Stochastic Modeling Methods

Dam Safety Office

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Introduction

This report summarizes work that was completed under a Service Agreement titled "Stochastic Modeling Methods", work order identification STOMM. This work was sponsored by the Bureau of Reclamation Dam Safety Office Research Program, and was completed during Fiscal Years 2000 through 2002. Research was performed in several areas: surveying the literature and reviewing stochastic rainfall and runoff models; reviewing the Stochastic Event Flood Model (SEFM); obtaining and examining recent stochastic-related publications; and obtaining and evaluating several computer programs. This work was performed by TSC personnel and several external consultants, including: Dr. George Kuczera, University of Newcastle, Australia; Hydrocomp, Inc. (Dr. Norman Crawford); and Applied Weather Associates (Dr. Edward Tomlinson). This report summarizes the tasks, results and deliverables of the research work completed by Technical Service Center (TSC) personnel and that performed by the consultants. Objectives of the research are presented in Section 2.00. A review of stochastic rainfall models is presented in Section 3.00. Reviews of SEFM are presented in Section 4.00. Reviews and software contributed by Dr. George Kuczera are in Section 5.00. Conclusions and recommendations from the research are listed in Section 6.00. Section 7.00 contains a listing of major technical documents obtained during the research. References are provided in Section 8.00.

1.1 Background

The research on stochastic modeling methods was motivated by two developments: (1) results from the 1997 Reclamation-sponsored workshop in Logan, Utah (USBR, 1999); and (2) the creation of the Reclamation Flood Cadre in 1999 to coordinate and develop extreme flood methods. The Logan workshop highlighted the continued need for development and research in extreme floods. The focus of that workshop was on the present status of extreme flood hydrology related to dam safety, and developing a framework to provide hydrologic loads for risk analysis. One additional part of the workshop was outlining practical hydrological modeling tools that produce output that could be used in risk analysis. However, it was recognized that much research and investigation was needed in several areas. One main recommendation (USBR, 1999 p. 45) focused on uncertainty: "Priority should be given to developing procedures for better understanding and incorporating uncertainty in the characterization of floods for baseline risk analysis and risk reduction analysis." Research conducted under stochastic modeling focuses on the random components, to better understand uncertainty.

1.2 TSC Expenditures and Consultants

The research work under STOMM was performed by TSC personnel and external consultants. The work under STOMM was originally proposed for Fiscal Year 2000, and was continued in Fiscal Years 2001 through 2003. The majority of the work (and over 80 percent of expenditures) was completed in FY 2000. Total project costs are less than the original service agreement amount. A copy of the original project plan, service agreement and project expenditures to date are available from the author.

The consultants that helped conduct the research have substantial experience in stochastic hydrology, modeling and hydrometeorology of extreme floods. These are: Dr. Norman Crawford of Hydrocomp, Inc.; Dr. Edward Tomlinson of Applied Weather Associates; and Dr. George Kuczera of the University of Newcastle, Australia. Drs. Crawford and Tomlinson provided brief reviews of the Stochastic Event Flood Model by MGS Engineering. Dr. Kuczera provided substantial reviews of Reclamation's techniques including paleoflood methods, stochastic modeling, and interim flood frequency procedures for Comprehensive Facility Reviews. He provided software, manuals and source code for flood frequency and Bayesian uncertainty calibration computer programs. Dr. Kuczera also gave recommendations on extrapolation and flood risk.

Dr. Norman Crawford is the president and founder of Hydrocomp, Inc. He is a recognized expert in hydrologic modeling. He is one of the original developers of the Stanford Watershed Model, and was previously an Assistant Professor of Hydrologic Engineering at Stanford University. Hydrocomp has completed projects throughout the United States and Canada, and in South America, Europe, Africa and Asia. Dr. Crawford's areas of expertise include streamflow simulation and forecasting, probable maximum floods, and analysis of surface and groundwater resources, reservoir reliability, and the impacts of land management practices on streamflow and water quality.

Dr. Ed Tomlinson is the founder of Applied Weather Associates in Monument, Colorado. AWA specializes in environmental information with emphasis in meteorological and hydrometeorological analyses. Applied Weather Associates has recently conducted site-specific PMP studies for the central and western Carolinas for Duke Power, the Muddy Creek and Elkhead drainage basins in Colorado for the Colorado River Water Conservation District and the Williams Fork drainage basin for the City of Denver, Colorado. Prior work as North American Weather Consultants included an EPRI regional PMP study for Wisconsin and Michigan.

Dr. George Kuczera received a Ph.D. in Water Resources from Harvard University in 1980, and currently is an Associate Professor in the Civil, Surveying and Environmental Engineering Department at the University of Newcastle, New South Wales. He has over 20 years of teaching, research and practical experience in flood frequency analysis, watershed model calibration, statistical and Bayesian uncertainty analysis. Dr. Kuczera has developed and maintained two computer models: FLIKE (a Bayesian flood frequency program) and NLFIT (a model calibration/identification program). Both models, including source code, were supplied to Reclamation under STOMM research. The FLIKE model can handle correlated data in flood frequency with paleoflood data. The NLFIT capabilities are unique in that no other hydrologic model subroutine can perform the calibration with uncertainty and be linked with existing hydrology models.

1.3 Acknowledgements

This research was made possible through funding by the Dam Safety Research Program in the Reclamation Dam Safety Office, under work order identification STOMM. Dam Safety Office personnel were supportive of the research ideas. The research was initiated as part of the former Reclamation Flood Cadre work. Several individuals contributed to the research through ideas, administration, reviews, and feedback. Marijo Camrud, a former TSC employee in the Flood

Hydrology Group, was the team leader for the project from its inception in January 2000 through September 2002. Flood Hydrology Group members Lex Kamstra, Jeanne Klawon, Ralph Klinger and Dan Levish, all former Flood Cadre members, participated in research discussions. Louis Schreiner, Group Manager, Flood Hydrology Group provided encouragement so that this summary report could be completed.

Objectives

The objectives, benefits and tasks of the dam safety research conducted under STOMM are listed below. A project plan for the research is available in Flood Hydrology Group files. The title of the research is Compilation and Review of Stochastic Modeling Methods.

Objective.—The purpose of this project is to perform a detailed analysis and review of stochastic rainfall/runoff models, including those currently used by Reclamation; compile and review other stochastic models available and evaluate their applicability to the BOR Dam Safety program objectives.

DSO Benefits.—The MGS stochastic model is one tool currently used by DSO to determine hydrologic risk. This study will allow the Probabilistic Flood Hazard Cadre to identify the strengths, weaknesses, and limitations of the MGS model and other stochastic models that will enable DSO managers to effectively and correctly apply the information. It is important that paleoflood data, one of several sets of data used by DSO to evaluate hydrologic risk, can be incorporated into these stochastic models.

Study Tasks.—Undertake an extensive search, review, compilation, and evaluation of other stochastic rainfall/runoff models to better understand the current state-of-knowledge. In addition, a detailed analysis and review of the MGS stochastic model shall be performed. The detailed analysis of the MGS model will include review by independent experts. Important aspects of the review shall address issues of uncertainty, sensitivity analysis, and plausibility of incorporating paleoflood data into the stochastic model.

Stochastic Rainfall Models Review

Precipitation is one of the major inputs to rainfall-runoff models, and is the dominant forcing variable. It is also well-known that precipitation is, in general, a stochastic variable. There have been many attempts and methods developed to stochastically generate precipitation time series and rainfall fields.

Currently, Reclamation has a need to utilize stochastic rainfall models as input, or to be combined with, surface runoff models of watersheds. These models are needed to: perform extreme flood runoff modeling for dam safety risk analysis; simulate runoff and examine reservoir operations and performance on a daily time step; and to forecast runoff into reservoirs on a daily or hourly time step. At this time, Reclamation does not have an operational stochastic rainfall model in use in the Technical Service Center in Denver, or in Regional Offices for input to extreme flood modeling.

A limited review of the current generation of stochastic rainfall models is performed as part of the research under STOMM. The intent is to document, critique, and provide recommendations for use of models that may be applied to the needs listed above. Of particular importance to Reclamation is the need for this information in the mountainous regions of the Western U.S. Because precipitation is highly variable in space and time, there are difficulties in modeling precipitation in space and time in this region, given the complex terrain and orographic effects. In addition, it is generally well-known that changes in the input precipitation field can have a large affect on the output-streamflow peak, runoff volume, and timing. Uncertainty in the generation of space-time rainfall fields needs to be considered to understand the potential variability in surface runoff model predictions for application by Reclamation in estimating extreme floods.

Because techniques to develop “design” storms (e.g., Stedinger et. al, 1993) to generate extreme floods have been widely used in practice, the current literature on spatial and temporal modeling of extreme precipitation is also briefly reviewed. These “synthetic storm” methods (NRC, 1988), such as regional precipitation frequency analysis, depth-duration frequency analysis, and stochastic storm transposition, have been traditionally separate from stochastic rainfall modeling efforts. However, these methods do include stochastic elements that can overlap those used in stochastic rainfall modeling. Reclamation currently uses regional precipitation frequency analysis (e.g., Hosking and Wallis, 1997) to estimate extreme rainfall for runoff modeling.

The major focus of this review is limited to those approaches that have been tested with actual data, show some practical application, and can be used for design and analysis applications. There is much recent work that has been completed on scaling and scale invariance in hydrology and precipitation research over the past ten years. Foufoula-Georgiou and Krajewski (1995) review research from 1990-1994, and point out that there are several issues that remain unresolved. For example, Ferraris et al. (2000) show that some rainfall fields derived from radar are multifractal, and more work is needed to define the advection velocity, U, and log-Poisson distribution parameters. Because the majority of this research is very new and has not been applied in practice, it receives limited attention in the present review.

3.1 Objectives of Review

The main objectives of this work are twofold: to perform a limited, updated literature review of the state-of-the-art and state-of-practice in stochastic rainfall models; and to complete an initial data analysis study to highlight some of the practical issues. This study will be limited in two respects: the focus is on stochastic rainfall models that may be combined with surface runoff models; and models with daily or hourly temporal scales. In addition to these factors, the focus will be weighted toward models that can be applied to both time and space. Mixed-population precipitation (rainfall/snowfall) modeling and orographic factors will also be considered, because these issues affect the spatial distribution of precipitation in the majority of the watersheds of interest in the Western U.S.

Significant work and research in various areas has been performed since the last review (Foufoula-Georgiou and Krajewski, 1995). To this author's knowledge, there has not been a detailed review and summary of stochastic rainfall models applied with surface runoff in practice. A summary of existing and current approaches and recent research is needed. Comparisons of model performance, parameter parsimony, and data requirements are also needed.

The specific objectives of the review are:

1. Perform a current, up-to-date limited literature review of stochastic rainfall models that can be linked with and/or output used by surface runoff models.

2. Following Salas (1993), Foufoula-Georgiou and Krajewski (1995) and others, classify stochastic rainfall modeling approaches.

3. Summarize approaches, parameter estimation, data requirements, model uses, applications, successes and limitations of stochastic rainfall models. Because the techniques have been applied in practice, probabilistic design storm approaches for extreme floods, such as stochastic storm transposition and temporal/spatial aspects of rainfall frequency analysis (e.g., NRC, 1988; Stedinger et al., 1993), are also briefly reviewed and summarized.

4. Provide recommendations for data, application and further research, focusing on the needs of the Bureau of Reclamation Dam Safety Office.

3.2 Classification of Current Rainfall Modeling Approaches

The current stochastic rainfall modeling and design rainfall modeling approaches are classified generally following discussions in NRC (1988), Salas (1993), Smith (1993), Stedinger et al. (1993) and Foufoula-Georgiou and Krajewski (1995). Two main modeling categories are differentiated here: stochastic rainfall models; and synthetic "design" storm models and approaches. These two main categories are used, as in NRC (1988), because they represent the major differences in basic approaches to rainfall modeling. There are several model classes for each main category. Each model class includes several subcategories (Table 1). These classes and subcategories used herein represent the models reported in the literature from about 1996 through April 2001.

Four model classes are defined for stochastic models: one-dimensional point process models; multistation models; space-time models and disaggregation models. There are several types of models for each class. Each of the stochastic models is briefly described in Section 3.30. Two classes are recognized for synthetic storms: depth-duration-frequency relationship methods, and storm transposition methods. Synthetic design storm approaches are described in Section 3.40.

Table 1.—Classification of Current Stochastic Rainfall Modeling Approaches

Modeling category	Model classification	Sub-classification type
Stochastic rainfall models	One-dimensional point process models	Simple point processes (e.g., Poisson)
		Cluster processes
		Hybrid processes
	Multistation models	Markov chain
		Non-parametric
	Space-time models	Cell cluster
		Modified Turning Band
		Nonhomogeneous random cascade
		Radar-based bead (wet block)
	Disaggregation models	Point models
		Artificial neural networks
Synthetic "design" storm models	Depth-duration frequency	Regional precipitation frequency analysis
		Areal reduction estimation
		Temporal modeling
	Stochastic storm transposition	

3.3 Stochastic Rainfall Models

The stochastic rainfall models described here are, in general, "empirical" statistical models according to Cox and Isham (1994). These models are statistical models fitted directly to observed data, and do not include much physics in the process, except for some simple assumptions made in cluster models. Each of the four main categories is summarized.
In contrast to research reported by Foufoula-Georgiou and Krajewski (1995), there have been some major efforts in improving point process rainfall models over the past five years. Point process models have been applied to single sites (points) and extended to multisite applications. Much of this research has occurred in the U.K. and has been motivated by the need to develop daily or hourly rainfalls to continuous runoff models. Salas (1993) summarized the main groups of point process models as simple point processes (single-stage white noise or rectangular pulse), and cluster (two-level mechanism) processes. Some research has been conducted on both types. However, the majority of work has focused on cluster processes because they are supposedly more realistic in representing the discrete nature of raincells within storms.

Three current classes of point process cluster models are recognized: Neyman-Scott, Bartlett-Lewis, and hybrid (Table 1). Both the Neyman-Scott and Bartlett Lewis cluster models that are under current investigation and improvement, use rectangular pulses for the random precipitation intensity, and duration burst In general, both cluster models have five to seven parameters that typically describe the duration of activity, number of cells, cell depth, cell duration and cell arrival. Cowpertwait et al. (1996a) utilized a clustered Neyman-Scott model to simulate hourly and daily data at single sites in the U.K. They noted that the variances of the hourly data needed to be taken into account for daily modeling, and that the model performed fairly well for both hourly and daily amounts. Notably, precipitation records were about 20 years in length. The model was extended for regionalization to ungaged sites using regression of harmonic variables on site variables (such as elevation) (Cowpertwait et al. 1996b) and incorporating convective and stratiform cells (Cowpertwait and O'Connell, 1997). The Neyman-Scott model parameters are typically estimated at two levels of temporal aggregation. Calenda and Napolitano (1999) demonstrated that there can be a substantial change in the parameter estimates based on changing the level of aggregation. They recommended an alternate procedure based on one level of aggregation. One problem with their study was that the results were based on a single rain gage. It does point out there are several issues that still remain regarding parameter estimation.

Several studies point out some limitations of point process and cluster models, and develop improved methods. Cameron et al. (2000) reviewed three point process models: a modified Eagleson exponential (simple point process) model; a data-based Cameron Generalized Pareto (simple point process) model; and a random parameter Bartlett-Lewis gamma cluster model with seven parameters. The focus of the study was the ability to reproduce extreme 1- and 24-hour point rainfalls at three sites. They noted that modeling needed to be done for separate April-September and October-March seasons, using different parameter sets for each season. The results indicated that the Generalized Pareto performed best for 1-hour extreme rainfalls, and the Bartlett-Lewis cluster performed reasonable for standard statistics (Cameron et al., 2000). They suggest that the results demonstrate the need for careful model choice, depending on the application. One can see that the both recommended models need some improvement from their study results. Based on this work, Cameron et al. (2001) make some improvements to the Bartlett-Lewis model for extreme rainfall applications. Here, they use the main six-parameter Bartlett-Lewis model from previous work, most recently developed by Onof and Wheater (1993), and add a Generalized Pareto distribution to represent high intensity raincell depths. This addition resulted in two additional model parameters, for a total of eight; they note parameter estimation is a challenge (Cameron et al., 2001), but try and demonstrate the value in a Generalized Likelihood method to accept/reject parameter sets. The model is improved over the original model, when compared to 1-hour data at one site during the summer season. Onof et al. (2000) review point process models based on the Neyman-Scott and Bartlett-Lewis models, and are motivated by development of the models to be applied to space-time modeling. They do point out several developments, such as space-time modeling (discussed below), and that a lot of further research is required. There are still some substantial problems with the models to reproduce many of the observed statistics. Onof et al. (2000) strongly recommend that one focus on reproducing key statistics and modifying weights of moments in estimation for the problem of interest.

One other area in point process modeling is hybrid models. These models are essentially variants on existing models. Gyasi-Agyei and Willgoose (1999) present one such model, which is a product of two random processes: a jitter model and a binary chain model. The binary chain model is intended to replace the Bartlett-Lewis pulse; the jitter is the exponential of an Autoregressive process (Gyasi-Agyei and Willgoose, 1999). Two binary models were compared using simulation and 15-minute data: a Markov chain, and a non-randomized Bartlett-Lewis. Results indicated both were acceptable, but the Bartlett-Lewis was recommended as it had less parameters.

Based on the work described above, there is no clear case that either the current class of Neyman-Scott or Bartlett-Lewis models perform substantially better than one another. In addition, there is much work to be done to utilize this class of models in application to drive continuous runoff models (Onof et al., 2000).

There have been several recent developments in multistation models. The approaches generally use Markov chains or nonparametric techniques to simulate data at several sites, preserving correlations between sites or variables. The multistation models are based on two-state Markov chains for precipitation occurrence and some (typically skewed) distribution for the precipitation amount. Nicks et al. (1995) describe such a model that has been used as a weather generator for the Water Erosion Prediction Project. The model uses a skewed normal distribution to represent daily precipitation for each month, with an exponential distribution for storm duration. The model also simulates temperature, solar radiation, wind velocity and direction, and dewpoint temperature. The model uses daily data, and is able to generate data at 2,600 individual locations in the U.S. (Nicks et al., 1995). Wilks (1998) extended the approach to simultaneously generate daily data at multiple locations. A mixed-exponential distribution was used for rainfall amounts, and a first-order Markov dependence model was used for occurrence. The approach used was to drive the individual station-level models with spatially correlated but temporally independent random vectors (Wilks, 1998). In contrast to the parametric method, a nonparametric approach was used by Brandsma and Buishand (1998) to generate daily rainfall and temperature at seven sites in Germany. A resampling method was conditioned on atmospheric circulation, and also tested in an unconditional mode. The results indicated that extreme N-day precipitation amounts were preserved (Brandsma and Buishand, 1998). Rajagopalan and Lall (1999) developed a multivariate k-nearest-neighbor model for six daily weather variables. This is an alternative to the approach used by Nicks et al. (1995), and is equivalent to a multivariate lag-1 Markov process. Based on application to 30 years of weather at Salt Lake City, the model adequately reproduced the sample statistics and eliminated the need to separately model precipitation and weather variables. Rajagopalan and Lall (1999) suggest the approach is better than previous methods at preserving the cross-dependence structure between variables, but does not produce values that have not already been observed.

There have been several recent developments in space-time modeling. These are arbitrarily classified based on main concepts: cell clusters, Turning Band (TB)/Modified Turning Band (MTB) methods, random cascade, and radar-based analyses. Chandler et al. (1997) focus on using radar fields to model temporal rainfall processes at fixed locations using: homogeneous Poisson processes for storm locations (space and time); Bartlett-Lewis clusters within a storm; Neyman-Scott structure for spatial clustering; and circular or elliptical cell patterns. The model is called the "Gaussian displacements spatial-temporal model" (GDSTM), and is fitted to a 1-hour sequence of radar images (individual storms) from one station (Northrop et al., 1999). The model appears to reproduce the data reasonably well; but there are some parameter estimation issues such as non uniqueness and subjectivity, as well as the major assumption that the field is stationary in space for an individual event. Some further investigations of the model, as well as other approaches were recently completed by Wheater et al. (2000). They noted that the full spatial-temporal model of Northrop et al. (1997) is the most powerful, but has some major data restrictions (radar) at this time. Shah et al. (1996) and Mellor (1996) use the TB and define the MTB model. These models are based on Gaussian and non-Gaussian random fields to simulate frontal rainstorms. Pegram and Clothier (2001) developed a space-time model derived from radar data called the "String of Beads". They state this model was developed by putting together some well-known ideas in a simple fashion to create an up-to-date model. The model is only applicable to wet periods, and radar data. It is based on considering the rainy (scattered and general) processes as beads on a one-dimensional "string" of time, and models the random fields as stationary. The model performance appears reasonable considering verification and validation tests (Pegram and Clothier, 2001), but more work is needed. A completely different approach was taken by Jothityangkoon et al. (2000), who develop a two-component model based on nonhomogeneous random cascades. A four state Markov chain model generates daily time series of regionally-averaged rainfall, and a spatial disaggregation model based on random cascades is used to distribute the amounts spatially. The model was applied to 490 stations in a 400 km by 400 km region. The model agreed well with the gaging network for basic statistics, but needs some improvement to handle storm durations and interstorm periods. Jothityangkoon et al. (2000) note that this model demonstrates promise, but many more theoretical advances are needed before random cascade models can be used to simulate rainfall over any large region.

There has been some work in the area of rainfall disaggregation in space and time. This topic is included as part of a review for stochastic models, but the review here is incomplete. Cadavid et al. (1992) developed temporal disaggregation models for daily and hourly precipitation based on simple Poisson and Neyman-Scott white noise processes. They note that there is much work to be done in the area of precipitation disaggregation. Several investigators have expanded models they have developed to handle disaggregation. For example, Cowpertwait et al. (1996b) developed a method to disaggregate hourly rainfall into 5-minute series, based on the Neyman-Scott rectangular pulse model. Likewise, Gyasi-Agyei (1999) extended the hybrid point process model to perform temporal disaggregation of daily rainfall. Instead of parametric models, Tarboton et al. (1998) considered nonparametric techniques for streamflow; the technique might be applicable to precipitation. Using a completely different approach, Burian et al. (2001) use Artificial Neural Networks (ANNs) for temporal disaggregation of hourly rainfall into subhourly increments. Three sites were used. Two important conclusions were found: the important role of data standardization, and the ability to use a distant station (Burian et al., 2001). Salvucci and Song (2000) derived models for disaggregating monthly precipitation using simple Poisson processes. Much of the most recent work relates to downscaling of fields from atmospheric models (e.g., MM5) to hydrologic models. One recent example for modeling rainfall-runoff in Pennsylvania is Bindlish and Barros (2000). Another recent example is Venugopal et al. (1999).

In terms of practical applications, NRC (1988, p. 61) raised three points and two questions regarding stochastic rainfall models. The points were: that space-time modeling requires a large number of parameters; no space-time models have been fitted to actual data; and in many practical applications the lack of a sufficiently dense network may make space-time modeling infeasible. The questions raised were: how well do space-time models represent extreme rainfalls; and what level of space-time detail is required for runoff modeling (NRC, 1988)? From the research noted above, it appears that significant inroads have been made to address these questions, but there remains a lot of work to be done.

3.4 Synthetic "Design" Storm Models and Approaches

In comparison to research, much less attention has been paid to the stochastic models presented in Section 3.30 for simulation and design purposes in practice, with the notable exception of the multisite weather generators used by the USDA (e.g., Nicks et al., 1995; Wilks, 1998). It appears that these techniques are used because they are simple and well tested across the U.S. (Nicks et al., 1995).

For hydrologic analysis and design of floods with exceedance probabilities less than about 0.1 (10-year return period), techniques used in practice focus on extreme rainfalls linked with event runoff models. Both the United Kingdom and Australia have recently completed guidelines for hydrologic engineering and design, focusing on the flood estimation problem (Institute of Hydrology, 1999; Nathan and Weinmann, 1999). Notably, there is no mention of stochastic rainfall models for use in flood estimation by practitioners in the United Kingdom (Institute of Hydrology, 1999). The recommended procedures are L-moments based regional rainfall frequency analysis, and a depth-duration-frequency (DDF) model. No stochastic rainfall models based on time series, such as point process or space-time models are used. Output from the rainfall frequency and DDF models are used as the precipitation input to a runoff model (Institute of Hydrology, 1999). Similar to the United Kingdom, a regional frequency analysis-based rainfall estimation procedure is used for estimating extreme floods in Australia (Nathan and Weinmann, 1999).

Two subclasses are used for synthetic storms (NRC, 1988, 1994; Stedinger et al., 1993): depth-duration-frequency relationship method, and storm transposition methods. The depth duration-frequency relationship method consists of three main parts: rainfall frequency analysis, areal reduction estimation, and temporal modeling. Much of the work in the area of point rainfall frequency can be considered relatively “mature” in terms of traditional modeling with probability distribution functions. Reclamation has used the regional L-Moment techniques popularized by Hosking and Wallis (1997). However, there are still areas for investigation and development, including assessment of the index flood (station-year) method, extrapolation bias with different distributions, and defining homogeneous regions (e.g., Castellarin et al., 2001). There has been some interesting research and development in the estimation of depth-duration frequency curves and areal reduction factors. Burlando and Rosso (1996) used scaling properties of rainfall to help determine the shape of DDF curves. Several improvements were made to estimating areal reduction factors by Sivapalan and Bloschl (1998) and Asquith and Famiglietti (2000). There is still work to be done in this area, especially for large areas. The key problems are linking the parts that are “independent”, especially the areal reduction factor. Northrop et al. (1999, p. 226) point out several well-known problems with the design approach: pre-specified storm duration, symmetrical distribution, and that areal reduction factors are not derived from the same frequency.

Based on review of current applications, it appears that hydrologic practice is currently entrenched to using the depth-duration frequency method and its variants for extreme storm modeling. However, there has been some movement toward using continuous rainfall-runoff models for extreme flood estimation (e.g., Calver et al., 1999; Cameron et al., 1999). This has motivated much of the research on point process and space-time stochastic models described in Section 3.30, especially in the U.K.

Stochastic storm transposition (SST) is an alternative method to station-based rainfall analyses. NRC (1994) reviewed approaches to estimating Probable Maximum Precipitation (PMP) in the United States. They noted the conflict between storm-based and station-based analyses, and that current PMP techniques are based on storm analyses. In looking at alternatives to PMP, NRC (1994) recommended pursuing the stochastic storm transposition procedures (e.g., Fontaine and Potter, 1989; Foufoula-Georgiou, 1989). They noted that these techniques are not mature. There has been some limited progress and applications in this area over the past 10 years. Bradley and

Potter (1992) utilized the technique to expand storm samples for flood frequency simulation in the Midwest. Franchini et al. (1996) extended the technique to focus on design flood estimation, by including stochastic descriptions of antecedent moisture and storm temporal distributions. Agho et al. (2000) focused on the problem of regional homogeneity for SST, and developed a nondimensionalized approach to overcome statistical nonhomogeneity of depth exceedance probabilities.

3.5 Summary

Much work has been completed over the past ten years in stochastic rainfall modeling. There has been somewhat of a resurgence in point process model investigations and developments. Much of this work has been completed recently in the U.K. for use with continuous runoff models. It appears that radar data is a very important part of space-time model development. Several recent models based on radar have been proposed. Most, if not all, require further development and testing. There is no clear choice that there is a "best" point process/cluster model such as Neyman-Scott, Bartlett-Lewis, or some hybrid. There has been some specific focus to improve the Bartlett-Lewis model for estimating extreme events, but this comes at a price of more parameters and neglecting other statistics.

While there appears to have been less research focus in the "design" storm modeling area, there remain many opportunities. Two areas that have demonstrated some development and practical application are related to DDF modeling and SST techniques. Both areas can be improved, especially in orographic areas such as the inter-mountain western U.S.

To improve development in many areas, work is needed in data collection and investigation. It is recommended that data investigations be performed to: (1) increase the data base of storms; and (2) there is a great need for radar-based climatology, storm and spatial investigations.

Stochastic Event Flood Model Reviews

This section summarizes the results from reviews of reports related to the Stochastic Event Flood Model (SEFM): two reports on using SEFM at A.R. Bowman Dam (Schaefer and Barker, 1997, 1998); and the first SEFM technical manual (MGS, 1998). The three reviewers listed in Section 1.20 examined the model. Their reports are listed in Section 7.00 and copies are included in the Appendix. Dr. Crawford's report is attached as Appendix A. Dr. Tomlinson's report is attached as Appendix B. Dr. Kuczera's report is attached as Appendix C. Overall, the reviews and suggestions on SEFM are favorable.

4.1 Dr. Norman Crawford, Hydrocomp - Summary

Dr. Crawford's main concerns and conclusions are listed below. A complete report is in Appendix A.

Estimating flood frequency for peak flows and flood volumes are classic problems in hydrology, and classic problems gain this notoriety by being very difficult to resolve. They are passed from one generation to the next and research on methods to improve estimates for rare floods will continue indefinitely.

To attain "every advantage" to reduce the uncertainties in rare flood estimates the hydrologic processes in a watershed must be modeled as fully and reliably as current technology allows. The General Storm Stochastic Event Flood Model does not do this. Simulation of hydrologic processes is simplistic and calibration with recorded data is much too limited.

The model Monte Carlo based approach may assume that an unbiased estimate of rare floods will emerge if the model structure is so simple that it is feasible to calculate hundreds of thousands of flood events. This will not happen if flood estimates are biased. In Crooked River the model creates floods in the mid-April to mid-May period that overtop A. R. Bowman Dam. This of course could happen, but this is a time of year when potential evapotranspiration is increasing toward its summer maximum and near surface soil moisture is being depleted. Runoff calculations should not be based on a single soil moisture storage that does not allow moisture in the soil profile to vary with depth. Another potential source of bias is Monte Carlo sampling for storm characteristics (24-hour and 10-day annual maxima and areal reduction factors). It is necessary to show that the probability distributions used for storm characteristics apply at the time of year when overtopping floods are created.

As was noted in Section 3.0 of the Crawford report (Appendix A), the General Storm Stochastic Event Flood Model includes: (1) statistical analysis of meteorological data, and (2) a model to simulate the physical processes of runoff.

It could be improved a good deal if a reliable continuous watershed model were used. If this were done the next issue to consider are the merits of developing regional probability distributions for storm characteristics for Monte Carlo sampling, vs. stochastic generation of precipitation and related meteorological time series. In prior studies of rare floods, continuous watershed models have been combined with stochastic precipitation models. Stochastic generation of precipitation has been studied for individual stations and for a network of stations in a region. Direct stochastic generation of meteorological variables operates on a short time steps, usually hourly, so this approach eliminates aggregation of time series into storm characteristics (depth-duration and spatial distribution probability distributions) and subsequent disaggregation into storm time series (hourly precipitation increments).

Meteorological data analysis and creation of additional records by any method is challenging, and is especially so when consistent multi-station data is needed and precipitation can occur as snow. Relatively short record lengths and sample size problems limit confidence in results.

There is some evidence that rare floods in semi-arid watersheds are most often caused by less rare precipitation events combined with rare high watershed initial soil moisture conditions. This possibility is easily explored by continuous simulation: the largest historic storms are combined with the highest initial soil moisture or snowpack found in the historical record on the date of the storm.

4.2 Dr. Edward Tomlinson, AWA- Summary

Dr. Tomlinson's main concerns and conclusions are listed below. A complete report is in Appendix B.

A question was on dividing the watershed into five zones based on mean annual precipitation, instead of based on 100-year rainfall distribution. Use of deterministic flood computations with Monte Carlo sampling procedures seems like a reasonable approach as long as correlations among the hydrometeorologic input parameters are consistent with those that are observed to occur in nature. MGS has recognized this constraint and has attempted to insure that the correlations are maintained. The problem of establishing these correlations for storm events is addressed as best as can be done currently using station data. What is really desired are correlations on a storm basis, but since there are no adequate climatologies developed on storms; station data are used in hopes that they are close. There may be a problem that for extreme events the atmospheric profile is probably not moist pseudo-adiabatic but more convectively unstable. Uncertainties related to parameter uncertainties arising from estimation of the various parameters used in the model and model uncertainties are not well quantified. Realizing that getting an adequate handle on these uncertainties may not be achievable in the near term, the existence of these uncertainties needs to be recognized and factored into the use of the results.

4.3 Dr. George Kuzera, University of Newcastle - Summary

The review comments from Dr. Kuczera are extensive. An overview and his recommendations are presented below. The complete review is included in Appendix C. Equations and report sections that are referenced below refer to those in his report.

The case study in Section 4 of the Kuczera (2000) report has highlighted the importance of the constraint imposed by paleo flood data on stochastic rainfall-runoff models. It has also given clue to the some of the formidable challenges to be overcome. Nonetheless, Reclamation has little choice but continuing to develop its stochastic rainfall-runoff model for the simple reason that flood frequency analysis only estimates the peak inflow into the reservoir, whereas decisions about dam safety depend on the risk of the structure overtopping and failing. This risk is dependant not only on the peak inflow but also on the volume and shape of the inflow hydrograph as well as the antecedent conditions controlling the initial water level in the reservoir. This is a complex joint probability problem for which stochastic rainfall-runoff modeling is, in principle, arguably the best approach.

Reclamation commissioned MGS Engineering Consultants (2000) to develop a stochastic rainfall-runoff model called the Stochastic Event Flood Model (SEFM). In reviewing this model the insights derived from the case study are taken into account. Overall Dr. Kuczera is of the opinion that SEFM is a competently developed model. The issue of most interest to Reclamation is whether models like SEFM are capable of providing credible estimates of overtopping. Accordingly, the review comments are directed more at the conceptual credentials of models like SEFM than at SEFM itself.

There is considerable doubt in Dr. Kuczera's mind that models of the genre to which SEFM belongs, can be trusted to produce credible estimates of the probability of overtopping. This is even though Dr. Kuczera considers SEFM to be a competently developed model. The following recommendations are made regarding SEFM's future development:

1. Although SEFM combines many random variables to simulate flood discharge it is primarily driven by the rainfall magnitude frequency curve. Even if its conceptualization of the hillslope runoff and channel routing processes were correct, its simulated discharge frequency curve depends on the credibility of extrapolating the rainfall frequency curve. At a minimum, SEFM must be consistent with paleo flood frequency curves. Once beyond the credible limits of the paleo flood frequency curve, the risk estimates made by SEFM must be tempered by good judgment.

2. The routing procedures used in SEFM should be reviewed to ensure the routing robustly describes the flow and temporary storage dynamics across all the scales encountered in extreme floods. Where storage-discharge relationships are considered to be nonlinear, such as when there is evidence of floodplain storage being activated in extreme floods, the extrapolation of linear routing methods can lead to gross errors. Some form of conceptual nonlinear routing (similar in concept to the bilinear model of Section 4.1.3) is worthy of investigation.

3. By distributed modeling standards, SEFM is moderately complex and data intensive. Nevertheless, given that its primary objective is to estimate the risk of overtopping major hydraulic structures, its complexity and data needs should be reviewed. Only those secondary stochastic processes that induce a nonlinear response in the flood frequency curve should be retained. A careful sensitivity analysis is recommended to identify opportunities for simplification.

4. SEFM should be capable of being calibrated to rainfall-runoff time series data and flood frequency curves derived from gauged and paleo data. As shown in the case study of Section 4, the paleo flood frequency curve can exert significant constraint on model parameterization.

5. Successful calibration of SEFM using automatic search methods such as employed in NLFIT requires several thousand simulations. For such calibration to be practically accomplished SEFM must be capable of simulating a record several thousand years in length in minimal CPU time. To this end several strategies are suggested:

    - Simplify the SEFM model to reduce the number of parameters requiring calibration and the effort gathering the necessary data.

    - Focus the calibration on lumped parameters following the scheme of eqn (27) in Kuczera's report.

    - Recode SEFM in a language more efficient than Visual Basic such as Fortran95 or C.

- Exploit parallelism in the Monte Carlo simulation using software architectures such as PVM (Parallel Virtual Machine).
- Implement the stratified Monte Carlo sampling strategy to minimize the number of simulations.

Review of Reclamation Flood Practice and Computer Programs by Dr. George Kuczera

The former Probabilistic Flood Hazard Cadre contacted Dr. George Kuczera as part of our developing methods to enable risk assessment in the extreme flood range for the purpose of dam safety evaluation. The Flood Cadre requested a review covering the following areas of flood risk assessment by Dr. Kuczera:

1. Conduct a review of the current Reclamation practice using flood frequency models.
2. Review stochastic modeling for Reclamation use discussing model limitations, positive features, and recommendations for improvement.
3. Review the paleoflood methodology developed by Reclamation and provide constructive criticism of frequency methods and usage of the analyses as a potential constraint on rainfall-runoff modeling.
4. Assemble documentation, source code and compiled programs, and example applications of FLIKE and NLFIT for distribution to Reclamation for research and development purposes and provide written suggestions for modifications to the programs to help solve Reclamation's flood hazard issues.

Dr. Kuczera completed all the work requested, and supplied FLIKE and NLFIT source code and supporting documentation to Reclamation. FLIKE is a Bayesian flood frequency analysis program summarized in Kuczera (1999). NLFIT is a Bayesian nonlinear regression program suite that facilitates calibration and uncertainty estimation for a user-specified model. A listing of software, related manuals and papers is in Section 7.00. A final report of Dr. Kuczera's work, summarizing the first three items listed above, is attached as Appendix C. The main report items are excerpted from the report and reprinted below. Equations and report sections that are referenced below refer to those in his report. Review comments and recommendations on the SEFM model are presented in Section 4.30.

5.1 Review of Paleoflood Methodology

The logical place to start the review is with Reclamation's paleoflood methodology. This methodology extends the observed flood record in streams with established flood terraces to annual exceedance probabilities (AEPs) of the order of 10^{-3}. Reclamation has made original contributions in its development of paleo discharge estimates, which it should publish in the refereed literature. However, its use of the paleobound data in fitting flood frequency distributions can be improved upon. Dr. Kuzcera suggested improvements to the likelihood functions in FLDFRQ3. He also noted that although the conceptualization described differs from that reported in Ostenaa et al. (1999) the differences are not great. Therefore, the changes to Reclamation's existing program FLDFRQ3 would be relatively minor. In concluding the review of Reclamation's paleo flood work the following recommendations are made:

1. For the purposes of flood frequency analysis, paleobound data at multiple locations should be condensed into composite exceedance and nonexceedance columns from which a paleo sequence is constructed.
2. Reclamation's FLDFRQ3 program should be modified to incorporate paleobound likelihood function.
3. The use of 2D hydraulic models to derive upper bounds on flood discharges should be further investigated. The 2D hydraulic models may allow upper flood bounds to be reduced considerably below those derived from dating nonexceedance deposits.
4. Paleo field campaigns should exploit the insight that the most recent deposits will be, on average, the most informative in a paleo flood frequency analysis.
5. The use of 4- and 5-parameter flood frequency distributions should be investigated for inclusion in the FLDFRQ3 program.

5.2 Simulation Case Study – Paleoflood Data Constraints on Models

As a prelude to review of the Reclamation's stochastic rainfall-runoff model, Dr. Kuczera presented a case study using an idealized stochastic rainfall-runoff model called genData. The purpose of the case study was to demonstrate:

1. The crucial importance of employing paleo flood data to constrain the extrapolations made by stochastic rainfall-runoff models;
2. The inherent weakness of extrapolating a model beyond the range of the data to which the model was calibrated; and
3. How a stochastic rainfall-runoff model can be hooked to the calibration software NLFIT to enable calibration to rainfall-runoff time series and to a flood frequency curve.

The genData model is an idealized continuous stochastic rainfall-runoff model. It has three modules dealing with stochastic rainfall generation, quick- and slow-flow runoff production and bilinear stream channel routing. In each module the intent is to simulate the dominant process dynamics. The complete model description and source code are included in Dr. Kuczera's report.

The routing model parameters were selected so that major floodplain storage is activated by floods with a return period in excess of 100 years. This situation was chosen to represent a river with multiple flood terraces with the lowest terraces accommodating the majority of floods and the highest terrace only inundated by extreme floods. The storage-discharge coefficient K is increased by a factor of 50 when the threshold discharge of 3500 m^3/s is exceeded. Using the parameters displayed in Figure 1, Figure 2 presents three frequency curves derived from two genData simulations: Rainfall and flood frequency curves based on 30,000 simulated years and a flood frequency curve based on 100 simulated years. There are several features to note:

1. The flood frequency curve based on 30,000 simulated years shows a clear break in slope around the 100 year return period corresponding to the activation of major floodplain storage. Indeed the flood frequency curve displays downward curvature despite that the fact the rainfall frequency curve displays upward curvature in the 100 to 1000 year return period range. This highlights the major role played by floodplain storage that is only activated in rare floods.

2. The flood frequency curve based on 100 years shows no evidence of downward curvature. This is because in a 100-year record there is little chance of major floodplain storage being activated. Indeed without knowledge of the underlying floodplain hydraulics one would be tempted to extrapolate the 100-year flood frequency curve using a straight line extrapolation. Such an extrapolation would rapidly diverge from the "true" frequency curve.

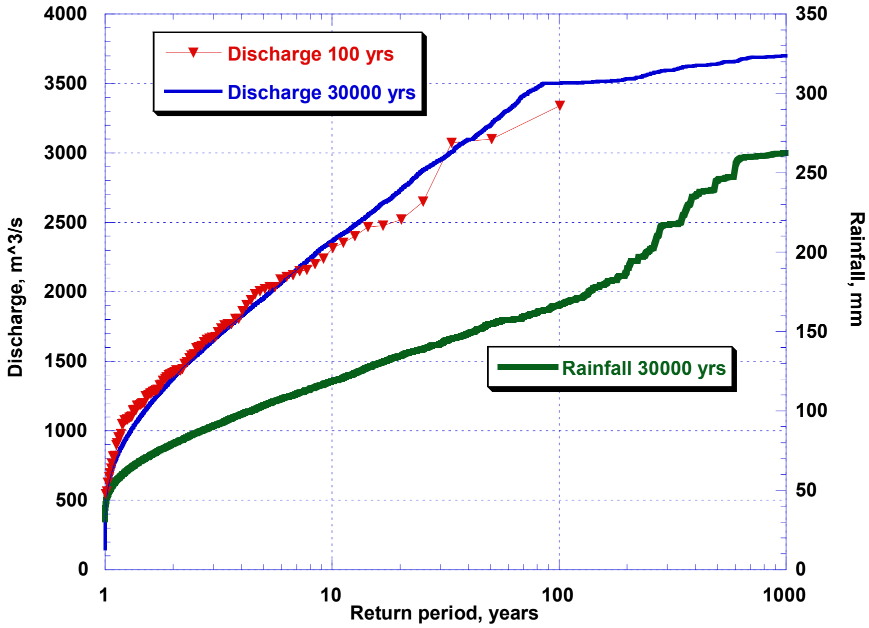

Figure 1.—Simulated rainfall and flood frequency curves with major floodplain storage activated at a threshold discharge of 3500 m^3/s (from Kuczera, 2000 Figure 10).

Figure 2 compares the flood frequency curves with and without major floodplain storage. Without major floodplain storage the flood frequency curve adopts the shape of the rainfall frequency curve which can be thought of as forcing the flood response. In sharp contrast, the activation of major floodplain storage radically alters the shape of the flood frequency curve. Although the case study idealizes the dominant rainfall-runoff dynamics it delivers a very strong message. Extrapolation of flood frequency curves fitted to gauged flow records, typically no more than 100 years in length, requires the exercise of considerable hydrologic judgment. The key issue to be addressed is whether the gauged record is representative of extreme floods that are yet to be observed. As demonstrated in the case study, the activation of major floodplain storage is not manifest in the 100-year record, yet profoundly affects the estimation of extreme flood risk.

Conceptual hydrologic models are relatively simple models requiring minimal data to run. Paradoxically this simplicity represents the greatest strength and weakness of this model genre. The weakness arises from the fact that conceptual hydrologic models require calibration to rainfall and runoff data. Even though a calibration can yield an impressively good fit this in itself is not a sufficient condition to accept extrapolations of the fitted model well beyond the range of the calibration data. Unless the correct dynamics are being approximated in the extreme flood range the extrapolated results may be worthless – Figure 2 forcefully makes this point.

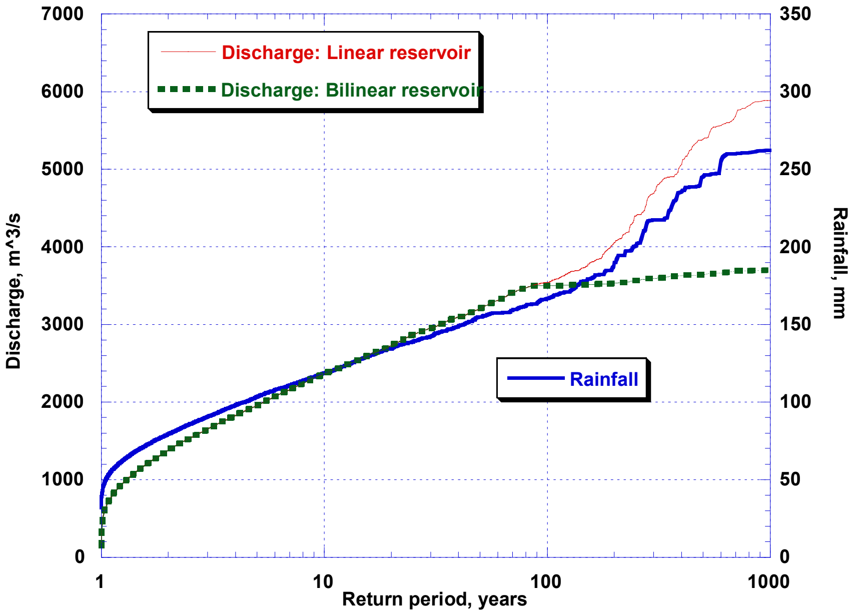

Figure 2.—Simulated rainfall and flood frequency curves with and without major floodplain storage (from Kuczera, 2000 Figure 11).

5.3 Review of Reclamation's Interim Flood Risk Procedures

Dr. Kuczera provided substantive review comments on two documents – the Comprehensive Facility Review (CFR) Flood Frequency Analysis (FFA) Guidelines and the draft North Platte Flood Hazard Study for Seminoe and Glendo Dams.

CFR FFA Guidelines Suggestions

The procedure places considerable emphasis on the development and interpretation of regional peak discharge envelope curves. It assigns what is acknowledged to be an arbitrary (but not unreasonable) return period of 100 to 500 years to the data that appear on the envelope curve.

It is Dr. Kuczera's opinion that Reclamation's preliminary analysis could make better use of the available regional gauged data. Although the regional peak discharge envelope curve provides a useful aid for identifying unusually big floods and for demonstrating the trend for flood discharge to grow with catchment area, it is deficient in the presentation of flood risks.

It is suggested that the regional envelope curve be complimented by a plot based on growth curves for gauges in the vicinity of the site under investigation. A growth curve is a nondimensional flood frequency curve. Here the growth curve is taken to be the plot of actual nondimensional floods against their estimated return period rather than a curve fitted to the nondimensional data.

Typically the nondimensionalisation is achieved by dividing annual maximum flood discharges by the mean annual flood. Because the mean annual flood discharge is known to be strongly correlated with catchment area and rainfall, nondimensionalizing annual maximum floods at multiple locations effectively removes the dependence of flood magnitude on location and size. By plotting multiple growth curves, as illustrated in Figure 3, two items of information complimentary to the regional envelope curve are obtained:

1. The growth curves implicitly make adjustment for catchment area. Therefore, they focus attention on flood magnitude and return period. Paleo flood data when nondimensionalised by the mean annual flood should display some consistency with the growth curves derived from the gauged data.
2. For a given return period less than 100 years there should be sufficient growth curves to estimate 5 and 95 percentile values. This allows construction of 90% confidence limits which approximately quantify uncertainty due to sampling variability as well as variation due to catchment heterogeneity. Excessive catchment heterogeneity can be avoided by only including sites with hydrogeomorphic characteristics similar to the study catchment.

It is suggested that the 90% confidence limits derived from the growth curves up to the 100-year return period be smoothly drawn to envelope the paleobound data and preserve the trend in the gauged growth curves up to about a 500-year return period, which must be considered the absolute limit of credibility of extrapolated gauged growth curves. Though an obviously subjective procedure it does have the virtue of allowing "the data to speak for themselves."

However, it needs to be stressed that probability models are only able to provide credible estimates when minimally extrapolated beyond observational data. Paleo data have extended this observational limit to the order of 1000 years. Beyond that risk estimation relies as much on the exercise of good judgment as on defensible science.

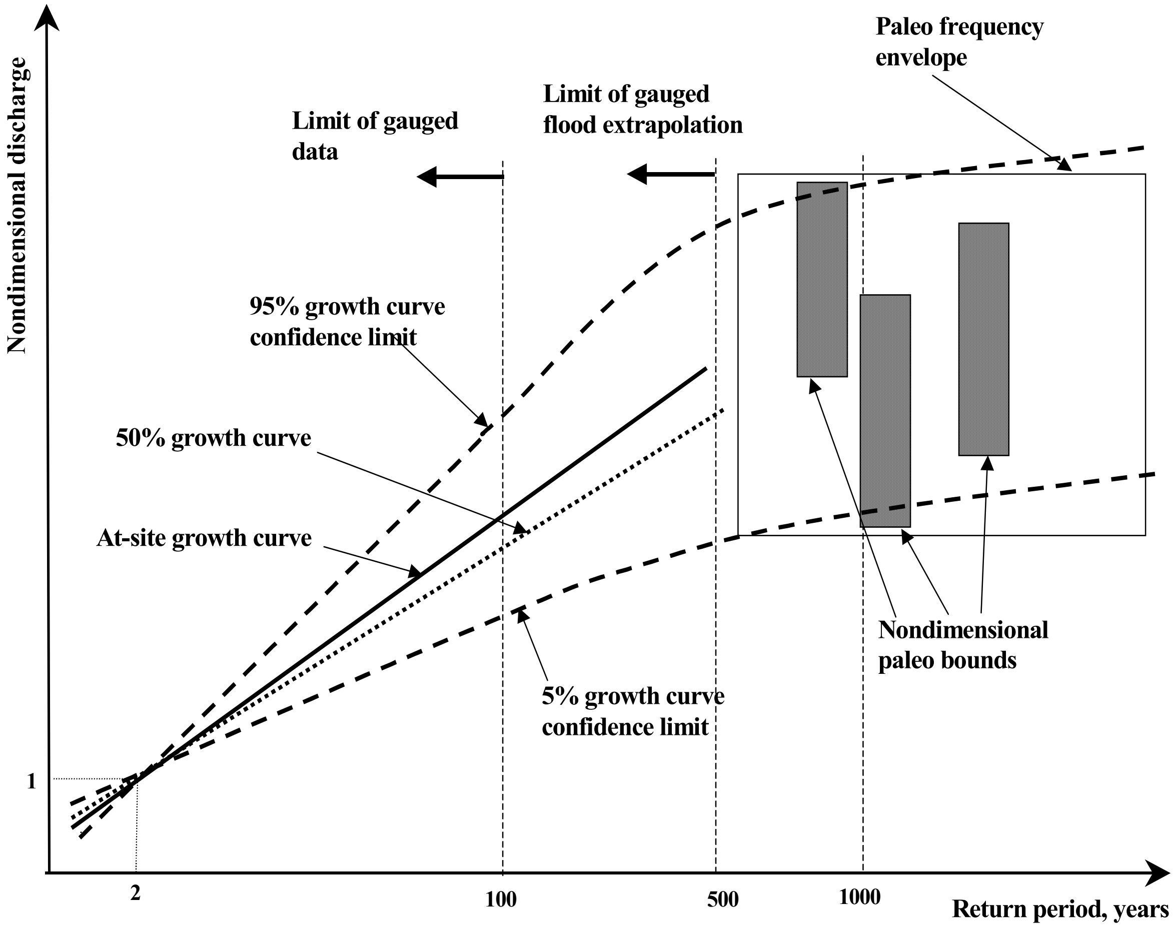

Figure 3.—Multiple regional growth curves. (From Kuczera, 2000 Figure 13).

Interim Overtopping Suggestions

The approach taken by Reclamation involves scaling dimensionless hydrographs selected from the sample of gauged hydrographs corresponding to historically big floods. This approach is open to several criticisms such as use of scaling rules similar to those used in unit hydrographs and the problem of distinguishing between fundamentally different flood production mechanisms arising from rainfall and snowmelt. Nonetheless, it is difficult to propose conceptually more satisfactory approaches short of the stochastic rainfall-runoff models currently under investigation by Reclamation.

Recognizing the interim nature of the approach, the review will focus on the missing link in the approach, namely the estimation of the water elevation frequency distribution. The problem is that use of multiple scaled dimensionless hydrographs will produce a range of peak water elevations in the reservoir for the same peak inflow. To resolve this it is necessary to employ a probabilistic framework for interpreting the results. Dr. Kuczera presented an approach to do this in his report (Section 6.2). It relied on three pieces of information: (1) a population of N dimensionless hydrographs with unit runoff volume derived from a statistically representative sample of large observed flood hydrographs; (2) a flood frequency curve defined by the probability density function p(q); and (3) reservoir topographic and hydraulic characteristics. The approach, with a complete list of equations to implement it, is described in Dr. Kuczera's report.

5.4 Comments on Flood Frequency Extrapolation

The two approaches reviewed in the report, flood frequency analysis and stochastic rainfall-runoff modeling; suffer from conceptual limitations which may limit their ability to provide credible extrapolations much beyond observational experience.

The flood frequency approach is fundamentally limited by the fact the true flood probability model is unknown. Arbitrary functions are used to fit flood frequency data. Therefore, it is difficult to assign credence to flood estimates much beyond the limits of the paleo data.

Flood frequency analysis on its own cannot furnish estimates of the risk of overtopping of major hydraulic structures – it only provides information about peak flows whereas reservoir routing requires inflow hydrographs. Some form of stochastic rainfall-runoff modeling is required. Unfortunately, because such models are built on an edifice of assumptions about the stochastic spatial and temporal characteristics of rainfall and catchment response, there is a high probability that model and data uncertainty will seriously undermine the credibility of extreme flood risks. This uncertainty is of a sufficiently great concern that Dr. Kuczera recommends stochastic rainfall-runoff models be constrained by paleo flood frequency data. In other words, for the present, paleo data define the credible limits of flood risk estimation.

It is recognized that major hydraulic structures have to be designed for risk levels beyond that which science can presently estimate with reasonable confidence. As a result it is necessary to furnish notional estimates of flood risk. Dr. Kuczera has several opinions on this issue, which conclude the review:

1. Without the benefit of observational data to challenge model assumptions and predictions, the only rational course of action is to develop extrapolative approaches which have the soundest conceptual foundations. The worst possible approach is to blindly extrapolate.

2. Nonetheless, whatever extrapolative approach is adopted it must be consistent with observed data; this requirement minimizes the extent of the extrapolation and improves the chance of the hydrologist making sound judgments. Jarrett and Tomlinson (2000, p.2980) illustrate a stochastic rainfall-runoff approach making predictions seriously at variance with paleo flood evidence.

3. Extrapolating the flood frequency trend on probability paper beyond the paleo data requires the exercise of good judgment about the nature of storm mechanisms and flood routing processes that affect extreme floods. If the hydrologist believes that the extreme

flood mechanisms have been sampled in the historic and paleo data then arguably there is justification in considerable extrapolation of the frequency curve. However, the case study illustrated above serves as a reminder of how wildly wrong extrapolated frequency curves can be if the hydrologist's judgment is flawed.

4. If paleo flood frequency curves reveal a downward curvature and independent evidence suggest that activation of major floodplain storage is responsible for the downward curvature, one can make the judgment that regardless of extreme storm mechanisms, the temporary storage on the floodplain will dampen growth in floodplain discharge. Under such circumstances, considerable confidence can be placed in extrapolating the flood frequency curve and using it as a constraint on a stochastic rainfall-runoff model.

5. If the paleo flood frequency curve has neutral or upward curvature then the prospect for gross extrapolative error is considerably greater than in the case of downward curvature. As already mentioned, judgments have to be made about extreme storm mechanisms and their frequencies along with extreme flood channel hydraulics. To make such judgments the hydrologist has to have a good knowledge of the related sciences that deal with phenomena affecting extreme floods.

6. One approach for dealing with extreme rainfall frequencies is stochastic storm transposition. This approach exploits space-for-time substitution and joint probability to reduce the degree of extrapolation of observed storm data. Unfortunately, the approach requires developing procedures which render large regions statistically homogeneous to exploit space-for-time substitution. The work by Agho et al. (2000) demonstrates the potential for nondimensionalising extreme rainfall in a transposition zone with mild topographic influence.

Nonetheless, the "Achilles heel" of storm transposition remains the estimation of topographic enhancement factors particularly in rough terrain – the analysis of the Rapidan storm [Smith et al., 1996], though somewhat compromised by questionable radar linearity, raises doubts about the ability of hydrometeorologists to transpose storms into rough terrain. Yet it is must recognized that current methods for evaluating topographic enhancement are crude. There is considerable scope for targeted research, using for instance meteorological models, to improve upon this situation and ultimately develop more capable stochastic storm transposition methods.

Extrapolation beyond observed data requires considerable exercise of judgment. Focused research can, in the longer run, reduce the dependence on judgment. In the interim, however, it is best that the necessary judgments be made by those most qualified to do so and that these judgments be the basis of a prescriptive approach. In essence this is the philosophy that oversees the development of the guidelines for extreme flood estimation in Australian Rainfall Runoff.

Conclusions and Recommendations

Based on the research conducted on “Compilation and Review of Stochastic Modeling Methods” and summarized in this report, five conclusions are made.

1. The overall objectives of the research were mostly met. Recent stochastic rainfall models were reviewed. Many documents and software related to stochastic modeling were obtained. Independent reviews of SEFM were completed. Stochastic software related to flood frequency; model calibration and time series were obtained. Reviews of stochastic components of runoff models, as well as evaluations of models for use in Dam Safety work were not completed.

2. A review of rainfall models indicated that much work has been completed over the past ten years in stochastic rainfall modeling, especially in point process model investigations and developments. Much of this work has been completed recently in the U.K. for use with continuous runoff models. Radar data is a very important part of space-time model development. Several recent models based on radar have been proposed. Most, if not all, require further development and testing. There is no clear choice that there is a “best” point process/cluster model for applications. Two areas that have demonstrated some development and practical application in design storm modeling are related to Depth Duration Frequency modeling and Stochastic Storm Transposition techniques.

3. Three independent reviews of SEFM were performed. These reviews were in general favorable for continued use of SEFM by Reclamation. The reviews generated a number of comments and suggestions related to correlation of data, continuous modeling, and model improvements. Much work needs to be done in the area of stochastic runoff modeling. Overall Dr. Kuczera is of the opinion that SEFM is a competently developed model. The issue of most interest to Reclamation is whether models like SEFM are capable of providing credible estimates of overtopping. Accordingly, his review comments were directed more at the conceptual credentials of models like SEFM than at SEFM itself. There is considerable doubt in Dr. Kuczera’s mind that models of the genre to which SEFM belongs, can be trusted to produce credible estimates of the probability of overtopping. This is even though Dr. Kuczera considers SEFM to be a competently developed model. The

4. Dr. Kuczera provided reviews and the FLIKE and NLFIT software to Reclamation. There are several conclusions from his work. Reclamation’s paleoflood methodology extends the observed flood record in streams with established flood terraces to annual exceedance probabilities (AEPs) of the order of 10^{-3}. Reclamation has made original contributions in its development of paleo discharge estimates. An idealized, continuous stochastic rainfall-runoff model was developed by Dr. Kuczera for Reclamation. He used the model for three purposes: (1) the crucial importance of employing paleo flood data to constrain the extrapolations made by stochastic rainfall-runoff models; (2) the inherent weakness of extrapolating a model beyond the range of the data to which the model was

calibrated; and (3) how a stochastic rainfall-runoff model can be hooked to the calibration software NLFIT to enable calibration to rainfall-runoff time series and to a flood frequency curve.

5. Based on reviews of paleoflood data and SEFM by Dr. Kuzcera, and stochastic modeling experiments conducted by Dr. Kuzcera, paleoflood data define the credible limits of flood risk estimation. Prescriptive approaches can provide a basis for flood frequency and rainfall-runoff model extrapolations beyond the paleoflood data.

From the reviews and analyses shown in this report, seven recommendations are made for implementing the procedures and continuing flood studies for dam safety within the Bureau of Reclamation.

1. Additional research in both stochastic rainfall and runoff models are needed in order to develop practical tools that may directly be used on projects for Dam Safety.

2. In order for practical stochastic rainfall models to be used, additional data development is needed. It is recommended that data investigations be performed to: (1) increase the data base of storms; and (2) there is a great need for radar-based climatology, storm and spatial investigations.

3. From the independent SEFM reviews, it is recommended by Drs. Crawford and Tomlinson that improvements be made when correlating data and model components; and the use of a continuous rainfall model could be investigated. Dr. Kuczera made five major suggestions, in addition to many others: (1) simplify the SEFM model to reduce the number of parameters requiring calibration and the effort gathering the necessary data; (2) focus the calibration on lumped parameters; (3) recode SEFM in a language more efficient than Visual Basic such as Fortran95 or C; .(4) exploit parallelism in the Monte Carlo simulation using software architectures such as PVM (Parallel Virtual Machine); and (5) implement the stratified Monte Carlo sampling strategy to minimize the number of simulations.

4. Dr. Kuczera made a specific recommendation that Reclamation publish its paleoflood work in peer-reviewed journals for wider dissemination, critical review and acceptance.

5. Further work is needed by Reclamation personnel to gain experience and practical expertise with Dr. Kuczera's stochastic model, NLFIT and FLIKE.

6. Dr. Kuczera's recommendations to improve the CFR flood frequency procedures should be further investigated. These include using a regional index flood approach with paleoflood data and explicitly estimating uncertainty.

7. Dr. Kuczera's recommendations to develop an interim overtopping procedure with hydrographs should be further investigated. These include: (1) a population of N dimensionless hydrographs with unit runoff volume derived from a statistically representative sample of large observed flood hydrographs; (2) a flood frequency curve defined by the probability density function p(q); and (3) reservoir topographic and hydraulic characteristics.

Listing of Major Technical Documents Obtained in Research

This section lists contract deliverables; major reports and books; computer software, manuals and papers; and doctoral dissertations obtained and examined as part of the research on stochastic modeling methods. Hardcopies of reports and copies of computer programs and backup material submitted on compact discs are available from the Flood Hydrology Group, D-8530.

7.1 Consultant Deliverables

Crawford, N.H. (2000) Comments and Discussion of: General Storm Stochastic Event Flood Model, Technical Support Manual, October 1998; Stochastic Modeling of Extreme Floods for A. R. Bowman Dam, November 1997; and Assessment of Risk Reduction Measures at A. R. Bowman Dam Using A Stochastic Model of Extreme Floods, October 1998 by MSG Engineering Consultants, Inc. Letter Report by Norman H. Crawford, Hydrocomp, Inc., Menlo Park, CA, September 14, 2000, 9 p.

Kuczera, G. (2000) Review of Extreme Flood Risk. Department of Civil, Surveying and Environmental Engineering, University of Newcastle, on behalf of TUNRA, University of Newcastle, Callaghan, NSW, 2308, Australia, for Probabilistic Flood Hazard Cadre, Bureau of Reclamation, December 2000, 45 p.

Tomlinson, E. (2000) Review, Comments and Discussion of the General Storm Stochastic Event Flood Model, Technical Support Manual, October 1998; and Stochastic Modeling of Extreme Floods for A. R. Bowman Dam, November 1997 by MSG Engineering Consultants, Inc. Letter Report by Edward M. Tomlinson, Applied Weather Associates, Monument, CO, April 26, 2000, 3 p.

7.2 Major Reports and Books

Australian Rainfall and Runoff (ARR) (2001) Volume One: A Guide to Flood Estimation (in eight books). The Institution of Engineers, Australia.

Barndorff-Nielsen, O.E., Gupta, V.K., Perez-Abreu, and Waymire, E. (eds.) (1998) Stochastic Methods in Hydrology: Rain, Landforms and Floods. Advanced Series on Statistical Science and Applied Probability, Vol. 7, 207 p.

Boughton, W.C. and Hill, P.I. (1997) A Design Flood Estimation Procedure Using Data Generation and a Daily Water Balance Model, Technical Report 97/8, Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia, October, 41 p.

Crowley, T.E II (2000) Using Meteorology Probability Forecasts in Operational Hydrology. ASCE Press, Reston, VA, 206 p.

Institute of Hydrology (1999) Flood Estimation Handbook (FEH) - Procedures for Flood Frequency Estimation (in five volumes). Institute of Hydrology, Wallingford, Oxfordshire, United Kingdom.

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Nathan, R.J., Weinmann, P.E., and Minty, L. (1997) Estimation of the Annual Exceedance Probability of PMP Events in Southeast Australia, Draft document. October 23, 1997, 16 p.

Rahman, A., Weinmann, E., Hoang, T., Laurenson, E. and Nathan, R. (2001) Monte Carlo Simulation of Flood Frequency Curves from Rainfall, Technical Report 01/4,Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia, March, 63 p.

Salas, J.D., Saada, N., Chung, C.H., Lane, W.L. and Frevert, D.K. (2000) Stochastic Analysis, Modeling and Simulation (SAMS), Version 2000, Technical Report No. 10, Computing Hydrology Laboratory, Water Resources, Hydrologic and Environmental Sciences, Colorado State University, Fort Collins, 91 p.

Singh, V.P. (1995) Computer Models of Watershed Hydrology. Water Resources Publications, Littleton, CO, 1130 p.

Srikanthan, R.J. and McMahon, T.A. (2000) Stochastic Generation of Climate Data: A Review. Project 5.2: National Data Bank Of Stochastic Climate And Streamflow Models. Technical Report 00/16, Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia, September, 34 p.

Weinmann, E. and Kuczera, G. (1998) Annual Exceedance Probability (AEP) of Probable Maximum Precipitation (PMP): Report on a Review and Recommendations for Practice. Prepared for the Institute of Engineers, Australia, 32 p. and appendices.

7.3 Computer Software, Manuals, and Papers

Beven, K. (1998) Generalised Likelihood Uncertainty Estimation (GLUE). Hydrology & Fluid Dynamics Group, Department of Environmental Science, Institute of Environmental and Natural Sciences, Lancaster University, UK, 5 p.

Chandler, R.E. (2001) Generalized linear modelling for daily climate time series, user's guide, Department of Statistical Science, Univ. Coll. London, February, 24 p.

Hydrocomp (1999) HFAM 1.1: Hydrocomp Forecast and Analysis System. Hydrocomp, Inc., Menlo Park, CA.

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Kuczera, G. (1999) Comprehensive at-site flood frequency analysis using Monte Carlo Bayesian inference, Water Resources Research, 35(5), pp. 1551-1558.

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The references are listed in three categories. Section 8.10 contains stochastic rainfall review citations that were discussed in Section 3.00. Those references cited in the remainder of the report are listed in Section 8.20. A number of general stochastic modeling references that are not discussed in the report are listed in Section 8.30.

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Mission Statement

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.