Stochastic Event Flood Model Improvements and Extreme Storm Analyses for A.R. Bowman Watershed

Dam Safety Office

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WATER RESOURCES MANAGEMENT.....FOR THE FUTURE

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Introduction

This report summarizes work that was completed under a Service Agreement titled “MGS Stochastic Refinements”. 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 two areas: improving the Stochastic Event Flood Model (SEFM) and analyses of extreme storms for the watershed upstream of A.R. Bowman Dam. This work was performed under two separate, external contracts with MGS Engineering Consultants, Inc. (MGS) and Applied Weather Associates (AWA). This report summarizes the tasks, results and deliverables of the research work performed by the contractors. Nearly all the text and results summarized here are directly obtained from work completed by the contractors for Reclamation. The work performed by Technical Service Center (TSC) personnel as part of the research was limited to contract development, administration, review, discussion and acceptance of contract deliverables.

1.1 Background

The research on improving SEFM and analyzing extreme storms was motivated by three developments: (1) results from the 1997 Reclamation-sponsored workshop in Logan, Utah (USBR, 1999); (2) the successful work and modeling by MGS using SEFM for Reclamation (Schaefer and Barker, 1997; 1998); and (3) 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 was on ultimately developing practical hydrological modeling tools that the output would be used in risk analysis (Table 1).

The research presented in this report focuses on improving two areas listed in Table 1: stochastic event-based precipitation-runoff modeling (SEFM improvements) and atmospheric modeling (extreme storm analyses for A.R. Bowman watershed). Both of these research areas were pursued to follow a research/development recommendation from the Logan document (USBR, 1999 p. 45): “There should be continued support for the development of methods for processing hydrologic information for characterizing extreme floods for risk assessments.”

Table 1.—Applicability of hydrologic methods of analysis and modeling to various risk assessment levels (USBR, 1999, Table 3-2); bold text indicates areas that research was performed and summarized in this report

Method of analysis and modeling	Risk assessment level		
	Baseline		Risk reduction
	CFR	Project team	
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

1.2 Contractors and Expenditures

The research work that was performed is the direct result of two Reclamation contracts. MGS conducted research and improvements to SEFM under Contract Purchase Order 99PG810040 (Modification 2), dated 06/2000. AWA completed analyses of extreme storms for the A.R. Bowman watershed under Contract No. 7CA8120003, dated 09/07/2000 and executed through the Reclamation IDIQ contract with URSG-WCFS. Reclamation TSC personnel labor and contract costs associated with this work are listed in Table 2. A copy of the service agreement and project expenditures to date are attached as Appendix A.

Table 2.—TSC labor and contract non-labor costs for research conducted under WOID MGSSR by fiscal year

Fiscal year	TSC staff days	TSC labor	MGS engineering	AWA
2000	14.25	$8,862.00	$9,140.00	$0.00
2001	15	$9,263.00	$42,928.16	$59,129.55
2002	0	$0.00	$0.00	$65,578.48
2003	5	$3,280.00	$0.00	$0.00
Totals	34.25	$21,405.00	$52,068.16	$124,708.03
Total contract expenditures				$176,776.19

The contractors that conducted the research have substantial experience in hydrology and hydrometeorology of extreme floods. MGS Engineering, Inc. has worked with the Reclamation TSC since about 1996 on precipitation frequency, Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) variability and extreme flood probability issues (e.g., Barker et al., 1996; 1997). The prototype of SEFM was developed for application to the A.R. Bowman watershed (Schaefer and Barker, 1997). A training course was conducted by MGS in June 1998 to instruct TSC Flood Hydrology Group personnel on using and applying the model. SEFM was subsequently generalized for use by Reclamation employees on other projects (e.g., Bullard and Schaefer, 1999). 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. For the work presented in this report, AWA utilized the subcontractor GeoClim Consulting Group (Providence, Utah) for three-dimensional atmospheric model simulation services.

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 MGSSR. 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 data. Robert Swain (D-8530) helped coordinate meetings, develop scope of work, and reviewed submittals from MGS. Richard Stodt (D-8510) provided detailed reviews of the AWA work, discovered technical errors and deficiencies, and ensured that deliverables were acceptable. He contributed a significant amount of work and expertise, courtesy of his projects funded by others, and helped Reclamation receive an adequate product.

Marijo Camrud, a former TSC employee in the Flood Hydrology Group, provided contract administration for the MGS and AWA contracts from 2000 through September 2002. Louis Schreiner, Group Manager, Flood Hydrology Group helped with contract difficulties, managed final completion of the AWA contract and provided encouragement so that the research and this summary report could be completed.

Objectives

The objectives of the research conducted under MGSSR are listed below for each area.

2.1 Stochastic Event Flood Model Improvements

The research was directed at making key refinements to the MGS Stochastic Model (SEFM) that has been previously used by MGS and Reclamation on several projects. The model will be improved by clarifying and adding sections to the SEFM Technical Support Manual, improving the post-processing software, performing sensitivity analyses, and expanding the model to allow for simulation of 1,000,000 runs. An important aspect of the model refinements is determining the important factors to be considered in extreme flood modeling for a particular location. The sensitivity analysis procedures help to answer this question, and are useful to help understand the variability in the results. Suggested future improvements, such as development of methodologies to estimate confidence intervals for model output, better incorporate model parameter uncertainty, and allowing for the incorporation of paleoflood data, will be noted.

2.2 Extreme Storm Development for A.R. Bowman Watershed

In order to develop a more comprehensive understanding of the atmospheric processes associated with extreme storm events for the region surrounding the A.R. Bowman Dam drainage basin, a comprehensive listing of historic extreme storm events is developed. This list identifies all historic extreme rainfall events for regions which are topographically and climatologically similar to the A.R. Bowman Dam drainage basin. The climatology of selected major storms is analyzed. These critical storms are then simulated using a three-dimensional mesoscale atmospheric model. This is an extreme storm development approach recommended by USBR (1999) that has not been previously attempted for Reclamation. The atmospheric modeling approach helps Reclamation in using multiple methods, recommended by USBR (1999). After development of climatology and mesoscale modeling of extreme rainfall events for the A.R. Bowman drainage basin, comparison of these extreme rainfall events are made to the input storm information to SEFM (Schaefer and Barker, 1998). Similarities between the SEFM input and historical storm parameters would provide confidence that the model simulations are representative of extreme storm events. Future work, consisting of generalizing the atmospheric modeling approach and developing a storm transposition methodology will be noted.

Research Approach

The approaches used in each portion of the research project are outlined by describing major contract tasks.

3.1 Stochastic Event Flood Model Tasks

Refinements to the SEFM program are identified in five main tasks that are performed by MGS. A meeting was held in Denver with the contractor to present results of the tasks and obtain reviews.

TASK 1.—*Provide additional documentation of the assumptions, justifications, input parameters, and model functions in the Technical Support manual.* The goal of this task is to achieve a better understanding and documentation of model assumptions, inputs, and operations in the SEFM model. This will allow reviewers to determine the applicability of the assumptions and will permit modification of the assumptions to examine model sensitivity to various parameters.

Maps shall be provided as an Appendix to the A. R. Bowman report depicting the location of precipitation gages, temperature gages, snow and streamflow gages and measurement points, basin location, and subbasin definition. Maps shall show scale, north arrow and shall be of sufficient detail to provide information regarding the location of gages. Summary tables of the location, elevation, period of record, and type of gage shall be provided in the Appendix. Other data screens may be added to the Appendix as needed to allow presentation of data used in the model for reproduction of study results. Any changes to the model or input data that effect A. R. Bowman study results shall be described in the Appendix.

TASK 2.—*Improve the existing output post-processor software component (MGS, 1998 p. 61) to include tables and plots for each of the input random variables and parameters.* The goal is to reconstitute the input to determine if each of the random variables and parameters are adequately sampled. For example, plot the resulting output storm dates and compare against the fitted distribution (e.g., Figure 3, MGS, 1998 p. 18). This Task is based in-part on Singh's (1999) recommendation that risk and reliability analysis be added to the model. Provide sample statistics, frequency histograms, probability-plots, or other means to confirm sampling characteristics for various hydrometeorological input parameters. Proof of the random sampling of variables shall be demonstrated using the A.R. Bowman dataset. A general discussion (write-up) shall be included in the Technical Support Manual, and a project specific discussion shall be included in the appendix to the A. R. Bowman report.

TASK 3.—*Perform a sensitivity analysis to identify those parameters that will most significantly affect the peak volume, peak discharge, and maximum reservoir elevation.* For parameters represented in the model by probability distributions, it is suggested to vary the parameters by up to 2 standard deviations (or up to 25 percent for fixed values) to the calibration run to measure the effects of the changes.

Information obtained from sensitivity analyses provides one element of the information needed for an assessment of the "reliability" of the flood estimates. To complete the picture, information is also needed on the relative uncertainty of the various parameters. Thus, if the flood outcomes are sensitive to a given parameter and the uncertainty about that parameter is high, the reliability of the model predictions is reduced. Conversely, if the flood outcomes are sensitive to a given parameter(s) and the parameter value(s) is based on a large representative data set(s), then greater reliability can be given to the predicted flood outcomes. In addition to the parameter sensitivity analysis, provide a written characterization of the uncertainty of each parameter. A general discussion (write-up) shall be included in the Technical Support Manual, and a project specific discussion shall be included in the appendix to the A. R. Bowman report.

The following 15 model and hydrometeorological input parameters should be evaluated in the sensitivity analysis: (1) Soil Moisture Storage; (2) Minimum Surface Infiltration; (3) Deep Percolation Rate; (4) Interflow Lag Time; (5) Interflow Peaking Factor; (6) Maximum Surface Infiltration Rate; (7) Channel Routing Coefficients - Muskingum K factor; (8) Channel Routing Coefficients - Muskingum X factor; (9) 24 Hour Precipitation Magnitude Frequency; (10) Temporal Distribution of Extreme Storms; (11) Spatial Distribution of Extreme Storms; (12) Antecedent Precipitation; (13) Antecedent Snowpack; (14) Temperatures for Snowmelt Calculations; and (15) Initial Reservoir Level.

Develop routines for incrementing parameters and plotting sensitivity results. Because of the size and complexity of the A.R. Bowman drainage basin, sensitivity analysis may be performed on one subbasin, rather than the entire model. The subbasin selected must be identified and approved by Reclamation prior to sensitivity analysis.

TASK 4.—*Based on the discussion by Bullard and Schaefer (1999, p. 8) expand the capability of the model to simulate 1,000,000 flood events.* Provide the user with the option of using a mega-simulation set (up to 1,000,000 simulations) or using the piecewise approach, which has been used previously. Demonstrate expanded capability by providing output from A.R. Bowman dataset. Describe the advantages and disadvantages for using each approach in the Technical Support Manual with a project specific discussion (write-up) included in the appendix to the A. R. Bowman report.

TASK 5.—*The Technical Support Manual should be modified to include the Training Notes which have been used in training workshops.* The Training Notes may be either incorporated into the Manual or added to the Manual as Part 2, with the Technical Support portion of the Manual as Part 1. The Manual shall be of sufficient detail to allow model users to select and input parameters and understand model results. Modeling assumptions and approaches shall be documented in the Manual.

3.2 Extreme Storm Development Tasks

Applied Weather Associates conducted research under four major tasks to analyze and develop extreme storms for A.R. Bowman Dam.

TASK 1.—*This effort would initially collect all station data of large storms identified in HMR 57 dataset provided by the Bureau of Reclamation and NOAA and those station data of large storms that may have occurred subsequent to the completion of the HMR 57 dataset.* These data can be collected from records at the National Weather Service Hydrometeorological Design Studies Center in Silver Spring, Maryland and from records available from the Bureau of Reclamation in Denver. Other sources of historic rainfall and storm data may be incorporated during the development of the extreme storm list.

The National Climatic Data Center (NCDC) station rainfall data will be analyzed to identify extreme rainfall observations. Dates and locations of large rainfall observations will be compared to the HMR 57 and subsequent storms to ensure all large storms which have occurred over regions which are climatologically or topographically similar to the A.R. Bowman drainage basin are included. If they are not, these storms would be identified and available data will be collected. The resulting storm list will identify all extreme rainfall events which have occurred over the climatological and topographical similar area around Bowman. These storms will be identified by date and location e.g. Central Oregon, September 9-11, 1958.

TASK 2.—*Climatological data storm files containing all available data will be developed from station data.* Depth-area-duration plots, mass curves, moisture analyses, and isohyetal maps will be prepared and analyzed in Spatial Analyst or compatible GIS format. All related information for historic extreme storm events identified in Task 1 will be procured from the various agencies which possess the archived storm information. A database of meteorological data and analyses will be assembled for each storm to provide as complete an analysis package of related meteorological information as possible for each storm event.

For each storm, the isohyetal rainfall pattern will be evaluated in the ESRI GIS format. Storm rainfall patterns will be developed using the Spatial Analyst software package and displayed using ArcView. Final storm rainfall analyses will be archived in the ESRI GIS format. These GIS formatted rainfall data will provide a standard format for both the temporal and spatial characteristics of each extreme rainfall event. The storm files will contain both paper copies of historic information and electronic files of analyzed data fields.

TASK 3.—*Using a public domain atmospheric program (fifth generation NCAR/Penn State Mesoscale Model (MM5)), selected storms (5-6) will be modeled to understand the meteorology of the storm; i.e. how they were produced.* The Utah Climate Center will provide the MM5 model runs. The MM5 model will be used to replicate each storm using observed meteorological databases to initialize the model. The actual terrain where the storm occurred will be used to provide the lower boundary in the model and will influence the atmospheric boundary layer to enhance rainfall, decrease rainfall, or determine the positioning of the rainfall center. Model parameters will be varied until the rainfall produced by the model matches as closely as possible the observed rainfall. Once the parameters in the model have been adjusted such that the model reproduces the rainfall from the observed storm, the magnitude of the parameters, correlations, and the correlations among parameters will be noted.

TASK 4.—*The particular characteristics of each storm event will be evaluated.* Identify similar characteristics among the extreme storms and evaluate how these characteristics could combine in an optimum manner to maximize the volume of rainfall which could be produced by an extremely efficient storm in combination with an abundant supply of atmospheric moisture.

The final effort will be to compare the extreme rainfall events and characteristics to the parameters and precipitation input to the Stochastic Event Flood Model for A.R. Bowman Dam. The magnitude of the input parameters used in the Monte Carlo approach of the SEFM will be compared to the magnitude of the same parameters associated with extreme historic rainfall events using the storm climatology. Additionally, correlations among the extreme input parameters used in the stochastic approach will be compared to correlations derived from the historic data. Other comparisons can be made depending on the explicit information available for the storm climatology.

Results and Discussion

This section briefly describes the results from the tasks of each contract. Deliverable dates and content of each task are listed. Conclusions and recommendation are made based on these results are presented in Section 5.00. A listing of the deliverables from the contracts is presented in Section 6.00.

4.1 Stochastic Event Flood Model

MGS completed five tasks. The results for each task were submitted by MGS to Reclamation on the dates listed in Table 3. A complete copy of the SEFM Technical Support Manual and computer software are available from the Flood Hydrology Group

Table 3.—MGS contract submittals by task

Task No.	Task name	Approximate submittal date	Content
1	Tech Support Manual additional documentation and improvements	July 2000	Report
2	Improve output post-processor	August 15, 2000	Software
3	Sensitivity analysis	January 21, 2001	Report
4	Expand number of model simulations	April 30, 2001	Software/Report
5	Include training notes in Tech Support Manual	April 30, 2001	Report

The major results from Task 1 include clarifying the gage locations for analysis with the model, and improving the Technical Support Manual. An example map for A.R. Bowman is shown in Figure 1. The technical support manual was completely revised and rewritten with many clarifications and additions. A table of contents for the manual is attached as Appendix B.

The output post-processor, as well as the input processor, were improved as part of Task 2. The general storm stochastic event flood model (SEFM) is comprised of seven software components: data entry; input data pre-processor; multiple sample parameter test workbook; HEC-1 template file; stochastic inputs generator; HEC-1 rainfall-runoff flood computation model; and an output data post-processor. The flowchart shown below depicts the sequence of actions required for

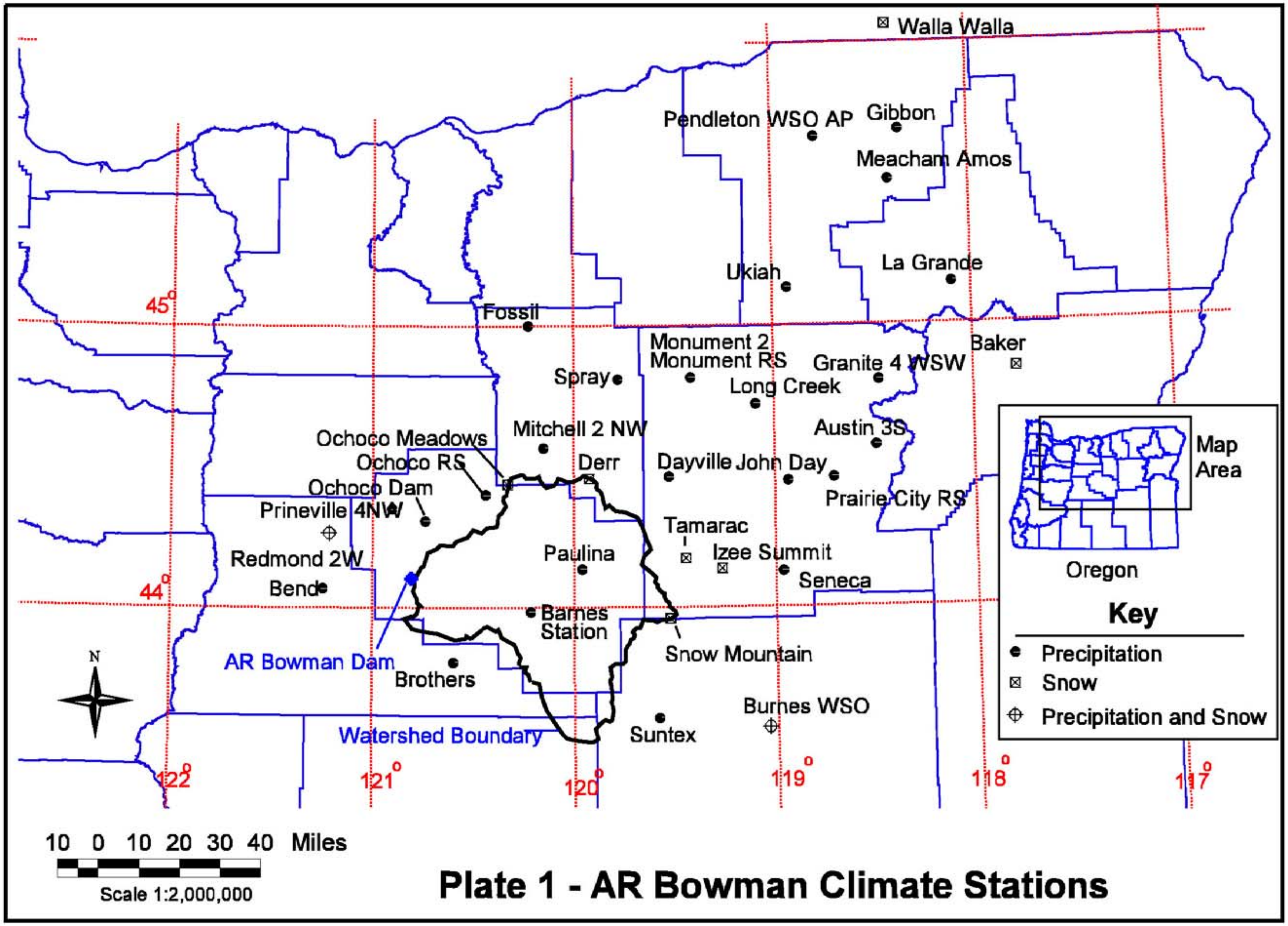
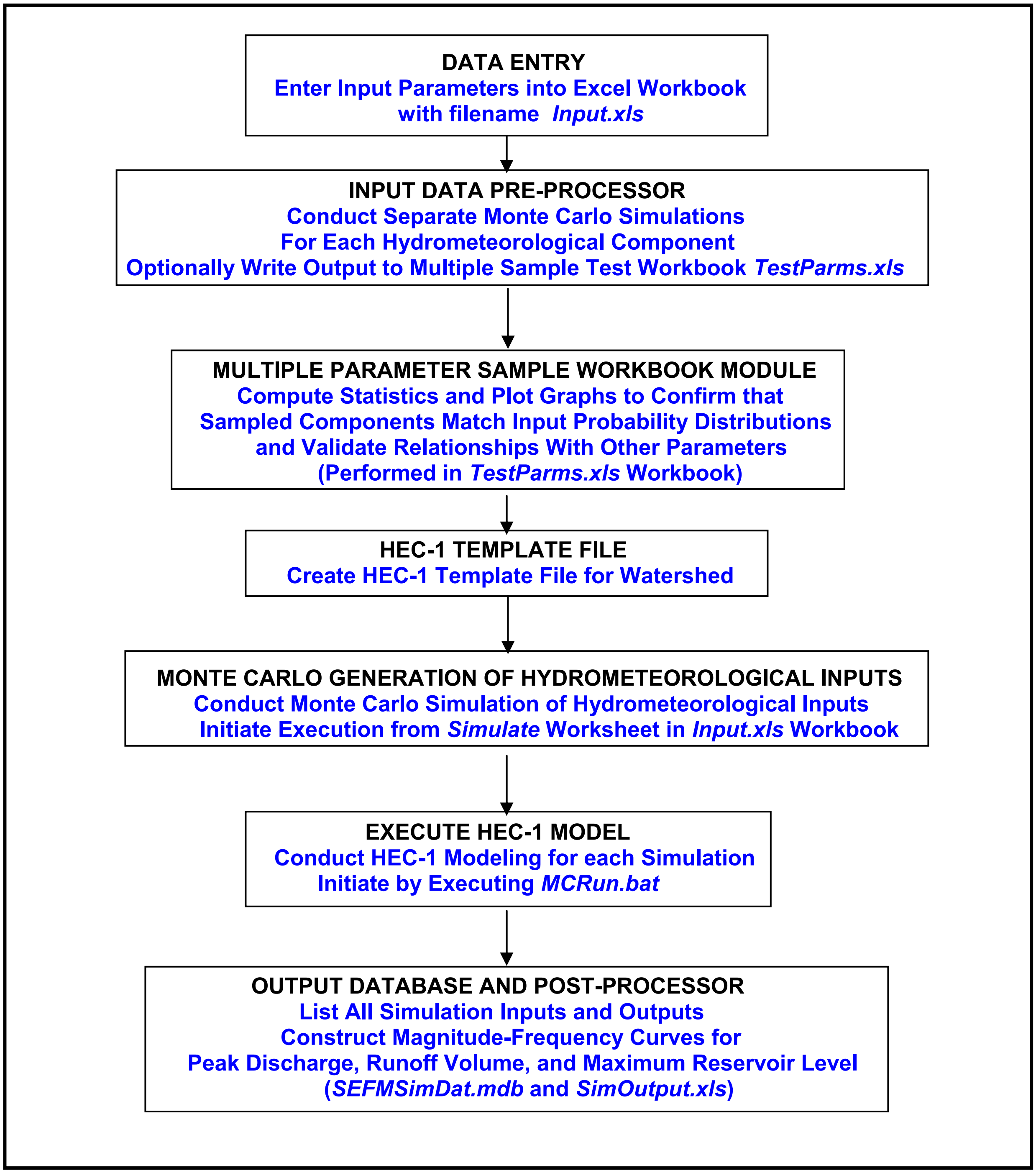


Figure 1.—Precipitation and snow gage locations used for A.R. Bowman watershed modeling with SEFM.

conducting the computer simulations using the software components. Each of these components is described in the SEFM Technical Support Manual.



As part of Task 2, the input processor was improved using an Excel spreadsheet (Figure 2), and the output was improved as well (Figure 3). The improvements are contained in software version 1.8 of SEFM.

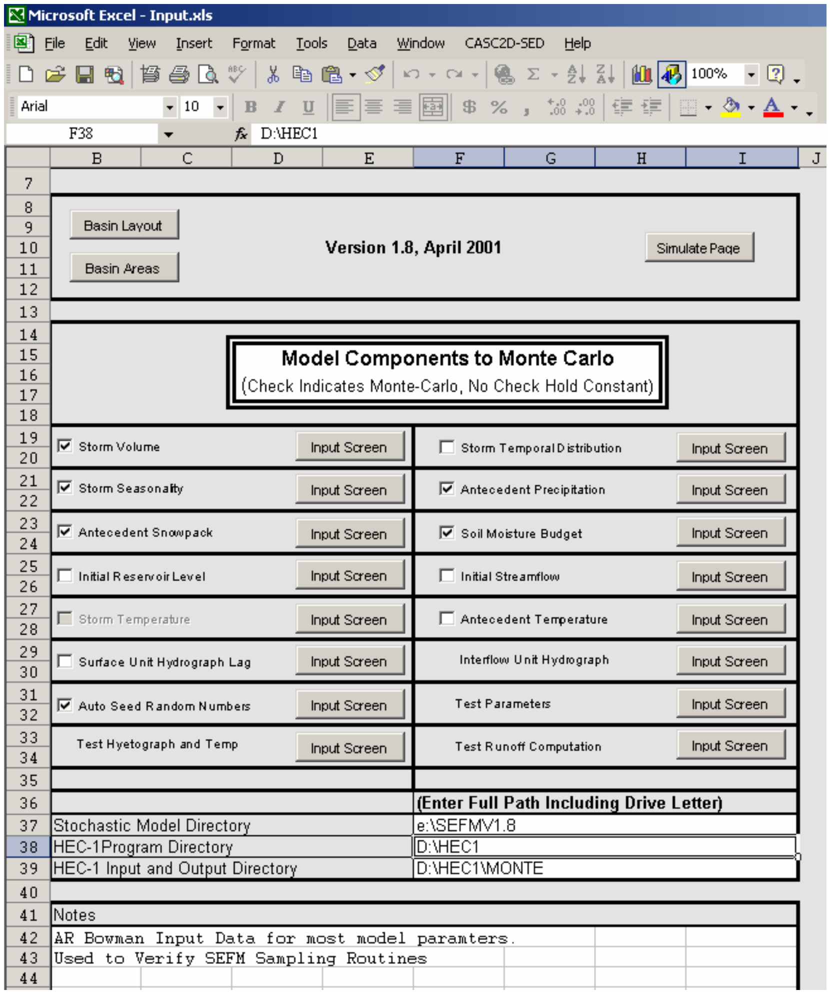


Figure 2.—SEFM Input screen.

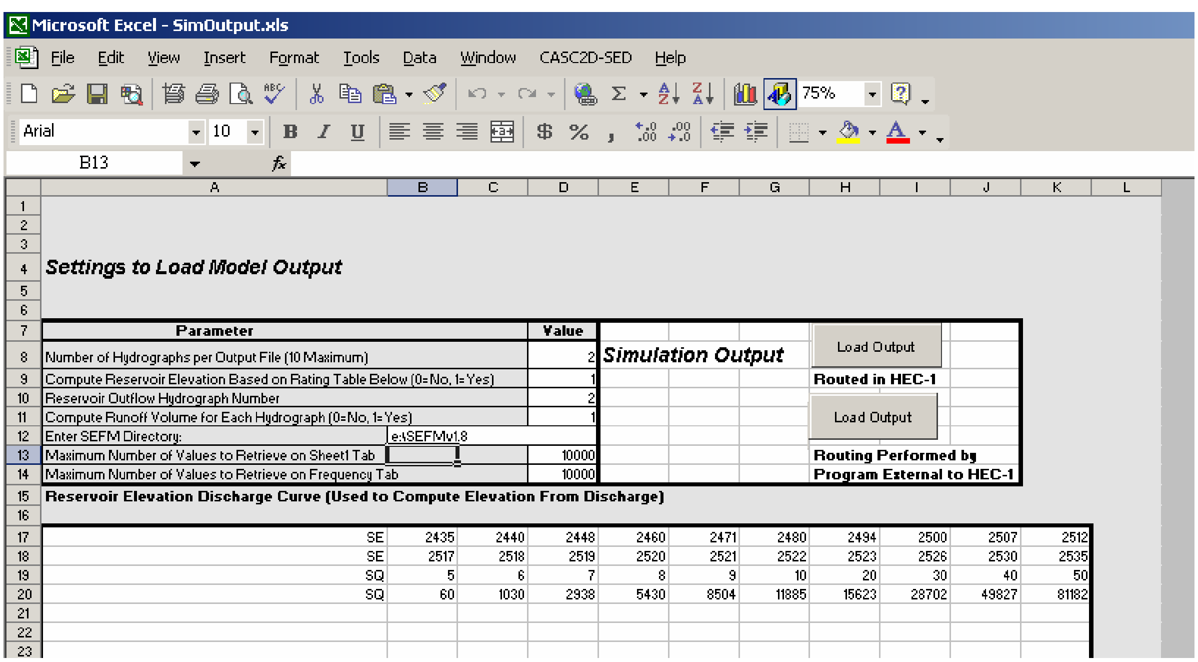


Figure 3.—SEFM output simulation options.

An extensive sensitivity analysis was run as part of Task 3. A summary of the sensitivity results is shown in Table 4. The sensitivity of each of the parameters was rated as low, moderate, or high. This rating was based on the relative magnitude of the change of the flood outcomes for a change of ± 25% around the control value for the selected parameter. The input parameters that have the greatest effect on the flood characteristics include: soil moisture storage capacity; 24-hour 10-mi^2 precipitation; storm temporal distribution; storm areal coverage; antecedent precipitation (antecedent snowpack); and storm temperature. The resultant floods were also sensitive to a lesser degree to the deep percolation rate, and storm centering over the watershed.

Table 4.—Summary of Relative Sensitivity of Flood Outcomes to Input Parameters for A.R. Bowman Watershed

	Flood peak		Flood volume		Maximum reservoir elevation	
Parameter	End of December	End of April	End of December	End of April	End of December	End of April
1. Soil moisture storage capacity	High	Mod	High	Mod	High	Mod
2. Minimum surface infiltration rate	Low	Low	Low	Low	Low	Low
3. Maximum surface infiltration rate	Low	Low	Low	Low	Low	Low
4. Deep percolation rate	Mod	Mod	Mod	Mod	Mod	Mod
5. Interflow lag time	Mod	Mod	Low	Low	Low	Low
6. Interflow peaking Factor	Low	Low	Low	Low	Low	Low
7. Channel routing - muskingum *K*	Low	Low	Low	Low	Low	Low
8. Channel routing - muskingum *x*	Low	Low	Low	Low	Low	Low
9. 24-hour 10-mi^2 precipitation	High	High	High	High	High	High
10. Storm temporal distribution	High	High	High	High	High	High
11. Storm centering over watershed	Mod	Mod	Mod	Mod	Mod	Mod
12. Storm areal coverage	High	High	High	High	High	High
13. Antecedent precipitation	High	Mod	High	Mod	High	Mod
14. Temperatures during storm	High	Low	High	Low	High	Low
15. Initial reservoir elevation	n/a	n/a	n/a	n/a	Mod	Mod

Several input parameters that are commonly sensitive in rainfall-runoff modeling analyses were found not to be sensitive in this analysis. These included the minimum surface infiltration rate and channel routing parameters. A complete report of the sensitivity study, listed in Section 6.00, is available from the Flood Hydrology Group.

The number of simulations that can be run with the model (Task 4) was improved so one can run up to 1,000,000 model simulations. This is accomplished by storing intermediate and final SEFM outputs in a Microsoft Access database, to overcome the Excel row limits of 65,586 lines. The model outputs are retrieved from the database as part of the standard process for analyzing the outputs for flood peak discharge, runoff volume, and maximum reservoir level. Thus, the only constraint on the number of simulations is the practical limitation of the amount of time required to conduct the simulations.

To complete Task 5, the training notes used in the June 1998 Reclamation training classes were included in the Technical Support Manual. These training notes were directly incorporated into the manual. The 1998 training notes included fifteen sections. The first fourteen sections from the original training notes were rewritten and included in Part II (Hydrometeorological Inputs and Data Entry) of the Technical Support Manual. The last section of the notes, titled statistical methods review, was significantly expanded and is now included in the Technical Support

Manual as Appendix A, Applied Probability and Statistics for SEFM – Basic Concepts. A complete table of contents for the Manual is attached as Appendix B.

The submittals made under the contract with MGS directly resulted in a practical and useful tool to conduct extreme flood hydrology studies for Reclamation dam safety projects. The objectives of the contract scope were clearly met. The primary results of this research – computer program and manual - can be readily used on projects for the Dam Safety Program. The SEFM model can be run in a completely stochastic mode where all hydrometeorological parameters are allowed to vary. It can be run in a completely deterministic mode with all parameters fixed, or it can be run in a mixed mode with some parameters treated as variables and other parameters fixed. A current, practical limitation with SEFM is the lack of in-house Reclamation experience with using the model at various sites. To date, one application has been completed by Reclamation personnel (Bullard and Schaefer, 1999). It is recommended that SEFM be applied at additional sites to increase Reclamation experience with the model.

There are some current limitations to SEFM and applicability to certain Reclamation sites. SEFM is currently configured for simulation of 72-hour general storms. There is no computational limit to the size of the watershed to which it can be applied. However, implicit in the development of the model is the condition that some hydrometeorological parameters are highly correlated spatially. As the watershed size increases, the requirement for high spatial correlation of multi-month precipitation and snowpack becomes more difficult to satisfy. This consideration suggests that the stochastic model is applicable to watersheds up to a nominal size of about 500 mi^2. For larger watersheds, the spatial variability of some hydrometeorological parameters may warrant that site-specific modules be developed to address the site-specific characteristics of the watershed under study. The model does not currently handle mixed-population general storm rainfall and snowmelt floods, or general storm and thunderstorm events. Additional routines would need to be added to handle these cases, as well as simulating any storms with durations that differ from 72 hours. These limitations may be relaxed as part of future research and improvements to the model, as well as additional applications. It is recommended that research in these areas be performed, in addition to research and application of the model at particular Reclamation sites.

4.2 Extreme Storm Development

AWA completed four tasks. The results for each task were submitted by AWA to Reclamation on the dates listed in Table 5.

Table 5.—AWA contract submittals by task

Task No.	Task name	Approximate submittal date	Content
1	Identify major storms	January 2001	Report
2	Data files for extreme storms	May 2001	Report
3	Mesoscale modeling of storms	December 2001; revised version July 31, 2002 with CDs September 17, 2002	Report and Data (CDs)
4	Storm analysis	September 20, 2002	Report

The major result from Task 1 was a storm listing of the significant storms that have occurred in the Pacific Northwest with similar climate and topography as the A.R. Bowman watershed. Three major data resources were used: Hydrometeorological Report No. 57 (HMR 57), National Climatic Data Center (NCDC) data from EarthInfo CD-ROMs and the Utah Climate Center (UCC) database. The HMR 57 database included 115 storms; those located in areas with similar climate and topography as A.R. Bowman are shown on Figure 4. Three storm durations were used for denoting a storm for the UCC databases: one, two and three-day totals. Major storms derived from 3-day totals are shown on Figure 5. The HMR storm list was combined with the NCDC data search and the UCC data search. The results indicated 290 storms from NCDC records and 135 storms from the UCC 3-day totals. These storm lists are subsequently filtered and analyzed for Task 2.

The main result from Task 2 was the evaluation of the largest storms identified in Task 1. These are listed in Tables 2 and 3 on pages 6 and 7 of the AWA Task 2 report. Major storms identified using 3-day rainfall totals were: February 5, 1937, March 14, 1950, January 10, 1951, January 27, 1951, April 7, 1952, October 11, 1953, February 17, 1954, May 17, 1955, May 6, 1956, July 3, 1956, January 19, 1957, April 24, 1957, January 5, 1982 and January 24, 1982. The major storms from HMR 57 that were judged possible to be transposed to the A.R. Bowman watershed were May 29, 1906, November 20, 1921, March 31, 1931, October 2, 1957, January 14, 1961, December 23, 1964 and January 18, 1974. Overall, the results from Task 2 were mixed as some spurious storms were identified due to erroneous data within the NCDC data base. The selected storms to be modeled with MM5 in Task 3 were later revised because of errors in storms analyzed as part of Task 2.

Five storms were modeled using MM5 as part of Task 3. These are: December 19-26, 1964; June 7-11, 1969; August 29-September 2, 1984; July 20-25, 1987; and November 17-20, 1996. These include the largest of the storms that occurred over regions that are climatologically and topographically similar to the A.R. Bowman watershed. The modeling methodology initially included forcing the MM5 model so the results would match the known storm totals; this work was completed in December 2001. After Reclamation reviews, the methodology was changed to better reflect actual moisture fields and not force the model. Final model runs were completed and accepted in September 2002. The MM5 model results for most of these storms agree well with the storm analyses using surface weather station data. For some storms, the area coverage was different because of errors in the MM5 modeling and/or errors in the station data analysis due to the sparseness of observations in the region. Overall, the MM5 model was able to simulate the rainfall events relatively well in both spatial coverage and rainfall totals. The total storm rainfall isohyetal from the model for each of the 5 storms is provided in the AWA reports listed in Section 6. Model output for the December 1964 storm, as simulated in place, is shown in Figure 6. The storms modeled with MM5 were subsequently transposed to the A.R. Bowman watershed. The storms were transposed by translating the storm center, defined as the location of maximum total precipitation during the storm, to the Bowman watershed. A transposed version of this event to the A.R. Bowman watershed is shown in Figure 7.

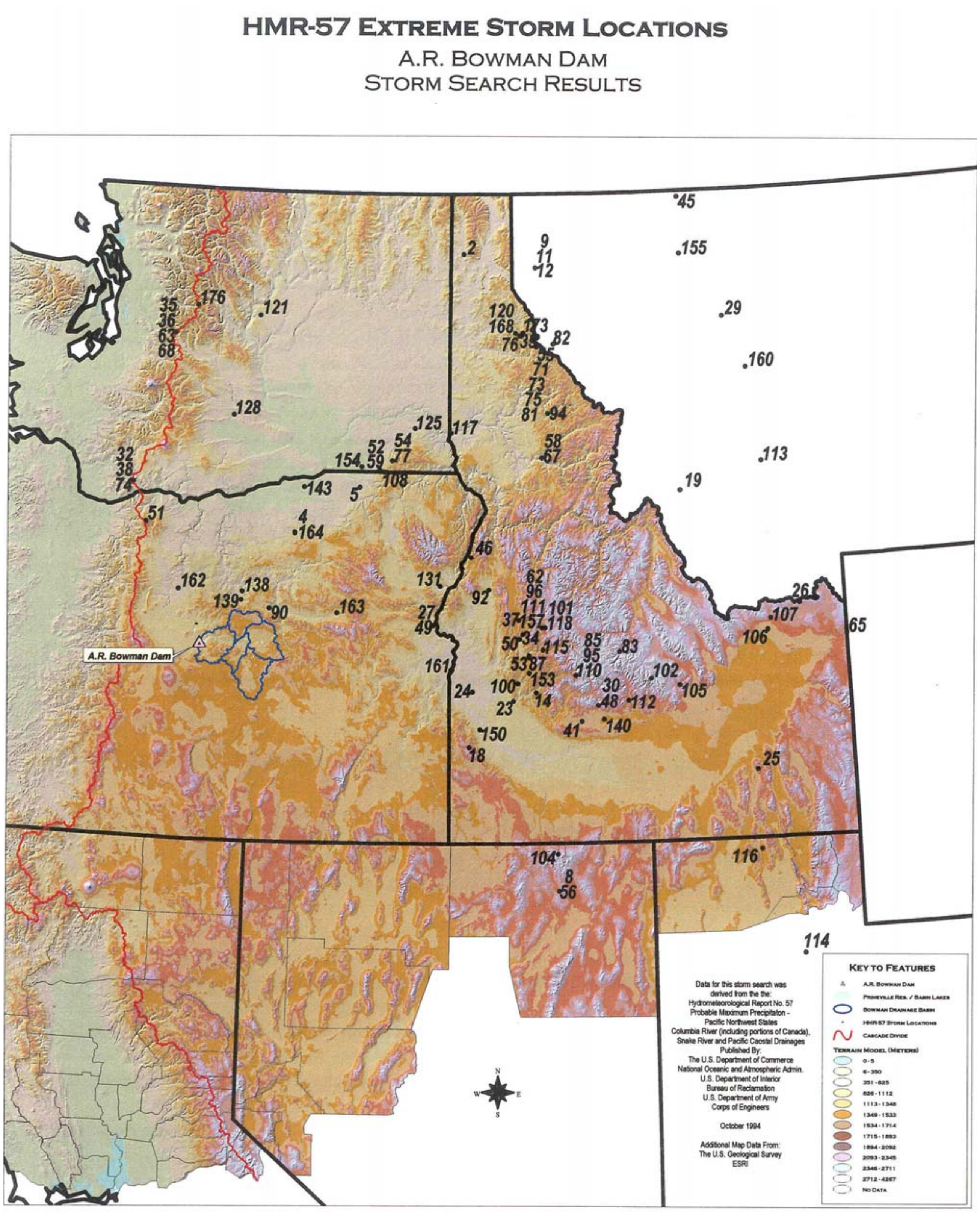


Figure 4.—Location of storms from *Hydrometeorological Report No. 57* (Figure 5, Task 1, AWA report).

Three-Day Extreme Storm Locations
A.R. Bowman Dam
Storm Search Results

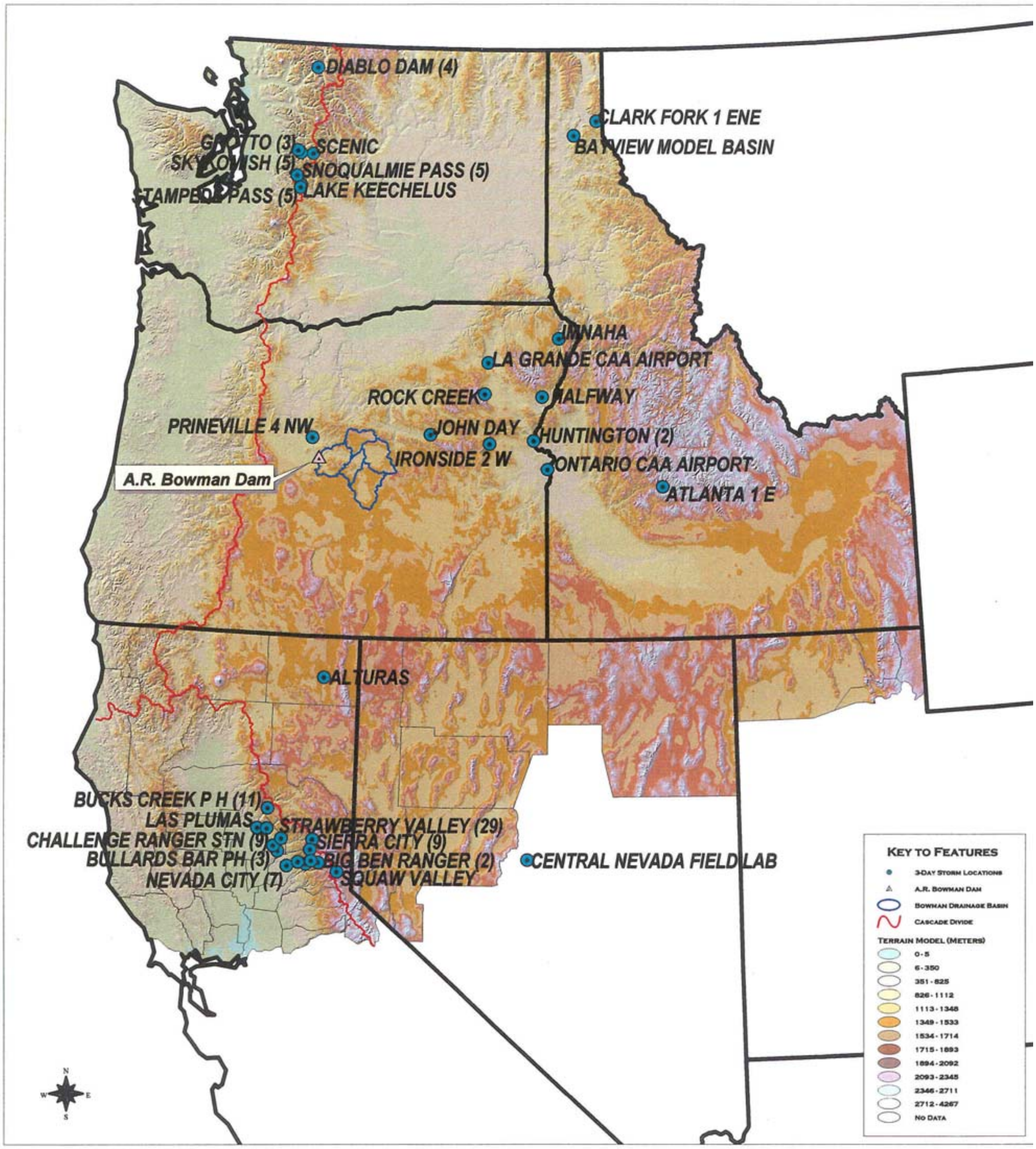


Figure 5.—Location of largest storms using three-day rainfall totals derived from NCDC data (Figure 9, Task 1 AWA report).

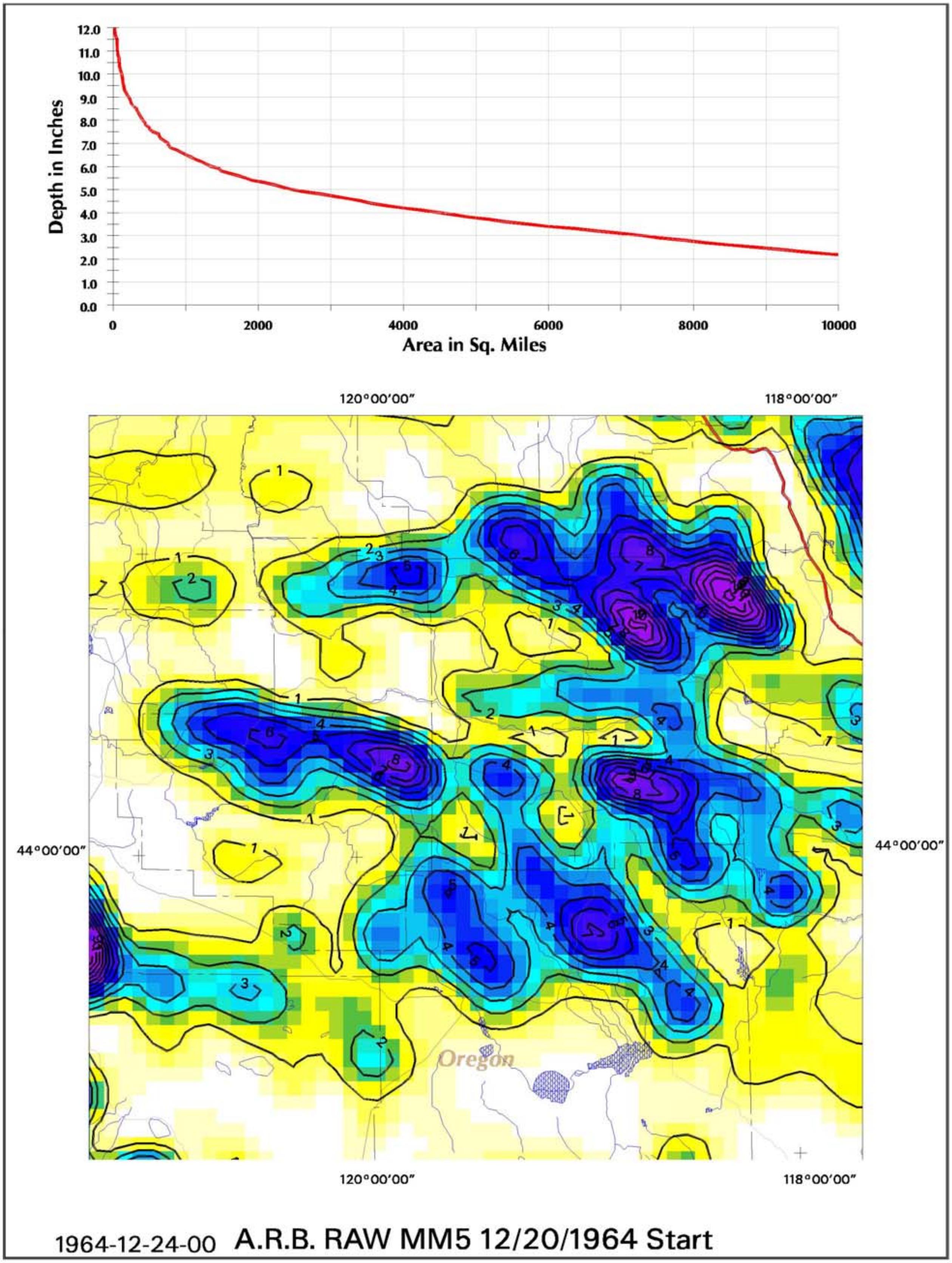


Figure 6.—MM5 simulation storm total results for December 1964 (in place); an inner model domain is shown.

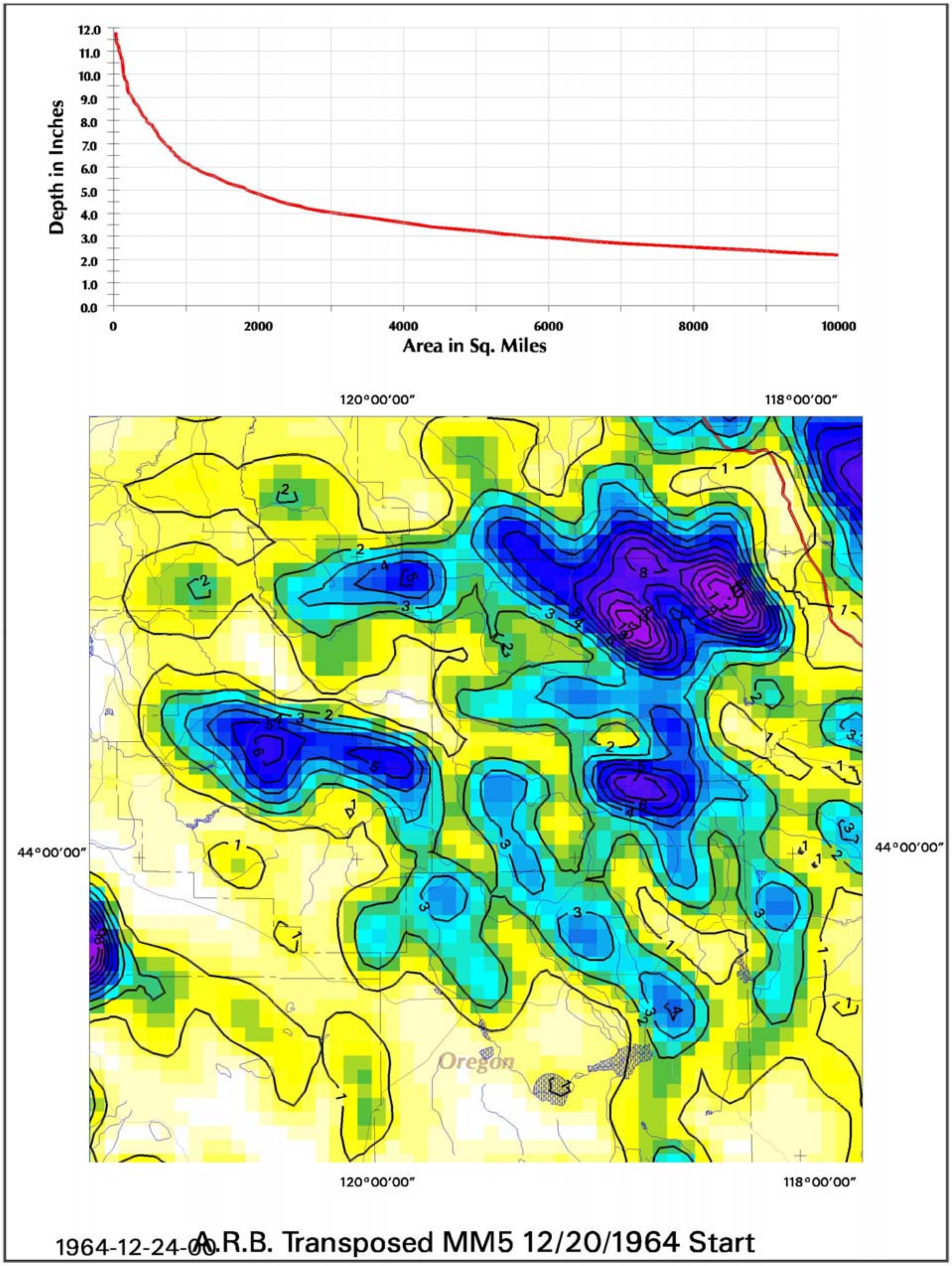


Figure 7.—MM5 simulation storm total results for December 1964 transposed to the A.R. Bowman watershed; an inner model domain is shown.

The results from Task 4 included storm analyses for warm and cold seasons, identifying similar storm characteristics, optimization of storm characteristics, and comparisons to SEFM precipitation. The storm characteristics and optimization are summarized here.

Several similar characteristics have been identified among the five storms in the database. Of the five storms in the database, two were winter storms, one a fall storm and the other two summer time events. The two summer time events had winter-like characteristics - the dynamics and synoptic conditions were similar to the winter storms. A summary of similar storm characteristics is listed below.

- Rain-on-snow: Both winter events were characterized by a period of cold, snowy weather followed by the main event, which was relatively warm and wet (e.g. rain-on-snow). The effects of rain-on-snow exaggerated the flooding during both storms.
- 500 mb winds: The winter storms had west to southwest winds aloft with wind speeds of 200 mph. Summer storms were characterized by relatively light south to southeast winds aloft associated with upper-level cut-off lows or troughs south of the region.
- 500 mb temperatures: Summer time storms consistently had readings as low as -15^{o}C.
- Surface wind direction: All storms had winds with a south to southeast component.
- Moisture source: The winter storms tapped sub-tropical moisture from over the Pacific Ocean.
- Dynamics: Although local topography enhanced precipitation through orographics, the main storm dynamics were associated with large-scale synoptic conditions, such as upper level troughs/short waves.
- Spatial extent: Each of the events covered relatively large areas and was not highly-localized convective events.

AWA evaluated how similar storm characteristics could combine in an optimum manner to maximize the volume of rainfall, which would be produced by an extremely efficient storm combined with relatively abundant atmospheric moisture. Based on the storm database, the characteristics that would result in an extremely efficient rainfall-producing storm are:

- A winter time storm
- A strong, slow-moving upper-level low pressure area off the coast of British Columbia.
- A long fetch of saturated, sub-tropical air extending from near Hawaii to Oregon (known as the “Pineapple Express”).
- Low level warm air advection from the south resulting in warm surface temperatures and rain (as opposed to snow).

- Cold air aloft supporting atmospheric instability and heavy precipitation from embedded convection within the otherwise stratoform precipitation.

Overall, the results from the extreme storm study were reasonable and the objectives were met. There were some problems with erroneous data in the databases that were used; this was subsequently corrected. Also, the MM5 methodology was changed after Task 3 was submitted. The analyses were subsequently rerun. Additional work is needed to directly apply the research results to a particular project. Further numerical comparisons need to be developed and made between simulated storms with MM5 and SEFM storm inputs. MM5 or other atmospheric models are valuable tools and need to be considered for extreme studies. Future work would consist of improving in-house capabilities with these models and conducting extreme storm research for input to runoff models. Additional analyses and model experiments could be performed based on the results from Task 3. MM5 model parameters for the storms could be examined and perturbed to simulate additional extreme storms, instead of reproducing existing storms.

Conclusions and Recommendations

Based on the research conducted on improving the Stochastic Event Flood Model by MGS Engineering Consultants and summarized in this report, four conclusions are made.

1. The objectives of the research were met. The submittals from the five tasks improved documentation and understanding of the Stochastic Event Flood Model.

2. The Technical Support Manual was significantly improved, and is a comprehensive document for practical usage.

3. The SEFM computer program was enhanced and expanded and can readily be used for Reclamation Dam Safety work.

4. The parameter sensitivity study provided a valuable way to determine important modeling factors in the A.R. Bowman watershed. The methodology and results can be transferred to other locations.

The research conducted on analyzing extreme storms for the A.R. Bowman watershed by Applied Weather Associates and summarized in this report leads to three conclusions.

1. The objectives of the research were met. The submittals from the four tasks helped in understanding extreme storms in areas that are topographically and climatologically similar to the A.R. Bowman watershed.

2. Extreme storms critically important to the region surrounding the A.R. Bowman watershed could include: a winter time storm; a strong, slow-moving upper-level low pressure area off the coast of British Columbia; a long fetch of saturated, sub-tropical air extending from near Hawaii to Oregon (known as the “Pineapple Express”; low level

warm air advection from the south resulting in warm surface temperatures and rain (as opposed to snow); and cold air aloft supporting atmospheric instability and heavy precipitation from embedded convection within the otherwise stratoform precipitation.

3. The MM5 model replications of four large storms, including December 19-26, 1964; June 7-11, 1969; August 29-September 2, 1984; July 20-25, 1987; and November 17-20, 1996 were reasonable.

One important component of the extreme flood framework (USBR, 1999) was the recommendation that multiple hydrologic methods be pursued. "Several approaches for characterizing extreme floods using at-site and regional data sets should be pursued to provide alternative lines of scientific evidence to support the results and to increase their credibility for use in dam safety risk assessment" (USBR, 1999 p. 44). The use of an atmospheric model by AWA in this research helps partially meet this goal.

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

1. The Stochastic Event Flood Model should be used by Reclamation personnel on Dam Safety projects in order to increase in-house expertise with the model and in simulating extreme floods.

2. Improvements should eventually be made to the Stochastic Event Flood Model to make it more generally applicable to Reclamation sites, including watersheds greater than 500 mi^2, and simulating mixed-population storms and storms with durations other than 72 hours.

3. An understanding of extreme storm mechanisms within a region is critical in modeling extreme flood response for a dam of interest. Extreme storm-based studies, similar to those conducted for A.R. Bowman, should be performed at additional locations. These studies need to consider storm transposition, generation and improved linking to precipitation frequency estimates.

4. Future work on the MM5 or other 3-dimensional atmospheric models, consisting of improving in-house capabilities with these models and conducting extreme storm research for input to runoff models, should be pursued.

Listing of Deliverables from Contracts

Reports, appendices and computer programs submitted to Reclamation as part of each contract and associated tasks are listed below. Hardcopies of reports and copies of computer programs and backup material submitted on compact discs are available from the Flood Hydrology Group, D-8530.

MGS Engineering Consultants, Inc. (MGS) (2001) *Sensitivity Analysis of Input Parameters for Stochastic Flood Modeling* at A.R. Bowman Dam, Appendix C. Prepared for Bureau of Reclamation, Flood Hydrology Group, January 2001, 41 p.

MGS Engineering Consultants, Inc. (MGS) (2001) *General Storm Stochastic Event Flood Model (SEFM) - Technical Support Manual*. Prepared for the United States Department of the Interior, Bureau of Reclamation, Flood Hydrology Group, March 2001, various paging.

MGS Engineering Consultants, Inc. (MGS) (2001*) General Storm Stochastic Event Flood Model (SEFM) – Computer Program*. Prepared for the United States Department of the Interior, Bureau of Reclamation, Flood Hydrology Group, April 2001, libraries and spreadsheets on CDs.

Tomlinson, E.M. and Williams, R.A. (2001) *Extreme Storm List*, A.R. Bowman Dam, Interim Report, Task 1, Identification of Major Storms. Applied Weather Associates, Monument CO, January 2001, 47 p.

Tomlinson, E.M. and Desereau, D.A. (2001) *Extreme Storm List*, A.R. Bowman Dam, Interim Report, Task 2, Data Files of Extreme Storms. Applied Weather Associates, Monument CO, May 2001, 14 p. and Appendices A through T.

Tomlinson, E.M. and Desereau, D.A. (2002) *Extreme Storm List*, A.R. Bowman Dam, Interim Report, Task 3, Mesoscale Modeling of Major Storms, revised. Applied Weather Associates, Monument CO, July 2002, 27 p. and Appendix A.

Tomlinson, E.M. and Desereau, D.A. (2002) *Extreme Storm List*, A.R. Bowman Dam, Interim Report, Task 3, Mesoscale Modeling of Major Storms, revised – Appendix B. Applied Weather Associates, Monument CO and GeoClim, Providence UT, September 23 2002, 30 data CDs and 2 image CDs.

Tomlinson, E.M. and Parzybok, T. (2002) *Extreme Storm List*, A.R. Bowman Dam, Interim Report, Task 4, Storm Analyses. Applied Weather Associates, Monument CO, September 2002, 18 p. and Appendix A.

References

Barker, B., Schaefer, M.G., Mumford, J. and Swain, R. (1996) *A Monte Carlo Approach to Determine the Variability of PMF Estimates*. Proceedings of the 13th Annual Association of State Dam Safety Officials Conference, September 8-11, 1996, Seattle, Washington, pp. 107-122.

Barker, B., Schaefer, M.G., Mumford, J. and Swain, R. (1997) *Part I: A Monte Carlo Approach to Determine the Variability of PMF Estimates; Part II: Monte-Carlo Simulation* using *Variable Precipitation Volume* and *Temporal Distribution, Bumping Lake Basin Flood Frequency Estimate*, U.S. Bureau of Reclamation, 24 p.

Bullard, K.L. and Schaefer, M.G. (1999) *Stochastic Modeling of Extreme Floods, Cle Elum Dam, Washington. Draft Report*, Bureau of Reclamation, Flood Hydrology Group, June, 54 p.

Schaefer, M.G. and Barker, B.L. (1997) *Stochastic Modeling of Extreme Floods* for A.R. Bowman Dam. MGS Engineering Consultants, Inc., Lacey, WA, November 1997, 79 p.

Schaefer, M.G. and Barker, B.L. (1998) *Assessment of Risk Reduction Measures* at A.R. Bowman Dam using a Stochastic Model of Extreme Floods. MGS Engineering Consultants, Inc., Lacey, WA, October 1998, 21 p.

Singh, V.P. (1999) *SEFM and its Application to Cle Elum Dam* and A.R. Bowman Dam. Review by V.P. Singh, Arthur K. Barton Endowed Professor, Louisiana State University, July 2, 1999, 7 p.

U.S. Bureau of Reclamation (USBR) (1999) *A Framework for Characterizing Extreme Floods for Dam Safety Risk Assessment*. Prepared by Utah State University and Bureau of Reclamation, November 1999, 67 p.

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.