated flood control space. The focus of this research is to develop a simplified approach for estimating probabilistic hydrographs that can be used for appraisal or feasibility level studies, and to develop a simplified method of extrapolating flood frequency curves.

Basic streamflow hydrograph methods (e.g., Chow et al., 1988; Bras, 1990) are used to estimate properties for probabilistic hydrographs. These methods include peak and one-day mean discharge identification, selection of hydrograph shape and duration, base flow identification and separation, and direct runoff volume estimation. Peak discharge and mean-daily streamflow records are used because this source is the best information on flood magnitudes that are likely to occur in the future, based on what occurred in the past (Pilgrim and Cordery, 1993).

The key idea is calibration or scaling of hydrographs to match a particular peak discharge for a given probability. The approach relies completely upon the specification of a peak flow frequency curve that describes the probabilities of interest. Peak discharge estimates, n-day maximum mean flows, and observed hydrographs at the site of interest are used as a sample to represent potential extreme flood shapes and volumes. The largest peak and volume hydrographs are utilized as a basis to scale.

There are five major assumptions for developing the hydrographs: (1) the probability of peak discharge is sufficient to represent a probability of the composite hydrograph; (2) unit hydrograph (e.g., linearity) assumptions apply to the basin; (3) direct runoff volumes can be estimated from daily flow hydrographs; (4) peak discharge - maximum mean n-day flow relationships can be extrapolated; and (5) the recorded streamflow observations, historical information, and paleoflood data provide an adequate sample to base extrapolations to extreme floods.

The anticipated completion date for this project is early 2002.

Improved Flood Frequency Extrapolations and Runoff Modeling

The purpose of this research project is to develop improved methods to extrapolate flood frequency curves and develop extreme flood hydrographs. The major approach to flood frequency extrapolation will be based on a combination of rainfall extrapolation and derivation from physically based runoff mechanisms. Rainfall-runoff models will be used to derive the peak discharge frequency distribution from input basin characteristics and precipitation, and be used as the basis for frequency curve extrapolation. The CASC2D rainfall-runoff model will be evaluated and tested for application at Reclamation sites, and compared with a stochastic event runoff model (SEFM) developed by Dr. Melvin Schaefer for Reclamation. CASC2D is a 2-dimensional, distributed rainfall-runoff model that has successfully reproduced the 1997 Fort Collins flood. The main precipitation and stochastic components used in SEFM will be added to CASC2D. It is anticipated that model selection and extrapolation functions can be derived from the watershed topography, hydraulic routing characteristics, and precipitation characteristics at Reclamation dams. Input rainfall will be derived from frequency analysis or from stochastic storm generation. Flood frequency and hydrograph uncertainty bounds will be approximated by simulation. Models will be compared on a large (>500 mi^2) basin where paleoflood data are available.

Progress has been made in developing hydrograph-scaling techniques for appraisal and feasibility studies that require low effort and expense. These techniques have been applied to several projects such as Pineview/Deer Creek, Red Willow, North Platte, and Folsom Dams. Internal and external reviewers have pointed out several shortcomings of that work including, assumptions of linear runoff and extrapolation, use of observed hydrographs, failure to separate rainfall and snowmelt, and the challenges of using the techniques at larger basins (greater than about 500 mi^2). This research project attempts to address many of these concerns.

This research can be applied to Dam Safety projects where flood peaks and hydrographs are needed with return periods that exceed 1,000 years. The extrapolation research can be applied to sites where loss of life is large, as floods with return periods greater than 10,000 years are sometimes needed. The research will be span three fiscal years and conclude in 2004.

Rainfall-Runoff Modeling Using National Weather Service 1,000-year Return Period Precipitation Estimates at Causey Dam, Utah

Recently, the Flood Hydrology Group completed a study where the frequency estimates were extrapolated to a return period of 200,000 years. The method used a two-point extrapolation to 200,000 years using the mean of the gage data and the mean of the paleoflood range. This was the first attempt to extrapolate frequency data beyond a 10,000-year return period and several assumptions were made that may not be accurate. For example, the stream gage data in the Wasatch Range are dominated by snowmelt events, yet the distribution selected in the study was based on rainfall distributions. The intention of this study is to provide another independent data point and to verify the conclusions reached in the previous analysis.

This investigation will use the draft precipitation values developed by the National Weather Service (NOAA Atlas 14, Vol 1, DRAFT) to produce a 1,000-year assumed thunderstorm event at Causey Dam, Utah. These values will be input to a rainfall-runoff model (HEC-1 or FHAR) to develop the 1,000-year thunderstorm flood event for Causey Dam. This peak discharge estimate will be compared with the frequency analysis developed for Causey Dam. Causey Dam was selected as the test case because there is existing at site paleoflood data to use in comparison, the drainage area is relatively small (137 mi^2), and it has a significant amount of streamflow and other comparative data developed. The estimated completion date would be June 2001.

Probabilistic Flood Hazard Workshop

The introduction of risk analysis for dam safety signaled a significant change in the way the Dam Safety Office and the Technical Service Center conduct flood hazard assessments. The purpose of this project is to compile, review, and evaluate current state-of-the-knowledge on probabilistic techniques used in flood hazard assessment. External experts in various aspects of flood hazards will be brought in to Reclamation on an individual basis. It is intended that each person present a Technical Update Lecture (1-2 hours). Members of the Flood Hydrology Group will subsequently meet with them to discuss their research in detail and potential technology transfer to Reclamation.

About 12 experts participated in the workshop last year. These experts have helped the Flood Hydrology Group map out future methods, improve current methods, and plan a program for probabilistic flood hazard analysis to meet Dam Safety Office needs.

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Chow, V.T., Maidment, D.R. and Mays, L.W. (1988) Applied Hydrology. McGraw-Hill, New York, 572 p.

Pilgrim, D.H. and Cordery, I. (1993) Flood Runoff. In Handbook of Hydrology, Maidment, D.R. (ed.), McGraw-Hill, New York, Ch. 9, pp. 9.1-9.42.

Von Thun, J.L. and J.D. Smart (1996) Risk assessments support dam safety decisions, USCOLD Newsletter, Issue No. 110, Nov 1996, U.S. Committee on Large Dams.

RESEARCH NEEDS SUMMARY

Jerry Webb, Huntington District, Corps of Engineers

- Antecedent rainfall
- Multiple Reservoir Systems
- Probable Maximum Rainfall distribution included in HMS
- AEP of PMF
- Guidelines that incorporate
    - Orographic effects
    - Large drainage areas subject to frontal movement storms
    - Multiple reservoir systems
    - Addressing lack of historic data for calibration
    - Antecedent rainfall conditions
    - Variations in operational scenarios for extreme events

Jeff McClenathan – Omaha District, Corps of Engineers

- R&D Efforts
    - Portfolio risk analysis
    - Loss of life
    - Extend frequency curves beyond .001 event
    - Develop probabilities of various types of failure mechanisms
    - AEP of PMF
- Policy Needs
    - Concerns over site specific conditions such as topography impacting rainfall and runoff
    - The need for independent review of work to overcome the potential disagreements from the use of judgment in the analysis
    - How to make consistent, reproducible studies given the amount of judgment that will be needed
    - How and when to include paleoflood evidence (when available) and the appropriate level of detail
    - Consistency on the use of antecedent storm conditions
    - When to use risk analysis and the level of detail needed to incorporate it

James Chieh, Los Angeles District, Corps of Engineers

- General Research Needs
    - AEP of PMF
    - Procedure for filling the large gap between observed hydrologic data and PMF estimates
    - Hydrologic methods consistent over large areas due to need to assess multiple dam failures in same watershed
    - A practical approach to uncertainty analysis to enable better (more meaningful) evaluations than sensitivity analysis.
- Specific Research Items

    - Case studies of observed extreme flood events as compared with PMF and discharge and volume frequency estimates
    - Antecedent precipitation and soil moisture
    - Unit hydrograph characteristics (efficiency of runoff or time of concentration findings)
    - Compilation of paleo-hydrologic information nationwide and integration with PMF & discharge-frequency estimates; generalize findings if possible.

Earl Eiker – Headquarters, Corps of Engineers - Retired

- Traditional H&H Research Needs
    - Flood Series and Flood Runoff Volume
    - Spillway Erosin
- Risk Analysis Research Needs
    - Paleoflood hydrology
    - Stochastic hydrology
    - Use of meteorological and historical flood data to extend record lengths
    - H&H Parameters (antecedent conditions, unit hydrograph uncertainties, routing coefficients, dam breach formation, wave propagation, operational uncertainties)
    - Loss of Life estimates

Lou Schreiner, Bureau of Reclamation

- Current Research Projects
    - Flood hydrology database
        - Discharge estimates
        - Paleoflood data
        - Precipitation and temperature data
        - Soil characteristics
    - Precipitation-Frequency studies for the United States
        - Update precipitation-frequency atlases
        - Zone based analysis
    - Flood Frequency Extrapolations
        - Extrapolate flood-frequency curves and develop extreme hydrographs.

Michael Davis – Federal Energy Regulatory Commission

- Probable Maximum Flood Studies
    - Orographic impacts on the PMP
    - Additional research on combination of snowmelt contribution factors such as snowpack, temperature wind.
    - Distributed loss rate method and STATSGO data
- Dam Break Studies
    - Breach parameters for rock and earth fill dams

        - Unsteady flow computer models for complex dams and multiple spillways

Greg Lowe – Tennessee Valley Authority

- Risk Analysis
    - Development of methodology to analyze risks resulting from operational changes
        - Able to show impacts on full range of potential events
        - Impacts on local floodplain regulations relating to NFIP, elevation and flow duration
        - Impacts on Dam Safety

Matthew C. Lindon – Utah DNR

- Design Storm Analysis
    - Develop physically based models
        - Soil types
        - Vegetation
        - Spatial and temporal precipitation
        - Routing (RAS, HMS)
        - Calibrated models
    - Grow experienced modelers

Melissa Collord – California Division of Dam Safety

- Ungaged watersheds
    - Unit hydrograph development
    - Loss Rate determination
    - Channel routing
    - Flood hydrograph computation methods
    - Snowmelt impacts

Joe Skupien – Somerset County, New Jersey

- Lack of experienced modelers
    - Develop minimum education requirements
    - Small dam hydrology/hydraulic courses
- Failure parameters/policies for dams with corewalls or upstream face walls
- Unit Hydrographs
    - Standardize Time of Concentration computation methods
    - Methodology to estimate time of concentration for extreme events
- Small Dams
    - Design storm distribution
- Hydraulic Model Development
    - Develop guidelines for steady flow analysis
    - Develop inexpensive techniques to develop digital topography
    - Identification of applicable starting water surface elevation for hydraulic models

Ed Fiegle – Georgia Safe Dams

- Short Term Needs
    - Software Development
        - Complete HECHMS and make compatible with HECRAS, ARCVIEW, DAMBREAK
    - Develop software models for use at the state level
    - Perform sensitivity analysis of various hydrologic methods. Develop results by region.
- Long Term Needs
    - Update Curve Numbers and lag time routines
    - Better regionalization of PMP rainfall events
    - Define and update Antecedent Moisture Conditions
    - Development of the Green-Ampt loss rate function for nationwide application

Sam Hui – Bechtel Corporation

- Applied Research Needs
    - Basin runoff model parameters
        - Unit Hydrograph development
    - Flood Frequency Analysis
        - Inclusion of uncertainty factors
        - Confidence limits
- Fundamental Research Needs
    - Dam Break analysis for mud wave propagation in rivers
    - Tailings Dams

Anand Prakash – URS Corporation

- Categorize Dams
    - Risk based vs Standards related classifications
- Probable Maximum Flood development
    - Consistent methods
        - Magnitude, duration, sequence of the PMP
        - Lag times and loss rates vs size of basin
    - AEP of PMF
    - Methods to standardize reasonableness of PMP to generate consistent results among hydrologists
    - Rain on snow
    - Long duration storm events equivalent to PMF
- Dam failure rates and breach sizes
- Develop tangible and intangible dam failure risks
- Insurance costs of dam failures
- Loss of Life estimates

Cat Cecilio – PG&E, retired

- Update “Snow Hydrology” a Northwest Division publication

- Update “Generalized Snowmelt Runoff Frequencies”, a 1962 Sacramento District publication
- Continue update existing HEC hydrologic and hydraulic models.
- Develop uniform method of areal distribution of the PMP especially applicable in orographic areas.
- Tech review HMR 57 and HMR 58
- Develop a temperature sequence for PMP estimates with snow so that it reflects the diurnal variation of temperatures
- Windows based DAMBREAK

Rory Nathan – Sinclair Knight Merz, Australia

- AEP of PMP
- Techniques required to minimize bias in the AEP transformation between rainfall and floods.
- AEP of extreme rainfall depths

Des Hartford – BC Hydro, Canada

- Physical nature of phenomena involved
- Characterization of uncertainties
- Models to help with risk characterization
- Analytical process and procedures used for dam safety decision making

Ed Tomlinson – Applied Weather Associates

- Update the historic extreme storm rainfall data base
- Complete catalog of extreme rainfall events
- Update the US maximum dewpoint climatology
    - 12 hour persisting dewpoint temperatures
- Storm transpositioning
- Incorporate modeled data fields into PMP procedure
    - Wind
    - Temperature
    - Other parameters
- Computer models for maximum potential rainfall

Mel Schaefer – MGS Engineering

- Short Term
    - Resource center for research findings and case studies
        - Electronic bibliography
        - University maintained
- Long Term
    - Hydraulic Response of watersheds
        - Linear
        - Non-Linear
        - Develop Policy
    - Unit Hydrographs

        - Surface Runoff
        - Interflow
    - Mountainous area Depth-Area-Duration storm analysis
        - NEXRAD
        - Satellite Imagery
- Policy
    - Hydrologic and Flood Safety Criteria
        - New dam construction
        - Existing dam evaluation

David Bowles – Utah State University

- Risk Assessment
    - Probabilistic extreme flood estimates
    - Frequency curve extrapolation
    - AEP of extreme events

Bob Jarrett – US Geological Survey

- Physical Processes of flooding
    - Sediment Transport
    - Deposition during Floods
    - Sediment Deposition
    - Surface Erosion Thresholds
- Peak Discharge Estimates
- Paleoflood Peak Discharge Estimates
    - Hydraulic Modeling
    - Absolute Age Dating of Deposits
    - Validation of Relative Age Dating Methods
        - Guidelines for Flood-Frequency Parameter Estimation
        - Regional Flood-Frequency Analysis with Paleoflood Data

DISCUSSION

1. General – After the presentation of papers, and some general group discussion, the workshop participants divided into 3 smaller discussion groups. These groups, and their discussion subjects, were:

Risk Analysis Group – Items relating to uncertainty factors that influence reservoir inflow values and the computation of the Annual Exceedance Probability (AEP) of extreme floods.

- Storms and flood database
- Extension of flood frequency curves
- Develop regional hydrology parameters.

Standards Group – Items relating to physical factors that influence the methodology for the computation of extreme floods, including the PMF.

- Improve Technology Transfer
- Develop Regional Databases
- Loss Rate Function Analysis

Meteorology Group – Items relating to rainfall analysis from both the standards based analysis and a risk-based analysis.

- Precipitation Analysis
- Rainfall frequency analysis
- Real time storm analysis

Each group was challenged to boil down the research needs presented by each organization then generate, and prioritize, what they felt are the most pressing needs for dam safety research within their group. After a period of discussion in the small groups, the workshop participants reassembled and each group presented their opinions on research needs. The group related research items are presented below, in their order of group-defined importance.

2. Research Needs – After a period of discussion, the workshop participants reassembled and each group boiled down the research needs presented in each paper and presented their opinions on research needs. The research needs generated by each group are presented below in their order of group-defined priority.

Risk Analysis Group

- Develop a historical database of storms and floods that can be used for analysis.
- Develop an approach to extend flood frequencies to smaller AEP's.
- Develop regional hydrology parameters.
- Develop an approach to consider storm series.
- Continue to develop stochastic rainfall/runoff models.

- Continue to develop Paleo methods and expand the use of Paleo analysis into the Eastern United States.
- Develop site-specific Loss of Life (LOL) estimates.
- Improve Dam break parameters.

Standards Group

- Improve Technology Transfer
  - Model development and training
  - GIS – NEXRad – Metorologic Data
- Develop Regional Database
  - Storms
  - Antecedent moisture
  - Unit hydrographs
  - Storm durations and patterns
  - Instrumentation

- Loss Rate Function Analysis
  - Curve Number
  - Green-Ampt
  - STATSGO
  - Initial and constant
  - Variable
- Watershed Modeling
  - Calibration, verification, accuracy
  - Basin runoff parameters
  - Model adjustment
  - Instrumentation
  - Non-linear basin response
  - Initial reservoir levels

Meteorology Group

- Precipitation Analysis
- Antecedent storm analysis
- Real time storm analysis
- Extend rainfall frequency analysis to return periods > 1000 yr
- Analysis of the last 10 years storm data
- Analysis of older storms
- Application manual for orographic areas
- Standardize storm development

3. Ranking of Research Needs - After the workshop, all participants were sent a ballot and asked to rank the above research subjects in terms of importance and difficulty. Of the 26 workshop participants, 16 replied with their rankings. The subjects were to be rated 1 to 8 in terms of importance with one being the most important. No subject could have the same rating. Each subject was given a difficulty rating of 1 to 10 with 1 being the easiest. More than one subject could receive the same difficulty rating. Also, each participant was asked to pick what they considered to be the 10 most important subjects overall. These were again to be ranked 1 to 10 with 1 being the most important. Each of the 10 was also given a difficulty rating that ranged from 1 to 10 with 10 being the hardest. Only 15 of the 16 responses were usable for the overall ranking.

Once the rankings were received, they were tabulated based on their ranked importance and then weighted by their difficulty. For example, a subject that was very important but very difficult to study may actually end up with a lower ranking than a subject that was not quite as important but was easier to study. The weighted rankings are presented in the graphs below.

Risk Analysis

The members of the Risk Analysis group rated the 'development of a historical database of storms and floods' as most important, as shown in Figure 1. Extension of 'frequency curves to rare AEP' was ranked as the 2nd most important subject. However, it also was rated as one of the more difficult subjects. Weighting pushed this subject to a ranking of 3rd.

Standards

The members of the Standards group ranked 'technology transfer' as the most important subject. However, as shown in the Standards graph below, the 'development of regional database of storm and flood information' ranked the highest from the overall workgroup. Weighted by difficulty, the' regional database development' ends up being the highest ranked subject. After weighting, 'technology transfer' ends up as the fourth ranked subject. These results are shown in Figure 2.

Meteorology

Figure 3 shows that the members of the Meteorology Group ranked 'rainfall frequency analysis to return periods greater than the .001 event' as the most important subject. However, when weighted by difficulty, this subject dropped to 5th. 'Precipitation analysis' was the 2nd rated in terms of importance and ends up the top rated when weighted by difficulty.

Overall Top Ten

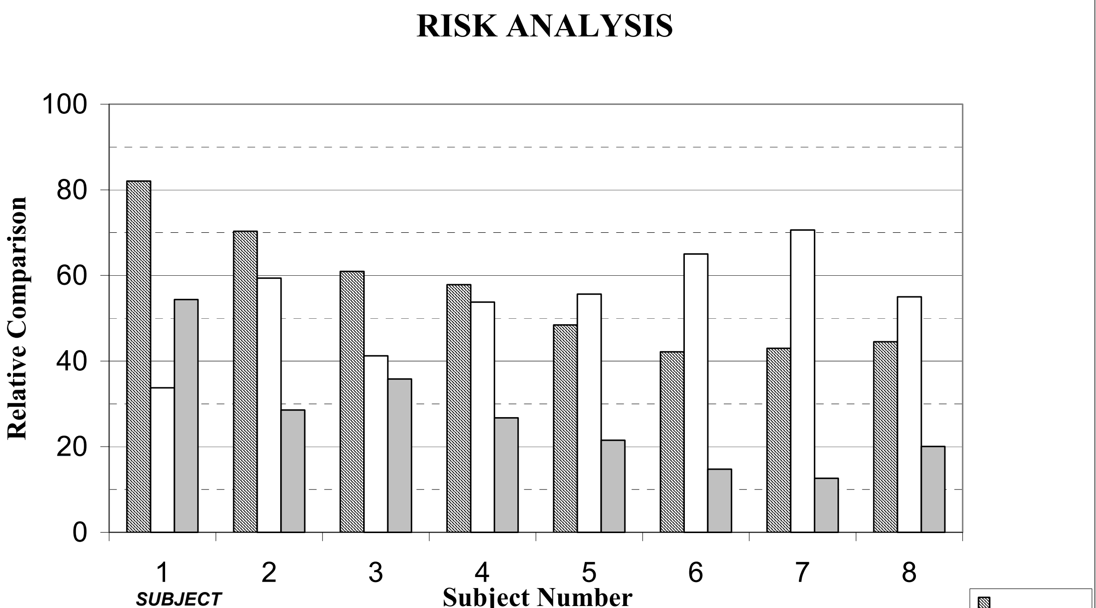
The overall top ten rankings are shown on Figure 4. For the top ten ranking, 'historical database of storms and floods' was ranked as the most important subject. After weighting by difficulty, it remained as the top rated subject. Of the 15 usable ratings, 10 participants included this subject within their top ten.

Conclusion

It is important to remember that these rankings are the opinions of 16 people. It is possible that 16 other people could generate a different set of rankings. With that said, the intent of the workshop was to invite people from organizations which have vested interest in the field of dam safety. It was felt that these people would provide a good cross-section of opinions on dam safety issues and therefore, a good basis for itemizing research subjects.

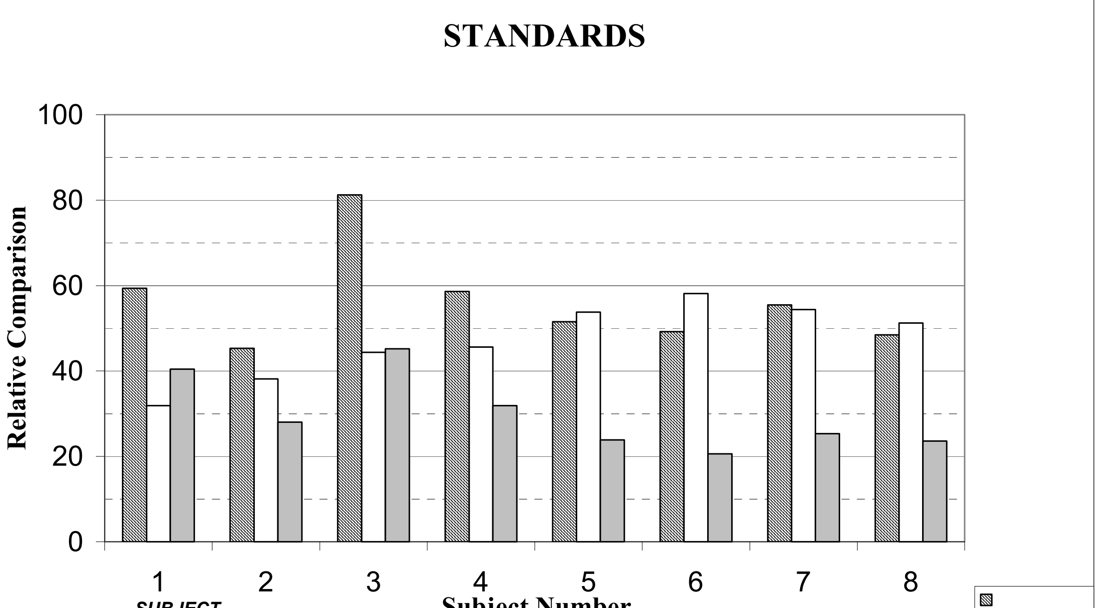
An overview of the results from the three groups shows a common thread among all the groups that there is a need for basic data. The general opinion of each group is that there is a need to generate an organized database of information on both floods and storms that can be shared among all. The Risk Analysis and Standards groups both listed storm and flood data as the most important research item. The Meteorology group listed precipitation analysis as the second highest ranked subject.

To further interpret the results, it generally appears that the next step would be to come up with methods for extrapolation of rainfall and flow-frequency curves to extreme frequencies along with developing an antecedent soil moisture database.



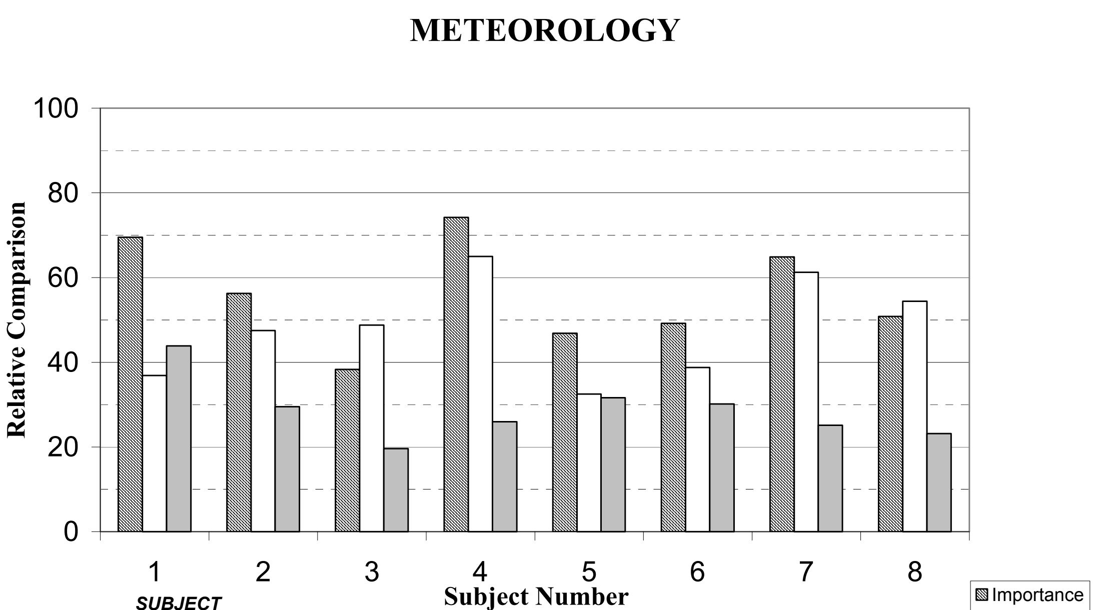
SUBJECT Number	Name	Weighted Value
1	Historical Database of Storms and Floods	54.3
2	Extend Frequency Curves	28.6
3	Develop Regional Hydrology Parameters	35.8
4	Storm Series Analysis	26.7
5	Development of Stochastis Rainfall/Runoff Models	21.5
6	Develop Paleo models and extend to Eastern US	14.8
7	Site-Specific Loss of Life estimates	12.6
8	Dam Break Parameters	20.0

Figure 1. Risk Analysis Graph



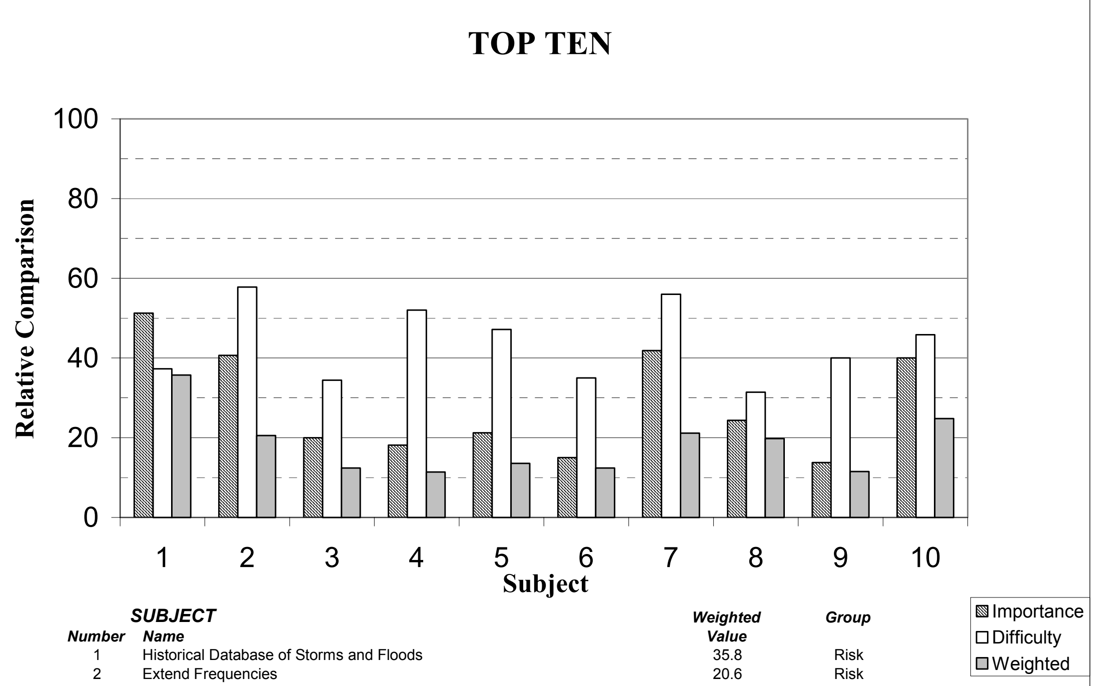
SUBJECT Number	Name	Weighted Value
1	Improve Model Development and Training	40.4
2	Improve Technology Transfer of GIS, NEXRad and Meteorological Data	28.0
3	Regional Database of Storm Amounts, Durations and Patterns	45.2
4	Regional database of Unit Hydrographs	31.9
5	Regional Database of Antecedant Moisture	23.8
6	Loss Rate Function Analysis	20.6
7	Basin Model Parameters for Watershed Development	25.3
8	Watershed Model Calibration	23.6

Figure 2. Standards Graph



SUBJECT Number	Name	Weighted Value
1	Precipitation Analysis	43.9
2	Antecedent Storm Analysis	29.5
3	Real Time Storm Analysis	19.6
4	Rainfall Frequency Analysis to Return Periods > 1000 yr	26.0
5	Analysis of last 10 Yrs Data	31.6
6	Analysis of Older Storms	30.1
7	Manual for Orographic Areas	25.1
8	Standardize Storm Development	23.2

Figure 3. Meteorology Graph



SUBJECT Number	Name	Weighted Value	Group
1	Historical Database of Storms and Floods	35.8	Risk
2	Extend Frequencies	20.6	Risk
3	Develop Regional Hydrology Parameters	12.4	Risk
4	Develop Paleo models and extend to Eastern US	11.4	Risk
5	Dam Break Parameters	13.6	Risk
6	Precipitation Analysis	12.4	Met
7	Rainfall Frequency Analysis to Return Periods > 1000 yr	21.1	Met
8	Improve Model Development and Training	19.8	Standards
9	Improve Technology Transfer of GIS, NEXRad and Meteorological Data	11.5	Standards
10	Regional Database of Storm Amounts, Durations and Patterns	24.8	Standards

Figure 4. Overall Top Ten Graph

WORKSHOP
ON
HYDROLGIC RESEARCH NEEDS
For
DAM SAFETY

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November 14-15, 2001

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