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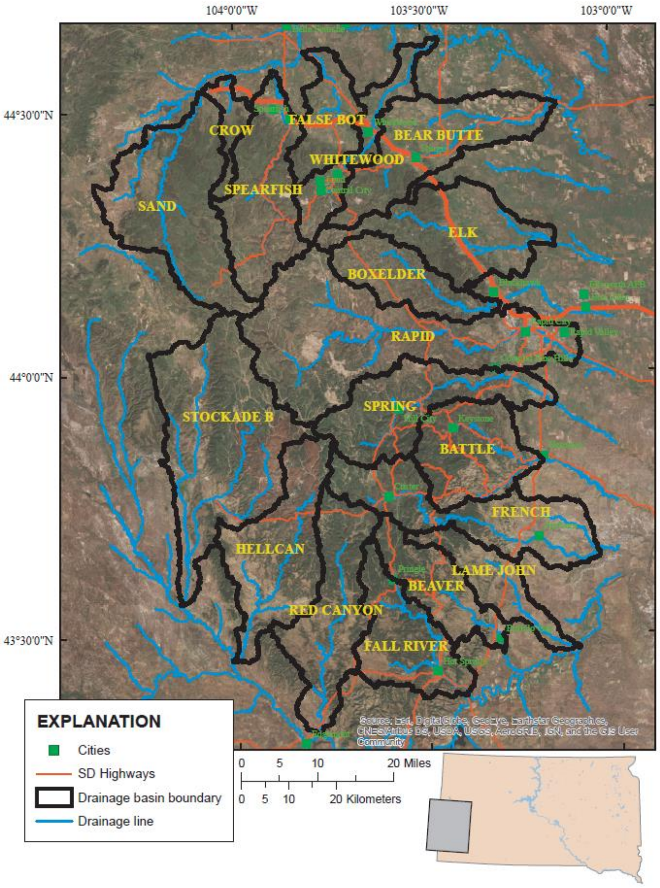

Rainfall-Runoff Modeling for Improved Peak Flow Estimates in the Black Hills Area of South Dakota

Study SD2013-03

Final Report

Prepared by U.S. Geological Survey
Dakota Water Science Center
Rapid City, SD

August 2017

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ACKNOWLEDGEMENTS

This work was performed under the direction of the SD2013-03 Technical Panel:

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. SD2013-03-F	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Rainfall-Runoff Modeling for Improved Peak-Flow Estimates in the Black Hills Area of South Dakota		5. Report Date 08/31/2017 6. Performing Organization Code	
7. Author(s) Galen Hoogestraat		8. Performing Organization Report No.	
9. Performing Organization Name and Address U.S. Geological Survey, Dakota Water Science Center 1608 Mt. View Rd. Rapid City, SD 57702		10. Work Unit No. HRY303 11. Contract or Grant No. 311193	
12. Sponsoring Agency Name and Address South Dakota Department of Transportation Office of Research 700 East Broadway Avenue Pierre, SD 57501-2586		13. Type of Report and Period Covered Final Report January 2014 – August 2017 14. Sponsoring Agency Code	

15. Supplementary Notes

An executive summary is published separately as SD2013-03-X.

16. Abstract

Peak-flow frequency estimates in the Black Hills area of South Dakota are complicated by the occurrence of extreme flood events that do not fit typical statistical distributions. Alternative methods such as a mixed population analysis have been used to help incorporate high-outlier peak-flow events in frequency analyses; however, more information may be needed to help define areas where causal factors for extreme peak-flow events are different than areas where extreme peak-flow events are less common. A rainfall-runoff modeling approach was applied to 18 drainage basins in the Black Hills with a goal of improving future peak-flow frequency estimates. Rainfall-runoff models were developed using the U.S. Army Corps of Engineers' HEC-HMS software. These event-based hydrologic models were calibrated to several rainfall events that occurred during 2010–2013, and some models also used calibration information from the catastrophic 1972 Black Hills flood event. After the HEC-HMS basin models were calibrated, hypothetical storm scenarios were developed to examine the effects of large runoff events over the Black Hills area. Outputs used from the hydrologic models to assess peak-flow characteristics include normalized peak flows and yield efficiency. Normalized peak flows demonstrate a tendency for lower flood risk in the upper parts of the Spring, Rapid, and Spearfish Creek drainage basins, generally corresponding with the location of the Limestone Plateau on the western flank of the Black Hills. Conversely, the middle sections of Elk, Boxelder, and Rapid Creeks along the eastern downslope flank of the Black Hills show the highest normalized peak flow areas. The same general findings are in previous reports on peak flow potential and flooding in the Black Hills area, but a key benefit of this modeling project is that these characterizations previously supported mainly by recorded streamflow history are confirmed using parametric hydrologic models. Application of a rainfall-runoff modeling approach shows some utility in estimating peak-flow characteristics in the Black Hills, but largely results in confirmation of previously reported characterizations. The spatial distribution of normalized peak flows produced from this research helps delineate regions (eastern flanks) where mixed-population analyses should be required and other regions (western Limestone Plateau area) where standard Bulletin 17B procedures may be appropriate.

17. Keywords Rainfall-runoff, peak-flow, hydrologic, models, Black Hills, South Dakota	18. Distribution Statement No restrictions. This document is available to the public from the sponsoring agency.		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 49	22. Price

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE OF ACRONYMS

Acronym	Definition
CN	Curve Number
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
PRMS	Precipitation-Runoff Modeling System
SSURGO	Soil Survey Geographic Database
USACE	United States Army Corps of Engineers
UHG	Unit Hydrograph
USGS	United States Geological Survey

1 EXECUTIVE SUMMARY

Rainfall-runoff modeling can be used to estimate peak-flow response for many applications, but typically is considered to be less reliable than estimates for gaged datasets, when available. Rainfall-runoff modeling can perform very well, however, in accounting for basin characteristics and could provide an excellent tool for improving peak-flow estimates for the Black Hills area, especially when calibrated using available precipitation and streamflow data.

1.1 Problem and Background

Peak-flow frequency estimates in the Black Hills area of South Dakota are complicated by the occurrence of extreme flood events that do not fit typical statistical distributions. Alternative methods such as a mixed population analysis have been used to help incorporate high-outlier peak-flow events in frequency analyses; however, more information may be needed to help define areas where causal factors for extreme peak-flow events are different from areas where extreme peak-flow events are less common.

1.2 Research Objectives

This study involved two objectives. The first objective was to investigate the feasibility of applying selected rainfall-runoff modeling approaches in estimating peak-flow characteristics associated with the complex hydrology in the Black Hills area and compare the peak-flow estimates for spatially uniform rainfall events when applied to different areas of the Black Hills. The second objective was to apply, test, and validate accuracy of the selected modeling approach for improving peak-flow estimation for the Black Hills area.

1.3 Task Descriptions

Ten specific research tasks were identified to guide research directions. Task 1 involved a literature summary and consultation with other agencies that commonly use, or would consider using, rainfall-runoff modeling for estimating peak-flow characteristics for engineering applications. Task 2 was a scheduled meeting with the technical review panel. Task 3 was to identify and evaluate existing rainfall-runoff modeling approaches with potential application to the Black Hills area. Task 4 was to identify and evaluate potential drainage basins and available hydrometeorological datasets for the Black Hills area suitable for application of selected modeling approaches. Task 5 was a meeting with the technical panel to review results of tasks 1 through 4 and to confirm plans for calibrating, applying, and validating selected rainfall-runoff modeling approaches.

Task 6 was to build and calibrate the selected rainfall-runoff models to accomplish improved peak-flow characterization for the Black Hills area. A rainfall-runoff modeling approach was applied to 18 drainage basins in the Black Hills with a goal of improving future peak-flow frequency estimates. Rainfall-runoff models were developed using the U.S. Army Corps of Engineers' HEC-HMS software (Scharffenberg, 2015). These event-based hydrologic models were calibrated to several rainfall events that occurred during 2010–2013, and some models also used calibration information from the catastrophic 1972 Black Hills flood event. After the HEC-HMS basin models were calibrated, hypothetical storm scenarios were developed to examine the effects of large runoff events over the Black Hills area.

Task 7 was to use output from model runs to better delineate regions of differing peak-flow potential to be used in the concurrent project between South Dakota Department of Transportation (SDDOT) and U.S. Geological Survey (USGS) updating at-site flood-frequency estimates. Tasks 8 through 10 involved final reporting, a technical panel meeting, and an executive presentation to the SDDOT Research Review Board.

1.4 Findings and Conclusions

Outputs used from the hydrologic models to assess peak-flow characteristics include normalized peak flows and yield efficiency. Normalized peak flows (event peak flow divided by drainage area raised to the 0.6 power) demonstrate a tendency for lower flood risk in the upper parts of the Spring, Rapid, and Spearfish Creek drainage basins, generally corresponding with the location of the Limestone Plateau on the western flank of the Black Hills. Conversely, the middle sections of Elk, Boxelder, and Rapid Creeks along the eastern downslope flank of the Black Hills show the highest normalized peak-flow areas. The same general findings are identified in previous reports on peak-flow potential and flooding in the Black Hills area mainly by using statistical analyses of recorded streamflow history, but a key science extension of this modeling project is that these characterizations are confirmed using parametric hydrologic models.

1.5 Application of Results

Application of a rainfall-runoff modeling approach shows some utility in estimating peak-flow characteristics in the Black Hills, and largely results in confirmation of previously reported characterizations. The spatial distribution of normalized peak flows produced from this research helps delineate regions (eastern flanks) where mixed-population analyses should be required and other regions (western Limestone Plateau area) where standard Bulletin 17B procedures may be appropriate.

1.5.1 Incorporate peak-flow spatial delineation into ongoing frequency update project

The SDDOT Bridge Program and USGS currently are engaged in a multi-year, two-component project for (1) a statewide update of at-site peak-flow frequency estimates for streamgages and (2) a subsequent regionalization component for estimating peak-flow characteristics for ungaged streams. A key problem with peak-flow frequency estimation in the Black Hills is the proper statistical treatment of past extreme thunderstorm flood events, such as those in 1972 (Schwarz and others, 1975) or 2007 (Driscoll and others, 2010). To address this issue, Sando and others (2008) used a "regional mixed-population analysis," that separated peak-flow records into two separate populations of flood events: ordinary peaks and high-outlier peaks. The findings of this rainfall-runoff modeling study indicate that distinctive differences in peak-flow potential for the Black Hills area are driven primarily by topography. It is specifically intended that the findings of this study can be used to help delineate regions of distinctively different peak-flow potential in the Black Hills area, such that different mixed-population analyses can be applied as part of the aforementioned first component of the ongoing statewide peak-flow frequency that is being conducted by SDDOT Bridge Program and USGS.

1.5.2 HEC-HMS files available for design use

HEC-HMS models were calibrated for 18 drainage basins in the Black Hills area using precipitation events during 2010–2013. The HEC-HMS hydrology model files will be available to SDDOT or other interested agencies from the USGS Dakota Water Science Center upon request for use as a design tool or other applications that might arise.

1.5.3 Benefits could be achieved by additional modeling efforts

This project demonstrated the utility of rainfall-runoff modeling for helping to improve peak-flow characterization for South Dakota. Additional benefits could be achieved by additional modeling efforts in two specific arenas, one being specifically within the Black Hills area and the other involving a statewide effort.

1.5.3.1 Additional modeling within the Black Hills area

Additional modeling would involve rainfall-runoff modeling for large drainage areas beyond the periphery of the Black Hills, where large attenuation potential exists along broad alluvial floodplains. Such effects are apparent in peak-flow records, and modeling would help to define the appropriate areas for application of another mixed-population zone.

1.5.3.2 Additional modeling throughout South Dakota

Additional rainfall-runoff modeling throughout South Dakota would be useful for helping address the second component of the ongoing statewide peak-flow frequency that is being conducted by SDDOT Bridge Program and USGS. There is large variability throughout South Dakota in several parameters that affect peak-flow characteristics (such as main-channel slope, channel or floodplain conditions, and soil type) that are not adequately reflected in regionalized peak-flow regression equations generated from data collected from the streamgaging network. A statewide effort for rainfall-runoff modeling would help in better characterizing areas where general similarities in peak-flow characteristics might be expected, which would help greatly in defining statewide subregions for developing and applying the regionalized peak-flow regression equations.

2 PROBLEM DESCRIPTION

Peak-flow characteristics for gaged streams typically are estimated by the USGS in statewide projects using probability analyses of datasets of the annual peak flow for streamgages. One example for South Dakota is Sando and others (2008). Error bars (uncertainties or bounds or uncertainty) about the statistical estimates from flood frequency curves based on annual maxima streamflow for any gaged stream (“at-site” estimation) may be relatively small for the smaller recurrence intervals, such as the 2-year through 10- or 25-year floods, but uncertainties increase substantially for increasing recurrence intervals. These at-site estimates typically are then used in statewide regionalization projects for estimating peak-flow characteristics for ungaged streams (for example, Sando, 1998).

The regionalization involves additional statistical modeling and additional increases in uncertainties are inherent. Peak-flow characterization is especially complex in the Black Hills region because geology, climate, and topography vary substantially across small spatial scales similar to the drainage area size of the basins. In the Black Hills, classifying many streamgages based on spatial proximity for regionalization estimates may not be the most accurate approach. A key problem with peak-flow frequency estimation in the Black Hills is the proper statistical treatment of past extreme thunderstorm flood events (such as those in 1972 or 2007). Such thunderstorm-induced floods often occur in limited spatial extent and, as a result, only a few streamgages in the region are affected. Thunderstorms can readily generate peak flows that are as much as 3 orders of magnitude greater than the remaining flood record. Extreme peak flows typically have the side effect of causing less reliable fits of flood frequency curves and large uncertainties when using standard procedures.

Various types of rainfall-runoff modeling can be used to estimate peak-flow response for many ungaged streams, but typically are considered to be less reliable than estimates for gaged datasets, when available. However, rainfall-runoff modeling can perform well in accounting for basin characteristics and could provide an excellent tool for improving peak-flow estimates for the Black Hills area, especially when calibrated using available precipitation and streamflow data. In particular, modeling could be used to identify specific drainage basins with distinctively different potential for peak-flow generation and to which different approaches for peak-flow characterization could be applied. Although regional scale applications are uncommon in the literature, use of simulated peak-flow estimates generated from precipitation events with a known frequency can be an acceptable approach for estimating flood frequency curves when limited information is available (Interagency Advisory Committee on Water Data, 1982).

Abundant literature exists regarding use of rainfall-runoff modeling for developing synthetic hydrographs and for estimating peak-flow characteristics, especially for urban settings. USGS has published reports regarding application of standard approaches that typically involve statistical analyses of annual peak-flow data (Jennings and others, 1994; Burr and Korkow, 1996; Sando, 1998; Sando and others, 2008). A cursory review, however, indicates that literature is sparse regarding use of rainfall-runoff modeling as an approach for developing peak-flow estimates. Commonly, the literature is restricted to urban settings.

Fulton (1990) provides an example for the application of rainfall-runoff modeling to flood-frequency analyses for a county in New Jersey. In Fulton (1990), a calibrated rainfall-runoff model was used to create a synthetic flood record for the period 1914–1979, and this series of annual peak flows subsequently was used in a standard flood-frequency analysis. Rogger and others (2012) compared flood-frequency statistical results based on streamflow data from streamgages with those simulated using design precipitation events (event-based model) in Austria, finding that if applied to the same drainage basin, the two methods often yielded different results. The results showed that for most drainage basins, the event-based model gave larger flood estimates than flood-frequency statistics. The reasons for the differences depended on the basin characteristics and different rainfall inputs that were applied and other unknown factors. Thomas and others (1999) also evaluated the two approaches for peak-flow estimation for ungaged drainage basins: (1) those based on statistical analyses of annual peak-flow data at streamgages and (2) deterministic rainfall-runoff models to convert rainfall excess to flood discharges. Thomas and others (1999) emphasized proper characterization of the uncertainty and suggested that future research should be oriented to determining the accuracy and precision of peak-flow estimates from design event rainfall-runoff models because the use of these models is prevalent in hydraulic design and floodplain management. If the accuracy and precision of peak-flow estimates from rainfall-runoff models could be effectively utilized, then the feasibility of weighting these estimates with regression estimates could be evaluated. In summary, rainfall-runoff modeling approaches integrated into statistical peak-flow frequencies are most applicable when detailed calibration datasets are available to quantify the uncertainty in the model estimates.

3 RESEARCH OBJECTIVES

The following were the research objectives of this project:

3.1 Investigate Rainfall-Runoff Modeling Approaches

Investigate the feasibility of applying selected rainfall-runoff modeling approaches in estimating peak-flow characteristics associated with the complex hydrology in the Black Hills area and compare the peak-flow estimates for spatially uniform rainfall events when applied to different areas of the Black Hills.

This objective was addressed through development of a calibrated rainfall-runoff model and application of a uniform rainfall simulation. Flow statistics derived from these simulations allow for spatial patterns of relatively greater flood risk to be delineated.

3.2 Demonstrate a Selected Rainfall-Runoff Modeling Approach

Apply, test, and validate accuracy of the selected modeling approach for improving peak-flow estimation for the Black Hills area. Integrate the modeling results into a procedure that can be used by SDDOT and others for infrastructure design purposes.

An update to peak-flow frequency estimates for the Black Hills will be produced upon completion of a separate companion project between the USGS and SDDOT bridge division. The rainfall-runoff modeling approach in this report will be integrated into that project to help address complexities with peak streamflow statistics in the Black Hills. Thus, this objective will not be fully satisfied until completion of the upcoming at-site peak-flow frequency update.

4 TASK DESCRIPTIONS

The following research tasks were established by the project's "Technical Panel" within Research Project Statement SD2013-03:

4.1 Review Literature

Review and summarize literature and consult with agencies such as Federal Emergency Management Agency and U.S. Army Corps of Engineers that commonly use rainfall-runoff modeling for estimating peak-flow characteristics for engineering applications.

This literature review task is summarized in section 2, with all references cited in section 10.

4.2 Meet with Technical Panel

Meet with the project's Technical (Review) Panel to review the project scope and work plan.

A technical panel meeting was held on September 12, 2013 that was focused on reviewing relevant literature, revising the planned project approach, and planning consultation with other relevant entities.

4.3 Evaluate Existing Rainfall-Runoff Modeling Approaches

Identify and evaluate existing rainfall-runoff modeling approaches with potential application to the Black Hills area.

The primary modeling package envisioned for this study was the USACE HEC-HMS software (Scharffenberg, 2015). The feasibility of using other models was evaluated, but no other models with better applicability for this study were identified. Preliminary review of other potential models was done in advance of the first Technical Panel meeting, and the decision to use the HEC-HMS software was made at that meeting. Additional details regarding model selection and other potential models evaluated are provided in section 5.2 (HEC-HMS model development).

4.4 Evaluate Drainage Basins and Datasets

Identify and evaluate potential drainage basins and available datasets for the Black Hills area suitable for application of selected modeling approaches.

The project area includes the greater Black Hills region of western South Dakota, which includes 18 drainage basins. Rainfall-runoff modeling is most applicable for drainage basins with streamflow data that can be used for calibration. Streamflow data were available for at least one location in 14 of the

18 Black Hills drainage basins. Precipitation inputs for the rainfall-runoff models were available as a gridded dataset in hourly time increments from the National Oceanic and Atmospheric Administration (NOAA). More information on this task is presented in section 5.

4.5 Meet with Technical Panel

Meet with the project's Technical Panel to review results of tasks 1-4 and to confirm plans for calibrating, applying, and validating selected rainfall-runoff modeling approaches.

A technical panel meeting was held on April 12, 2014, during which progress relative to tasks 1–4 was discussed. A presentation demonstrated the proposed HEC-HMS model, precipitation inputs, and calibration datasets.

4.6 Build and calibrate rainfall-runoff models

Build and calibrate the selected rainfall-runoff models to accomplish improved peak-flow characterization for the Black Hills area. Evaluate the accuracy of selected modeling approaches against known precipitation and streamflow inputs.

The goal of calibration is to identify reasonable parameters that yield the best fit of computed versus observed streamflow hydrographs. Precipitation inputs for model calibration were derived from readily-available geospatial information and meteorological data from NOAA. Calibration was made for streamgages within the basin models during several short-term runoff events that occurred during 2010–2013.

4.7 Delineate regions of peak-flow potential

Use output from model runs to better delineate regions of differing peak-flow potential to be used in the concurrent project updating at-site flood-frequency estimates.

Flow statistics from uniform model simulations (such as area-normalized peak flow and yield efficiency, presented in section 6 of this report) demonstrate the spatial variation of peak-flow potential in the Black Hills. The spatial patterns presented in this project will assist current and future updates to published at-site peak-flow frequency values.

4.8 Prepare Final Report

Prepare a final report summarizing research methodology, findings, preliminary conclusions, and recommendations.

This document represents the Project Final Report as called for in the description for this task.

4.9 Meet with Technical Panel

Meet with the project's Technical Panel to review results, findings, and recommendations.

A technical panel meeting was held on June 28, 2017, to review the draft final report.

4.10 Make Executive Presentation

Make an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the project.

An executive presentation was made at a regular meeting of the Research Review Board in August 2017.

5 RESEARCH METHODS

This section describes the study area investigated for applying the rainfall-runoff modeling techniques; the model development, including input, methods, and calibration; and the storm precipitation scenarios examined for characterizing the flood risk. Thus, this section documents the technical work performed under tasks 3, 4, and 6.

5.1 Description of study area

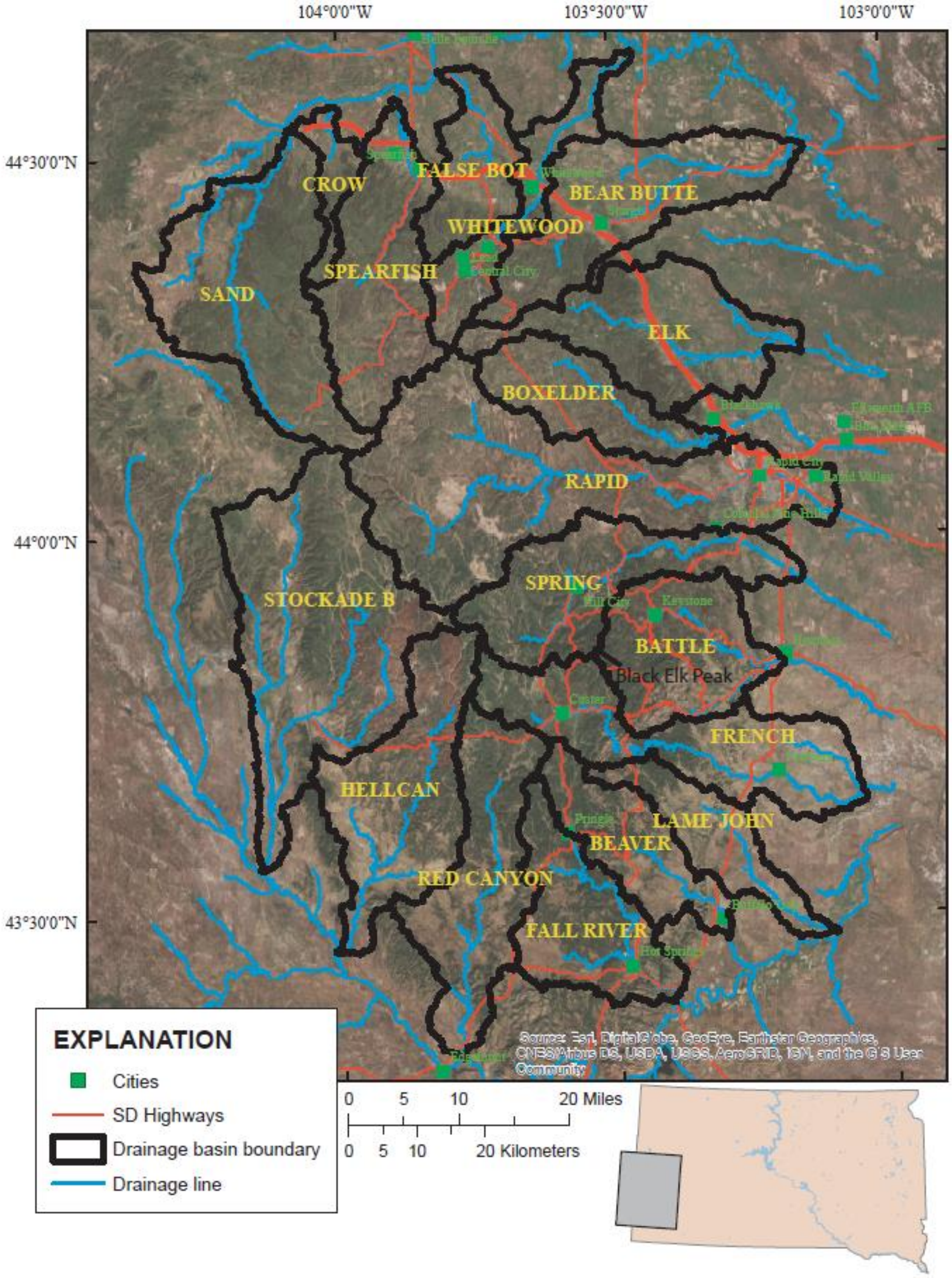
The study area for this investigation includes 18 drainage basins in the Black Hills area of western South Dakota (Table 1, Figure 1). The Black Hills uplift formed as an elongated dome that trends north-northwest and is about 120 miles (mi) long and 60 mi wide (DeWitt and others, 1986). Land-surface elevations range from approximately 4,000 to 7,000 feet (ft), with the highest elevation (7,242 ft) at Black Elk Peak. Streams generally flow from the highest elevations of the early Proterozoic- and late Archean-age rocks in the central core of the Black Hills radially outward across the Paleozoic- and Mesozoic-age formations that flank the Black Hills (Driscoll and Carter, 2001).

The Black Hills area has a history of damaging flash floods that have resulted primarily from exceptionally strong rain-producing thunderstorms. The best-known example to many hydrologic engineers, stakeholders, and others in the regional community is the thunderstorm event of June 9–10, 1972, which caused catastrophic flooding in several major drainages near Rapid City and resulted in 238 deaths (Schwarz and others, 1975). Physiographic and climatological factors affect flooding in the Black Hills area, as summarized by (1) a propensity for heavy precipitation to occur east of the major axis of the Black Hills, from the northern hills (near Spearfish) toward the southeast through the eastern foothills near Hermosa, and (2) a proclivity for short duration but intense convective precipitation events (thunderstorms) (Driscoll and others, 2010).

Table 1. Drainage basins modeled in Black Hills area

Drainage Basin	Figure 1 and Table A1 label
Sand Creek	SAND
Crow Creek	CROW

Spearfish Creek	SPEARFISH
False Bottom Creek	FALSE BOT
Whitewood Creek	WHITEWOOD
Bear Butte Creek	BEAR BUTTE
Elk Creek	ELK
Boxelder Creek	BOXELDER
Rapid Creek	RAPID
Spring Creek	SPRING
Battle Creek	BATTLE
French Creek	FRENCH
Lame Johnny Creek	LAME JOHN
Beaver Creek	BEAVER
Fall River	FALL RIVER
Red Canyon	RED CANYON
Hell Canyon	HELLCAN
Stockade Beaver Creek	STOCKADE B



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. Location of drainage basins simulated in Black Hills area, South Dakota (SD) [Labels are defined in Table 1]

5.2 HEC-HMS model development

The primary modeling package for this study was the USACE HEC-HMS software (Scharffenberg, 2015). The routines that compose HEC-HMS have been used extensively in the public and private sectors for hydrologic modeling purposes for more than 30 years, including the development of FEMA's Flood Insurance Rate Maps. Available in the public-domain, HEC-HMS is a computer model that simulates the rainfall-routing-runoff processes for a drainage basin. The major components of a HEC-HMS model include the meteorological model (precipitation inputs), losses (soil infiltration), direct runoff transformations, channel routing, and control or storage structures.

Although most rainfall-runoff models have similar capabilities (turning precipitation inputs and drainage basin losses into runoff hydrographs), HEC-HMS was selected for this study for several of reasons. HEC-HMS has the ability to operate in an event-mode at very short time steps (minutes), in contrast to another potential model, the USGS Precipitation-Runoff Modeling System (PRMS; Markstrom and others, 2015), that operates using a daily time step. The ability to use time steps on the order of minutes (short time scales) is critical for simulating thunderstorm events that respond very quickly in the Black Hills. The USEPA Storm Water Management Model (Rossman, 2015), which is yet another rainfall-runoff model, was not selected as it was designed primarily for simulation of runoff and water quality from urban areas. Furthermore, staff from local municipal governments and the SDDOT has experience with HEC-HMS for infrastructure design purposes, and model files could be directly transferrable to other users.

A HEC-HMS model begins with delineation of the contributing drainage basin to an outlet point. The basin is then divided into smaller subbasins with similar topographic and presumed runoff characteristics. In general, the HEC-HMS model requires estimation of four primary components: design storms, runoff losses, unit hydrograph transformations, and channel routing. Additional options are available to simulate base flow, channel infiltration, and hydraulic control structures. Systems of subbasins interconnected by the drainage courses were used so models could be calibrated using as many streamgages as possible. It is highly useful to have model basin outlets aligned to be at or near a streamgage, although this is not always possible. This system of subbasins will also allow models for smaller areas to be readily extracted for other applications. Calibration was made by adjusting select model parameters in order to match observed peak-flow data with simulated flows. Only model parameters whose values are uncertain or cannot be directly measured using available data were adjusted (primarily basin storage and timing coefficients).

5.2.1 Drainage Basin Delineation

The drainage basin for each model was delineated using a 10-meter spatial resolution digital elevation model (DEM) derived from the National Elevation Dataset (Gesch, 2007) within a geographic information system (GIS). A single elevation value was assigned to each 10- by 10-meter cell in the grid. The basins were divided into smaller subbasins to increase the accuracy of the hydrology model and allow for data output at desirable locations, such as road crossings. The basin and subbasin boundaries for the 18 HEC-HMS basin models are shown in Figure 2.

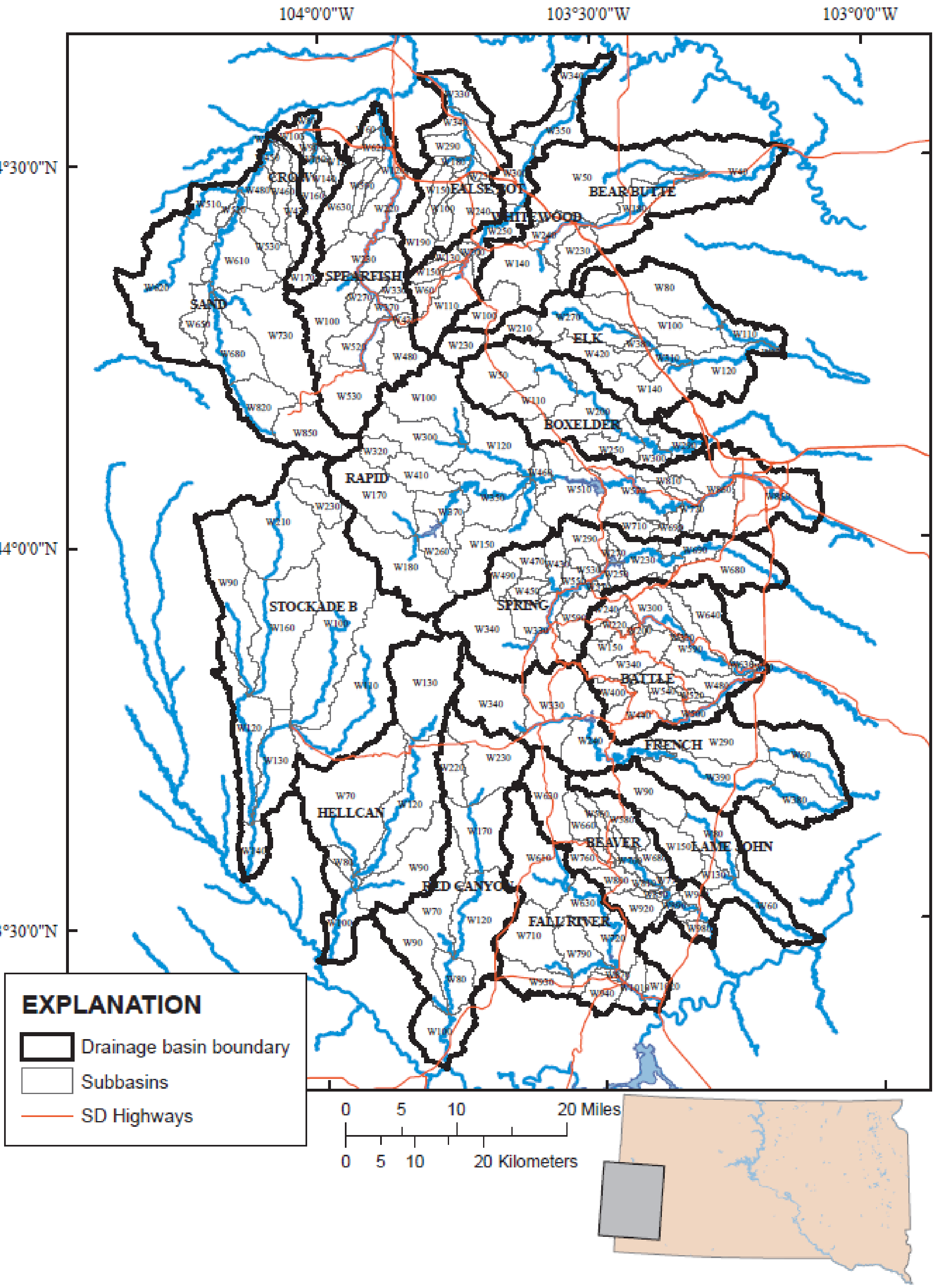


Figure 2. Subbasin delineation and identifiers used in HEC-HMS basin modeling

5.2.2 Runoff Losses

Precipitation that does not result in surface-water flow is defined as a loss. Losses primarily control the total runoff volume of a drainage basin in response to precipitation volume and also can affect the magnitude of peak streamflow. The primary components of losses are soil infiltration and initial abstraction. Initial abstraction refers to the total depression storage and vegetation interception that do not contribute to overland flow. The infiltration losses were estimated using the Natural Resources Conservation Service (NRCS) curve number method (CN; Gupta, 2001). The CN method estimates precipitation excess as a function of cumulative precipitation, soil group, and land use.

Soils are categorized into four hydrologic soil groups: A, B, C, and D. Group A soils have the highest infiltration capacity (0.4–1.0 inch per hour) and group D soils have the lowest infiltration capacity (0.01–0.05 inch per hour). A digital map of soil groups in the Black Hills is available from the Soil Survey Geographic (SSURGO) database provided by NRCS (U.S. Department of Agriculture, 2009). A CN is selected according to the unique combination of hydrologic soil group and land use available from various references (U.S. Department of Agriculture, 1986; Feldman, 2000), and CNs range from 0–100 with a value of 0 representing no runoff and 100 representing no losses. For a forested area with some forest litter covering the soil (the predominant land use in most Black Hills drainage basins), the CNs for the A, B, C, and D soil groups are 36, 60, 73, and 79, respectively. For each subbasin with more than one soil group within its boundary, an area-weighted CN was calculated. Initial abstraction was computed as 0.2 times the potential retention, which is a function of the CN. The 0.2 value is a heuristic multiplier in the standard definition of the CN (Feldman, 2000).

5.2.3 Unit Hydrographs

A hydrograph is a plot of discharge as a function of time. A unit hydrograph (UHG; Gupta, 2001) is the resulting direct runoff hydrograph from one unit of rainfall for one unit of time and is used to define the theoretical shape of a hydrograph during a rainfall event. Using parameterization of this empirical method, the timing and magnitude of the peak streamflow generated within a basin can be estimated. This component of the HEC-HMS model does not affect the total runoff volume from a drainage basin.

The Clark UHG method (Gupta, 2001) was applied to all basin models. For this method, two inputs to the HEC-HMS model are required: time of concentration (T_c) and basin storage coefficient (R). The T_c parameter is the conceptual, though unmeasurable, time it takes for direct runoff to travel from the farthest point in a drainage basin to the outlet. The time of concentration parameter in HEC-HMS is a coefficient-adjusted estimate of the T_c parameter. The time of concentration typically is separated into three components described by the type of runoff flow: sheet, shallow concentrated, and channel. Sheet flow typically occurs for a maximum distance of 300 ft, after which the flow accumulates into shallow gullies or rills (shallow concentrated flow) and is conveyed into the main channel drainages. Methods for estimating each of these three flow components for initial values are presented in Feldman (2000). Topographical features (channel length and slope) were estimated from the DEM using GIS software. The storage coefficient is a conceptual, lumped parameter that represents the aggregated impacts of basin storage and is an index of the temporary storage of precipitation excess in the basin as it drains to the outlet point, and is best estimated through calibration. Initial values for R were estimated as a function of T_c, subbasin drainage area, and longest flow-path distance. Both Clark UHG parameters were used as primary calibration parameters, during which R was allowed to vary independent of T_c.

5.2.4 Channel Routing

For subbasins that receive inflow from an upstream basin, a channel routing routine is used to convey the discharge through the main channel to the basin outlet. Subbasins that do not receive inflow from an upstream subbasin will not contain a routing element, and such subbasins are generally restricted to the most upland part of the greater basin. The routing component of HEC-HMS controls the attenuation of streamflow because of energy resistance and thus can control the magnitude and timing of peak flows. The routing component does not affect the total runoff volume generated within a basin. The Muskingham-Cunge method (Gupta, 2001) was chosen as an appropriate routing method because the continuity and momentum equations are solved using parameters that are physically based with assumptions that are not violated in natural channels (Feldman, 2000). Using length and main-channel slope derived from the DEM using GIS software and a specified channel geometry typical of the stream reaches, continuity and momentum equations were solved in HEC-HMS to estimate streamflow in the main channels. Routing parameters were identical to those used to determine the channel flow component of the Clark UHG portion of the model (described in section “5.2.3 Unit Hydrographs”).

5.2.5 Model calibration

The goal of calibration is to identify reasonable parameters that yield the best fit of computed versus observed streamflow hydrographs. Precipitation inputs for model calibration were derived from readily-available geospatial information and meteorological data from NOAA. Specifically, Doppler radar-derived precipitation was used for this study as the primary precipitation input (National

Oceanic and Atmospheric Administration, 2017). These data are produced by the National Weather Service River Forecast Centers and are available in a 4-by-4 kilometer gridded resolution. Peak-flow data for model calibration were obtained through the USGS National Water Information System (NWIS; U.S. Geological Survey, 2013). Peak-flow data are widely available along the northern and eastern downslope area of the Black Hills, but are sparser in the southern and western areas. The well-documented rainfall and flooding event of June 9–10, 1972, was also used as a calibration storm in the basins affected by this event, with precipitation data summarized in Driscoll and others (2010).

Calibration was made for streamgages within the basin models during several short-term runoff events that occurred during 2010–2013. Calibration events were screened to only include the most ideal datasets for the methods selected for HEC-HMS modeling. This includes preference towards (1) normal base-flow conditions prior to a peak event and return to near base-flow conditions within several days, (2) single streamflow peak events, (3) substantial runoff increase from base flow, (4) occurrences during the rainfall season (April through October), and (5) no variations in upstream reservoir releases. Using these criteria, the number of calibration events for each basin was reduced to no more than five events.

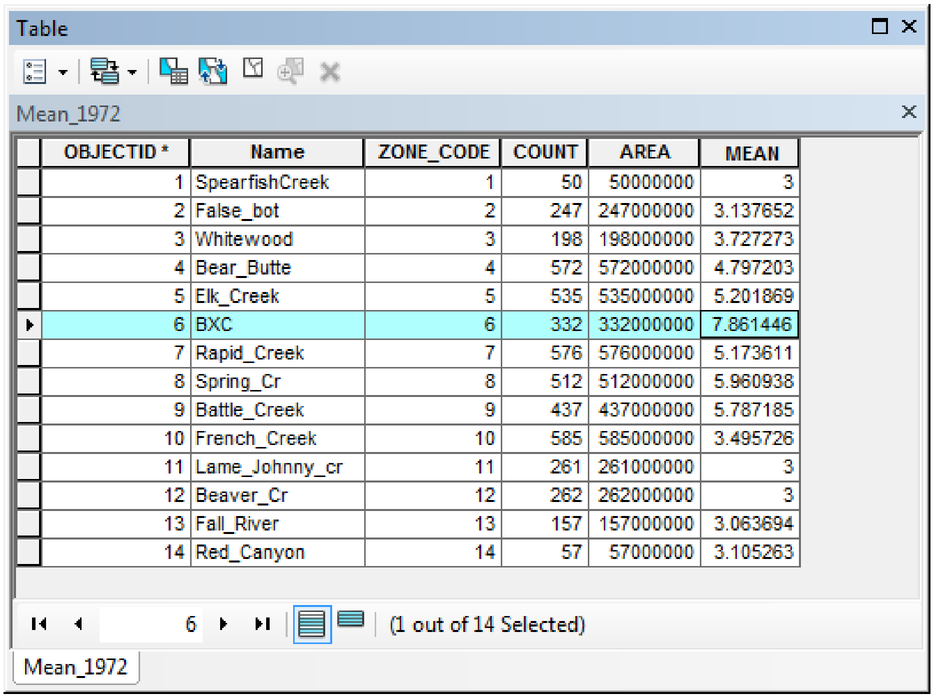
Parameters calibrated within HEC-HMS models were primarily the two most uncertain parameters within the Clark UHG process: Tc (time of concentration) and R (basin storage coefficient). For basins where these parameters were not highly sensitive, the CN also was adjusted to produce a better calibrated model. The HEC-HMS user interface contains a calibration routine (referred to as "optimization trials"), which was used for this effort. For all optimization trials, the Nelder-Mead method (Nelder and Mead, 1965), which is a general and robust multidimensional-numerical optimization technique, was selected as the search method for best-fit parameters using a maximum of 1,000 iterations. In some cases, the initial set of parameters was selected to best represent the observed hydrograph after determining the calibrated set of parameters did not improve the model (Beaver, Boxelder, and Elk Creek models). Table A1 (APPENDIX A) contains values of initial and calibrated parameters for each subbasin.

5.3 Storm scenario modeling

After the HEC-HMS basin models were calibrated, hypothetical storm scenarios were developed to examine the effects of large runoff events over the Black Hills area. This strategy involves the application of the same precipitation time series on all basin models. This uniform comparison will allow assessment of flood risk independent of the observed precipitation record. Current (2017) methodologies for developing precipitation and peak-flow frequency estimates rely on statistical analysis of the recorded data history; thus, peak-flow frequency estimates are typically much smaller for basins that have not experienced large flood events during the period of modern records (past 100 years).

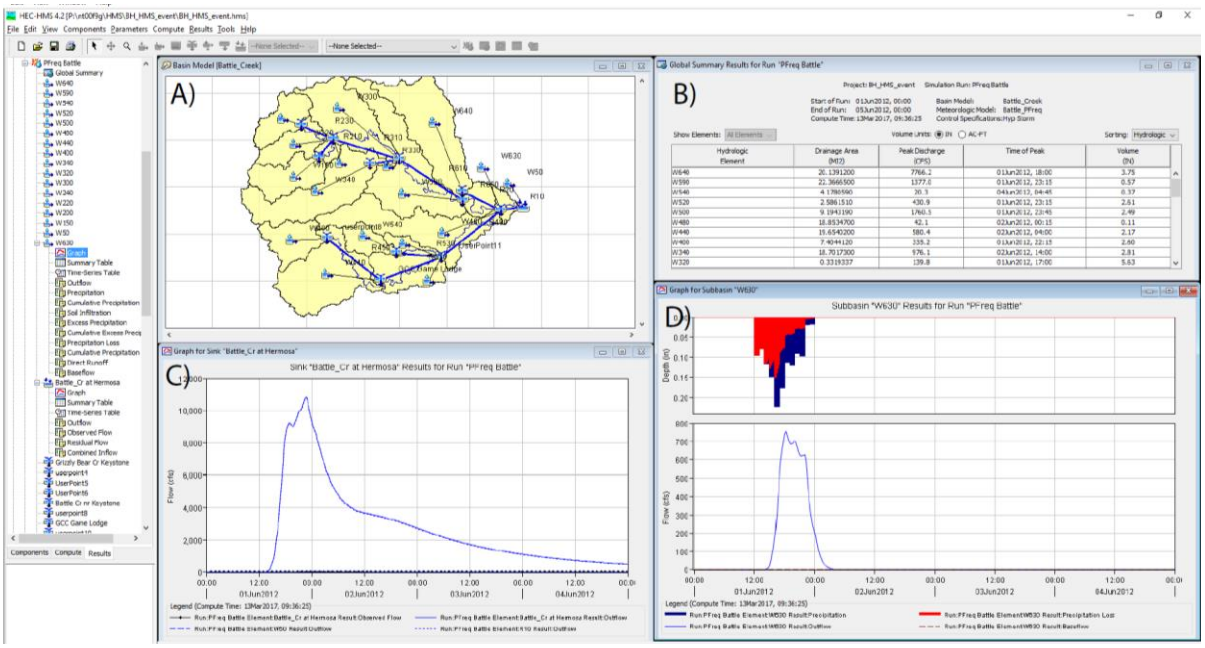
The time series of two hypothetical storms was developed to honor the intensity-duration frequency values for rainfall following the results from NOAA Atlas 14 (National Oceanic and Atmospheric Administration, 2013) and also is representative of the largest recorded event in the Black Hills (1972 flood). Figure 3 is a table that shows the basin means for all of the basins that were covered by the 1972 precipitation and flood event. The Boxelder Creek Basin (BXC in Figure 3) had a mean of 7.86 inches, which was recorded almost entirely within 12 hours (Schwarz and others, 1975). Applying a uniform event to each subbasin within each of the 18 basin models that lasts 12 hours and totals 7.86 inches would be representative of the most intense area of the 1972 storm. Using information from the precipitation frequency data server (National Oceanic and Atmospheric Administration, 2013), a point near Nemo within the Boxelder Creek Basin shows that a 12-hour storm event of 7.86 inches has an estimated annual return interval between 100 and 200 years. This first and larger design storm applied uniformly over all 18 of the basins in HEC-HMS fits this 100-year 12-hour distribution, and was termed “PFreq.” The timing distribution was estimated from mass rainfall curves presented in figure 16 of Schwarz and others (1975), where the peak rainfall intensity is positioned between hours 4 and 6 in the event. A second smaller design storm, “PFreq2,” is a similar scenario based on the mean 1972 precipitation amount in the Rapid Creek Basin (5.17 inches).

An example of the output information from the HEC-HMS scenario modeling is shown in Figure 4. Several input and output variables can be analyzed simultaneously using the HEC-HMS interface to assess validity of the model scenario. Procedures for verifying model output include (1) checking subbasin precipitation loss and runoff ratios, (2) comparing magnitude of peak flows at sites with streamflow data to ensure that reasonable estimates are produced, and (3) checks on the timing of peak flows to verify that runoff is not unrealistically delayed. Output tables from the individual subbasins (Figure 4B) were imported into GIS software to spatially display the information.



OBJECTID *	Name	ZONE_CODE	COUNT	AREA	MEAN
1	SpearfishCreek	1	50	50000000	3
2	False_bot	2	247	247000000	3.137652
3	Whitewood	3	198	198000000	3.727273
4	Bear_Butte	4	572	572000000	4.797203
5	Elk_Creek	5	535	535000000	5.201869
6	BXC	6	332	332000000	7.861446
7	Rapid_Creek	7	576	576000000	5.173611
8	Spring_Cr	8	512	512000000	5.960938
9	Battle_Creek	9	437	437000000	5.787185
10	French_Creek	10	585	585000000	3.495726
11	Lame_Johnny_cr	11	261	261000000	3
12	Beaver_Cr	12	262	262000000	3
13	Fall_River	13	157	157000000	3.063694
14	Red_Canyon	14	57	57000000	3.105263

Figure 3. Mean basin precipitation during the 1972 flood event determined from the geographic information system (ArcGIS; http://www.esri.com/arcgis/about-arcgis)



Project: BH_HMS_event Simulation Run: PFreq Battle

Start of Run: 01Jun2012, 00:00
End of Run: 05Jun2012, 00:00
Compute Time: 13Mar2017, 09:36:25

Basin Model: Battle_Creek
Meteorologic Model: Battle_PFreq
Control Specifications: Hyp Storm

Show Elements: All Elements
Volume Units: ● IN ○ AC-FT
Sorting: Hydrologic

Hydrologic Element	Drainage Area (MI2)	Peak Discharge (CFS)	Time of Peak	Volume (IN)
W640	20.1391200	7766.2	01Jun2012, 18:00	3.75
W590	22.3666500	1377.0	01Jun2012, 23:15	0.57
W540	4.1780590	20.3	04Jun2012, 04:45	0.37
W520	2.5861510	430.9	01Jun2012, 23:15	2.61
W500	9.1943190	1760.5	01Jun2012, 23:45	2.49
W480	18.8534700	42.1	02Jun2012, 00:15	0.11
W440	19.6540200	580.4	02Jun2012, 04:00	2.17
W400	7.4044120	335.2	01Jun2012, 22:15	2.60
W340	18.7017300	976.1	02Jun2012, 14:00	2.81
W320	0.3319337	139.8	01Jun2012, 17:00	5.63

Figure 4. Example of output from HEC-HMS scenario models showing A) basin model schematic; B) hydrologic element (individual subbasin) summary table for simulation run; C) simulated streamflow hydrograph for basin model outflow point; and D) individual subbasin precipitation and runoff plot

6 ASSESSMENT OF FLOOD RISK FROM MODELING RESULTS

The following sections present results from applying the PFreq and PFreq2 storm scenarios to HEC-HMS basin models. Assessment of the peak-flow characteristics for each subbasin in response to uniformly-spatial storms helps define areas of higher flood risk, independent from observed flood events. This section documents the technical work performed under task 7.

6.1 Normalized Peak-Flow Results for Hypothetical Storms

Two outputs from HEC-HMS are used in this analysis of hypothetical storms: normalized peak flow and yield efficiency. Normalized peak flow is the resulting peak flow from the simulated storm event (in cubic feet per second) divided by the subbasin's drainage area (in square miles) raised to the 0.6 power. The selection of drainage area raised to 0.6 is derived from a regression analysis described by Sando and others (2008, p. 24). Yield efficiency is the subbasin total runoff volume (in inches) divided by the total precipitation amount (in inches) that fell on the subbasin. The total runoff volume component of yield efficiency does not include base flow that was occurring prior to the runoff event. Figure 5 and Figure 6 show these spatial distributions for the PFreq scenario, and Figure 7 and Figure 8 show the distributions for the PFreq2 scenario.

Normalized peak flows in the PFreq scenario (Figure 5) demonstrate a tendency for less flood risk in the upper parts of the Spring, Rapid, and Spearfish Creek Basins. This generally corresponds with the location of the "Limestone Plateau" on the western flank of the Black Hills (Figure 9). Conversely, the middle sections of Elk, Boxelder, Rapid Creeks along the eastern downslope flank of the Black Hills show the highest normalized peak-flow areas. Fall River in the southern Black Hills also shows relatively high normalized peak flows. Yield efficiency maps (Figure 6) tend to reflect the peak-flow maps, with more infiltration capacity beginning in the upper Rapid and Spring Creek Basins and extending to the north and west that could result in lower peak flows. Although relatively high normalized peak flows are shown in modeling results in the southern Black Hills basins, three of these basin models (Lame Johnny, Red Canyon, and Hell Canyon) were not calibrated because of an absence of streamflow data. The lower ends of Fall River and Beaver Creek Basins show normalized peak flows similar to those on the eastern flank of the Black Hills, but it is difficult to assess the larger spatial trends in flood risk in this southern area without more calibration information. Normalized peak flows and yield efficiencies simulated using the smaller PFreq2 scenario (Figure 7 and Figure 8) show spatial trends similar to the PFreq scenario.

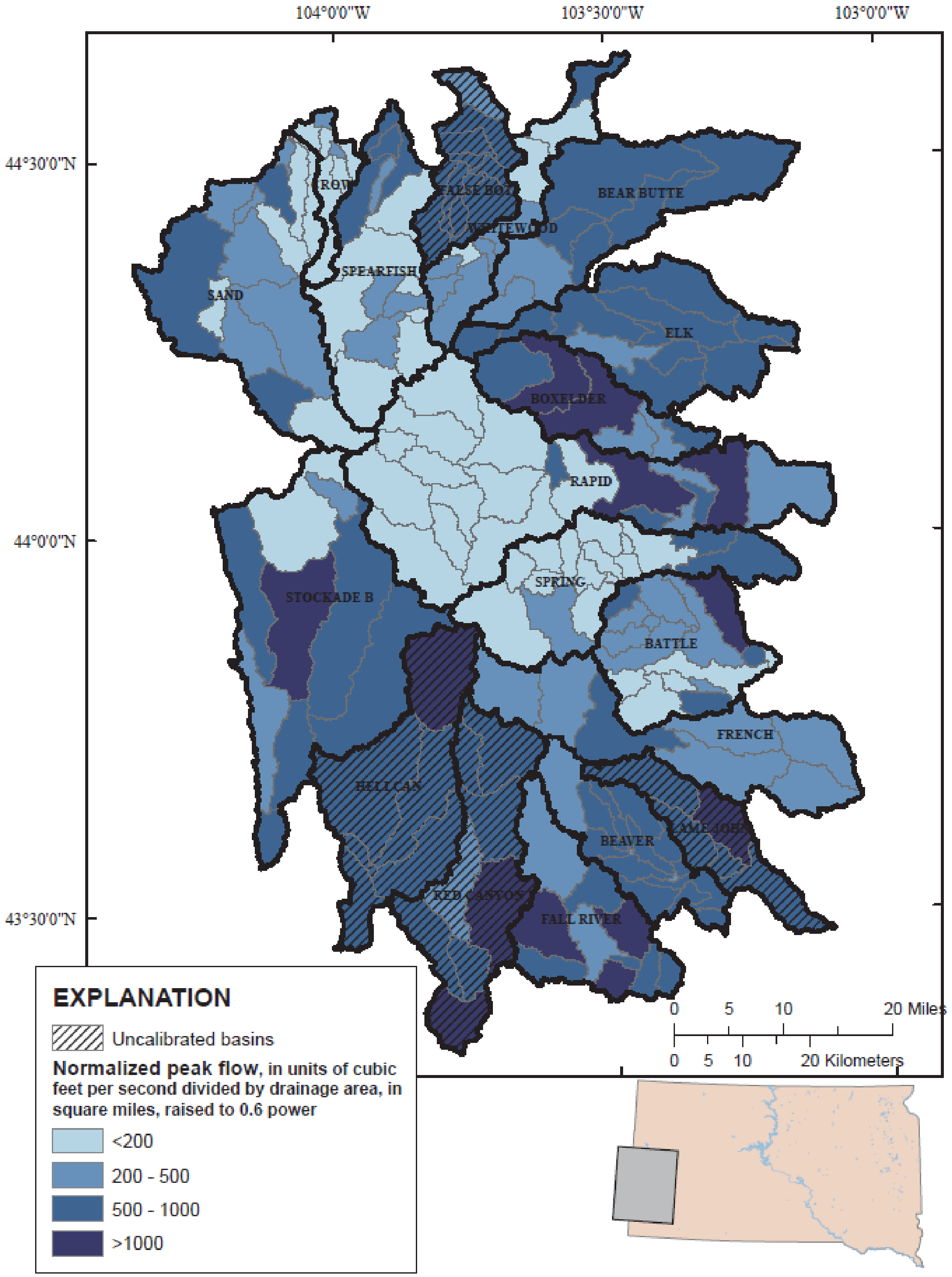


Figure 5. Normalized peak flow for PFreq scenario (7.86-inch precipitation) HEC-HMS simulation.

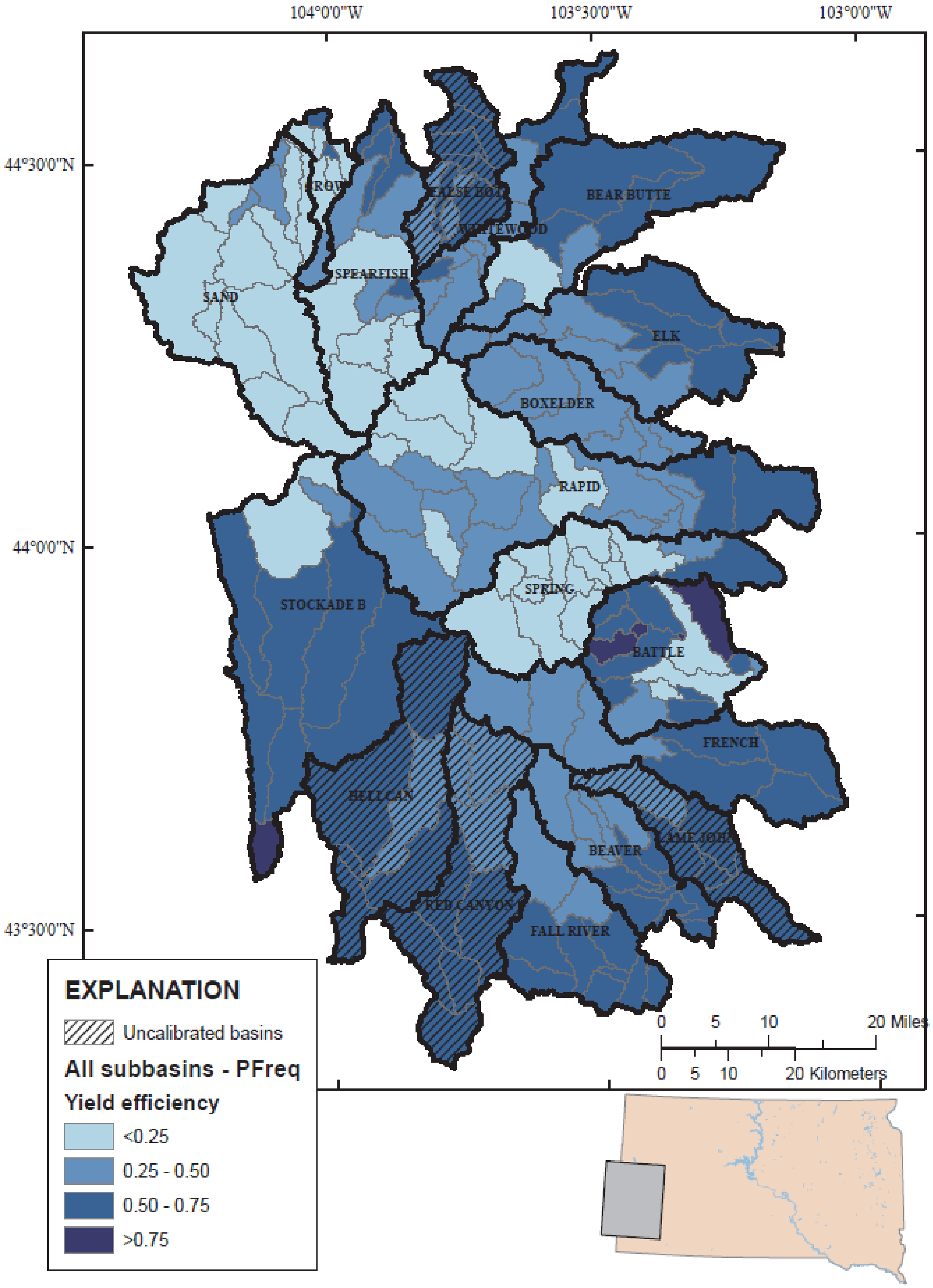


Figure 6. Yield efficiency for PFreq scenario (7.86-inch precipitation) HEC-HMS simulation

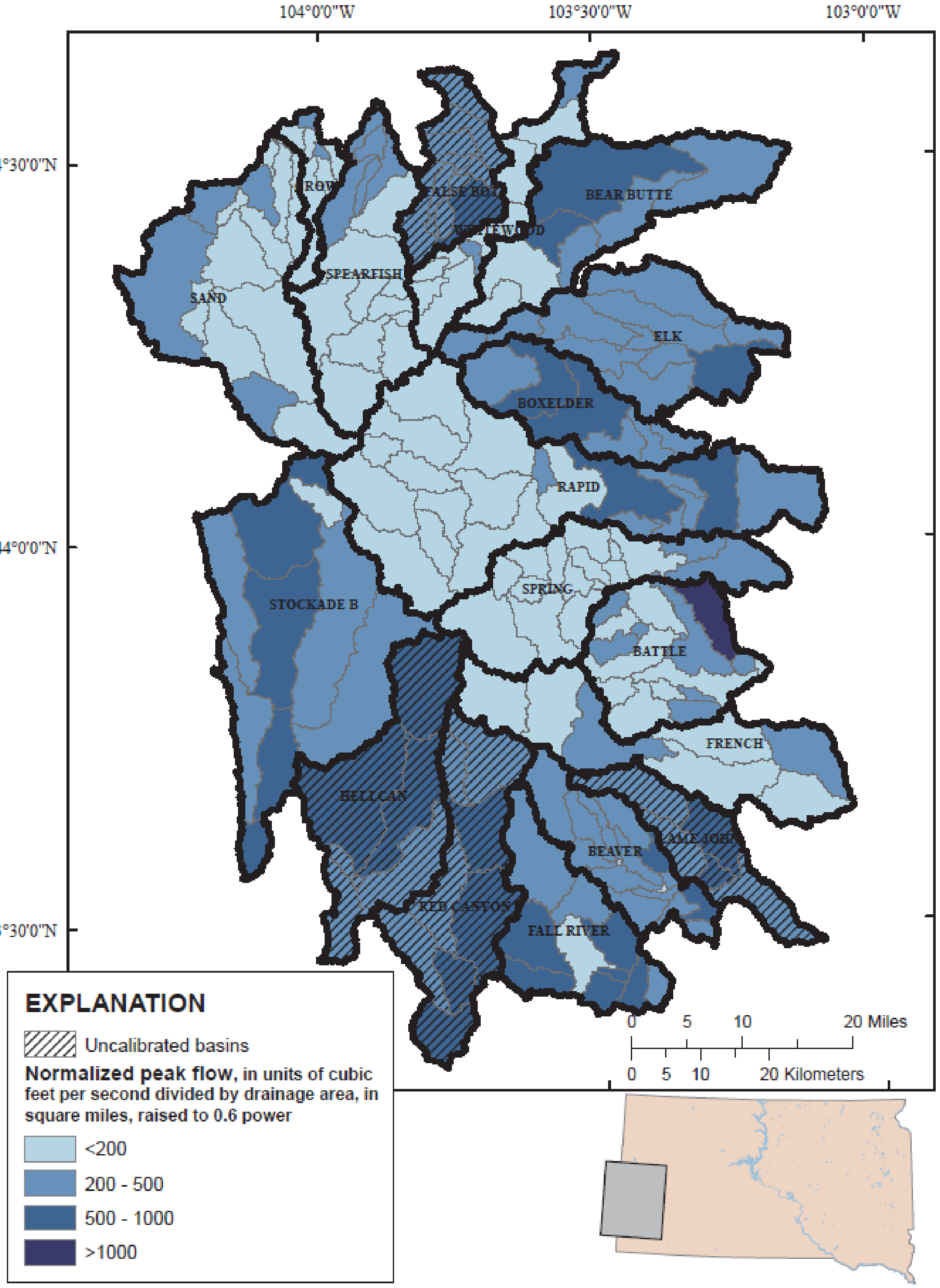


Figure 7. Normalized peak flow for PFreq2 scenario (5.17-inch precipitation) HEC-HMS simulation

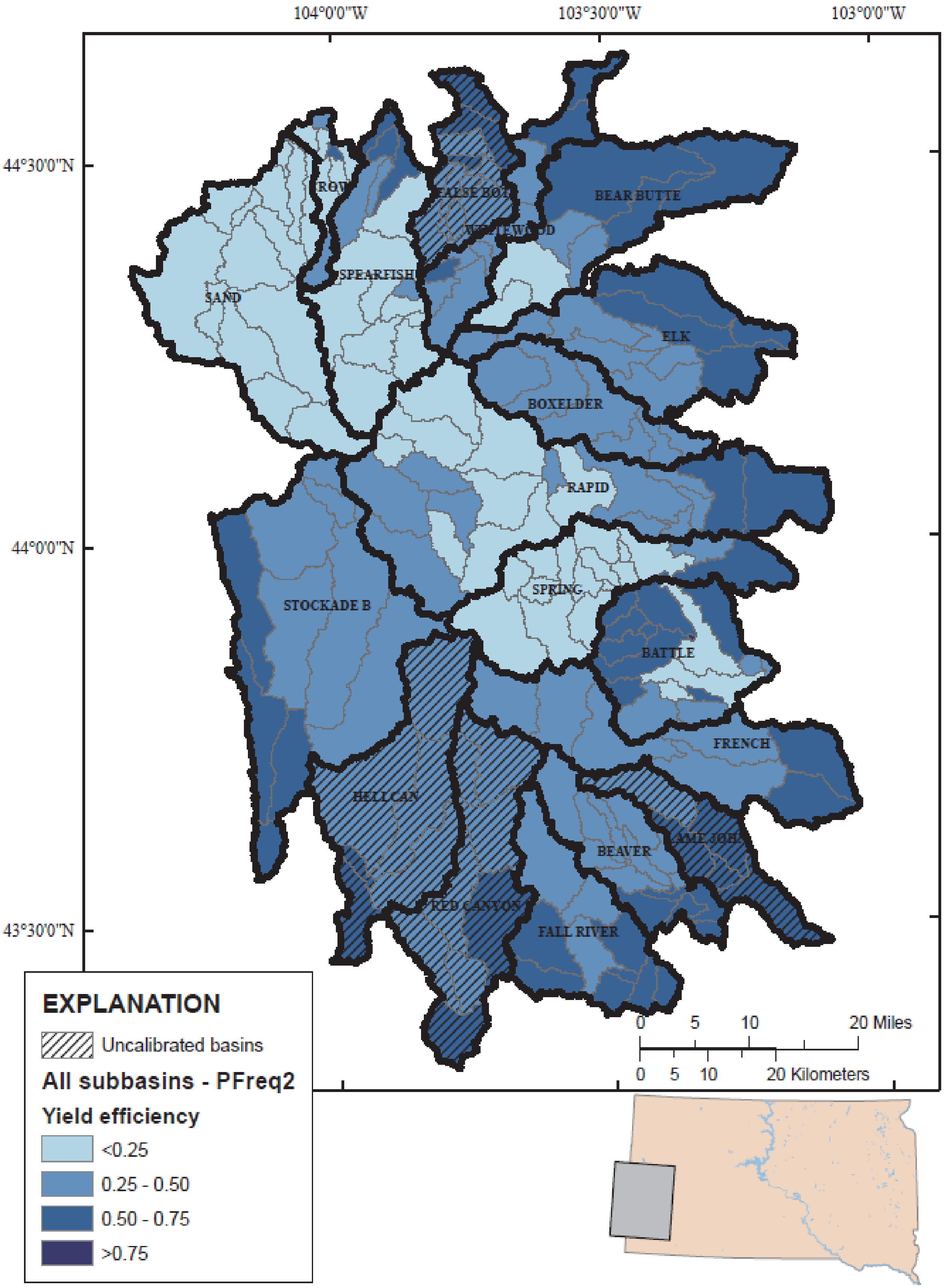


Figure 8. Yield efficiency for PFreq2 scenario (5.17-inch precipitation) HEC-HMS simulation

6.2 Relation of peak flow potential to basin characteristics

Peak-flow potential for basins in the Black Hills is largely affected by geology and topographical characteristics. The Limestone Plateau area in the western Black Hills is located within the outcrops of the Mississippian-age Madison (Pahasapa) Limestone and Pennsylvanian- and Permian-age Minnelusa Formation (Figure 9), and has suppressed peak-flow potential. Direct runoff on the Limestone Plateau is uncommon because of the high infiltration rate, and streamflow consists almost entirely of base flow originating as headwater springs (Driscoll and Carter, 2001; Driscoll and Hoogestraat, 2015).

Areas in the eastern downslope valleys of the Black Hills have experienced the most frequent and greatest magnitude flooding in recorded history. This area also corresponds with some of the steepest terrain, as shown by the map of mean subbasin slope (Figure 10). Stream channels in these areas generally are confined to narrow canyons where attenuation potential is limited. The far eastern areas of the basin models have generally low basin slopes where the streams enter alluvial plains. The floodplains east of the Black Hills are more conducive for attenuation of peak flows because wider channels in these areas disperse water laterally.

Compactness ratio (Figure 11) is geometric measure of the subbasin's perimeter compared to its drainage area. Drainage basins with a greater compactness ratio are narrow stream valleys, meander less, and typically correspond with relatively larger peak flows. In general, the same areas identified as having the greatest slopes also have greater compactness ratios. These topographical and geological factors help explain the distributions of normalized peak flow and yield efficiency in the Black Hills.

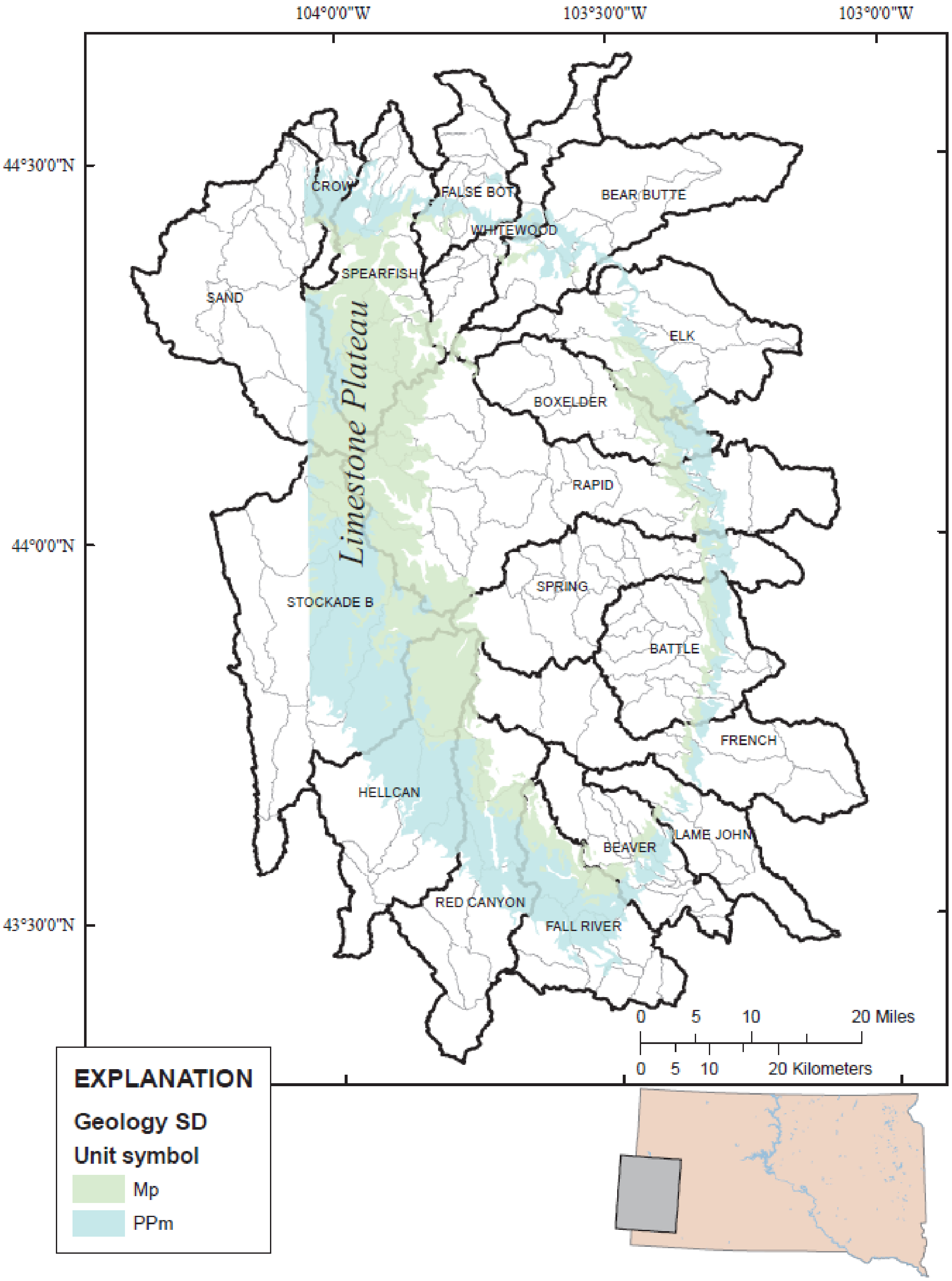


Figure 9. Location of Madison Limestone (Mp) and Minnelusa Formation (PPm) outcrops in Black Hills area (Redden and DeWitt, 2008). (Note the outcrops of the Madison Limestone and Minneslusa Formation extend farther west, but geology is truncated at the Wyoming border.)

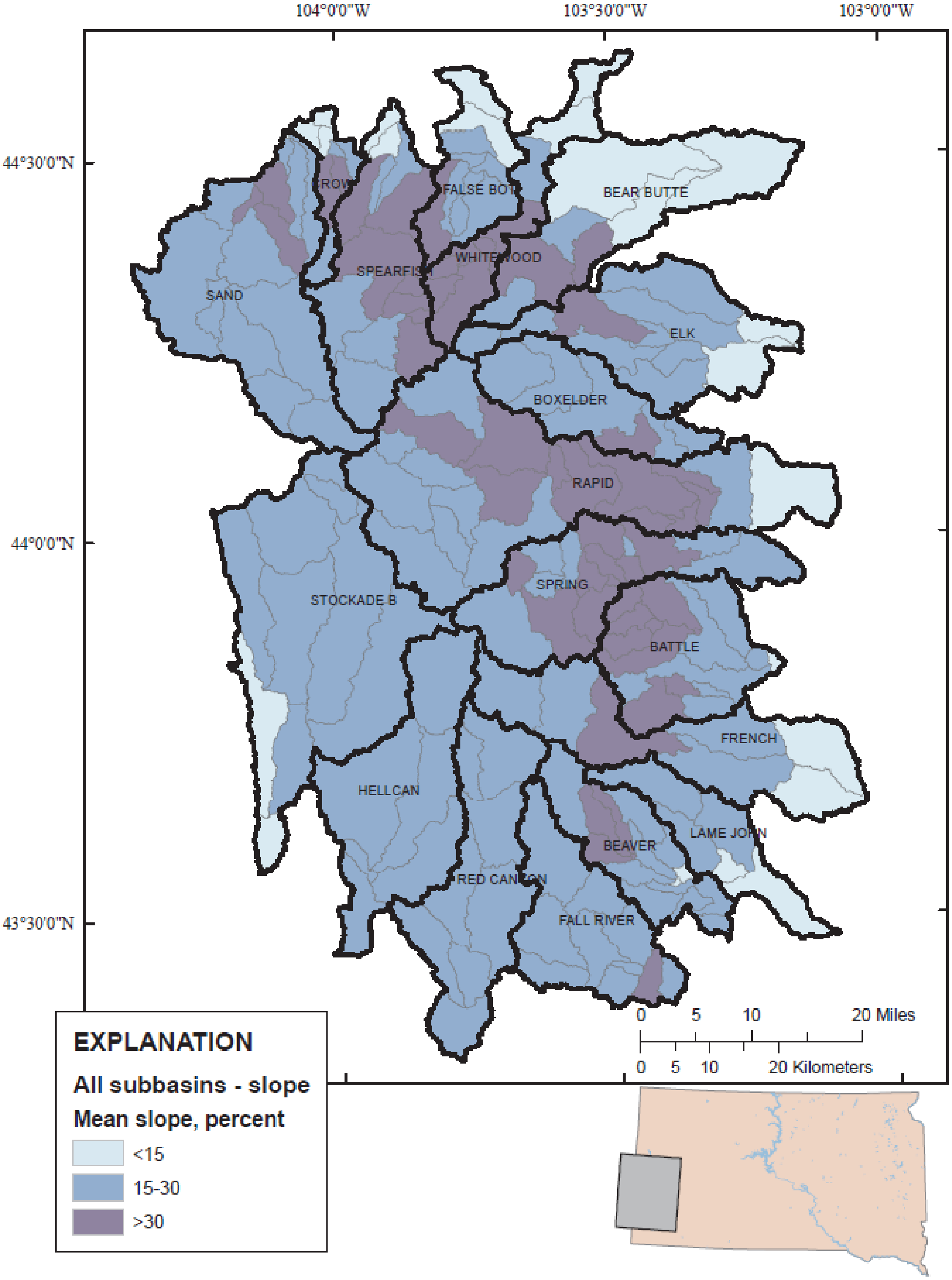


Figure 10. Mean subbasin slope in Black Hills area

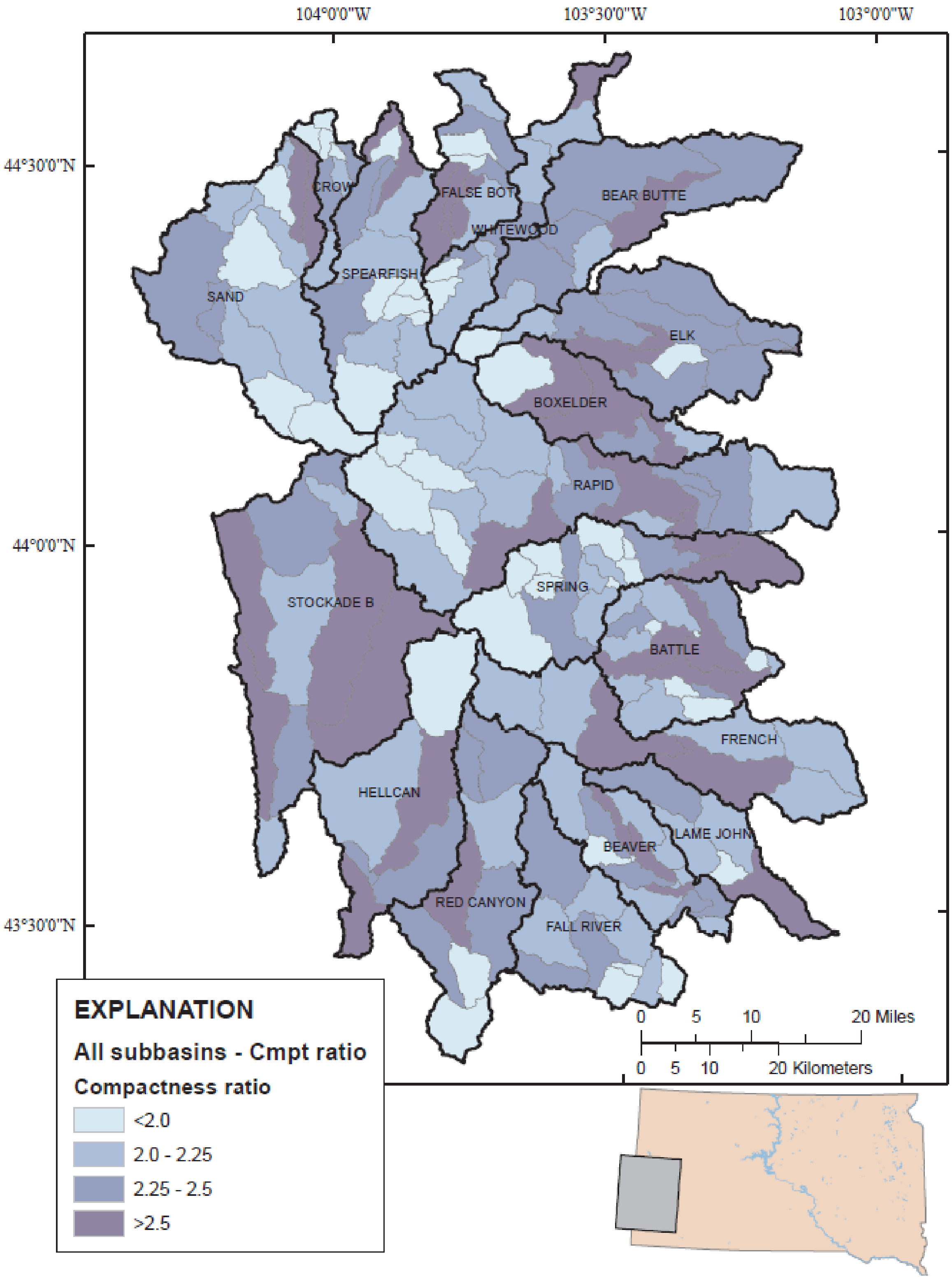


Figure 11. Compactness ratio for subbasins in the Black Hills

7 FINDINGS AND CONCLUSIONS

Application of rainfall-runoff modeling was found to be feasible for improving peak-flow characterization for the Black Hills area. This was accomplished primarily by comparing the peak-flow response for uniform rainfall events when applied to multiple subbasins within 18 simulated basins in the Black Hills. This rainfall-runoff modeling approach shows distinctive differences in peak-flow potential for different subbasins that are driven primarily by topography and has excellent potential for improving peak-flow frequency analyses for the Black Hills area. These findings are consistent with previously reported characterizations and take a major step forward in better quantification of peak-flow probability.

The HEC-HMS rainfall-runoff models were calibrated to a unique set of peak-flow rainfall events during the time period 2010–2013. Although storm events were selected to represent moderate antecedent conditions (not during extreme wet or dry cycles), any variations in base flow or prevailing moisture conditions within the basin can substantially affect the validity of the model output. Event hydrologic modeling (such as used for this study) documents how a basin might respond to one or more individual rainfall events. In contrast, continuous hydrologic modeling synthesizes hydrologic processes and phenomena (such as synthetic responses of the basin to a number of rain events and their cumulative effects) over a longer time period that includes both wet and dry conditions (Chu and Steinman, 2009).

The results from hypothetical (synthetic) storm events help delineate areas of greater flood risk in the eastern downslope flank of the Black Hills and lower peak-flow potential in the central core and western Limestone Plateau area (Figure 12). The same general results are consistent with those of previous reports on peak flows in the Black Hills area (Driscoll and others, 2010; Harden and others, 2011). A key benefit of this modeling project is that these characterizations, which were previously supported mainly by recorded streamflow history, are confirmed using parametric hydrologic models. This important distinction indicates that increased flooding potential in the eastern Black Hills is driven by physiographic factors, and not simply a result of having experienced more frequent large precipitation events in recorded history as compared to the central and western Black Hills. These results also demonstrate that, independent of precipitation variability, the flooding potential (streamflow normalized to drainage area) in the eastern flanks of the Black Hills will be much greater than other areas to the west, especially towards the high-elevation Limestone Plateau area. As described in Driscoll and others (2010), several terrain-induced processes (orographic lifting, thermally enhanced circulations, and obstacle effects) indicate that thunderstorm occurrence is also favored east of the major axis of the Black Hills, down through the foothills. In other words, similar topographical factors drive both the climatology (precipitation formation prior to reaching the land surface) and runoff (water flow after reaching the land surface) portions of the hydrologic cycle in the Black Hills area.

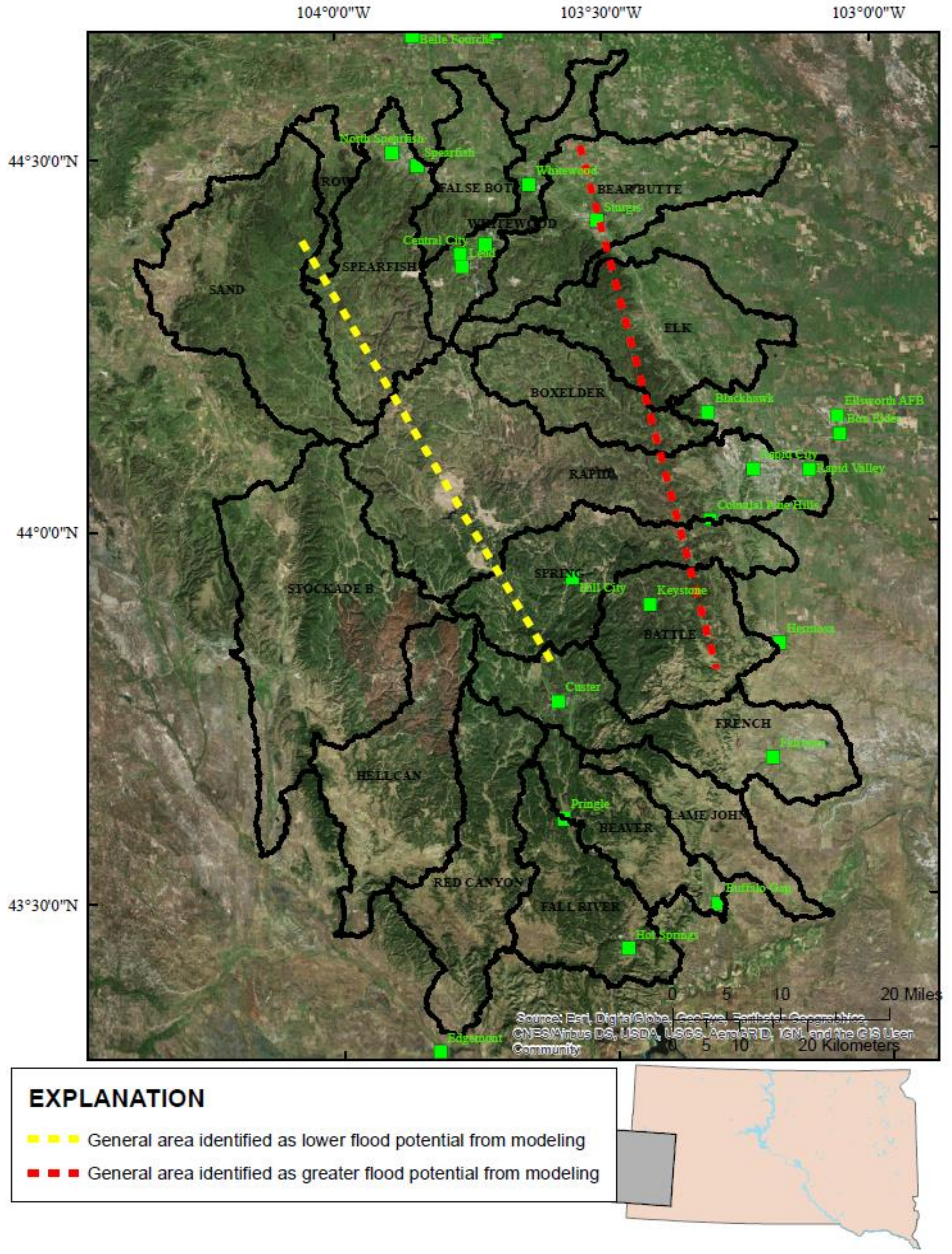


Figure 12. Relative comparison of high (red) and low (yellow) peak-flow potential regions identified from modeling.

8 APPLICATION OF RESULTS

Results from this research will have applicability to SDDOT in several ways, as described herein.

8.1 Incorporate peak-flow spatial delineation into ongoing frequency update project

The SDDOT Bridge Program and USGS currently are engaged in a multi-year, two-component project for (1) a statewide update of at-site peak-flow frequency estimates for streamgages and (2) a subsequent regionalization component for estimating peak-flow characteristics for ungaged streams. A key problem with peak-flow frequency estimation in the Black Hills is the proper statistical treatment of past extreme thunderstorm flood events, such as those in 1972 (Schwarz and others, 1975) or 2007 (Driscoll and others, 2010). To address this issue, Sando and others (2008) used a "regional mixed-population analysis," that separated peak-flow records into two separate populations of flood events: ordinary peaks and high-outlier peaks. In States outside South Dakota, mixed-population flood-frequency analyses have been performed on sites where different causal factors are responsible for the resulting peak flows (Ahearn, 2003). For example, coastal areas may have separate populations for "typical" peaks and those resulting from hurricane events. Similarly, mountainous drainage basins may have separate peak populations for events driven by snowmelt versus rainfall. In the Black Hills, nearly all peak flows are rainfall events that cannot be readily separated into different populations according to causal factors.

This mixed-population analysis was applied to all streamgages within the Cheyenne and Belle Fourche River drainage basins, with the exception of main-stem streamgages. However, Sando and others (2008) cautioned that for streamgages "where drainage areas are primarily within the limestone-headwater setting, abrupt increases in slopes of the frequency curves result from application of the mixed-population analysis, which may result in overestimation of peak flows for larger recurrence intervals" and "potential probably exists for overestimation of peak flows for larger recurrence intervals for other streamgages in other hydrogeologic settings." The findings of this study indicate that distinctive differences in peak-flow potential for the Black Hills area are driven primarily by topography. It is specifically intended that the findings of this study can be used to help delineate regions of distinctively different peak-flow potential in the Black Hills area, such that different mixed-population analyses can be applied as part of the aforementioned first component of the ongoing statewide peak-flow frequency that is being conducted by SDDOT Bridge Program and USGS.

8.2 HEC-HMS files available for design use

HEC-HMS models were calibrated for 18 drainage basins in the Black Hills area using precipitation events during 2010–2013. The HEC-HMS hydrology model files will be available to SDDOT or other interested agencies from the USGS Dakota Water Science Center upon request for use as a design tool or other applications that might arise.

8.3 Benefits could be achieved by additional modeling efforts

This project demonstrated the utility of rainfall-runoff modeling for helping to improve peak-flow characterization for South Dakota. Additional benefits could be achieved by additional modeling efforts in two specific arenas, one being specifically within the Black Hills area and the other involving a statewide effort.

8.3.1 Additional modeling within the Black Hills area

Additional modeling would involve rainfall-runoff modeling for large drainage areas beyond the periphery of the Black Hills, where large attenuation potential exists along broad alluvial floodplains. Such effects are apparent in peak-flow records, and modeling would help to define the appropriate areas for application of another mixed-population zone.

8.3.2 Additional modeling throughout South Dakota

Additional rainfall-runoff modeling throughout South Dakota would be useful for helping address the second component of the ongoing statewide peak-flow frequency that is being conducted by SDDOT Bridge Program and USGS. There is large variability throughout South Dakota in several parameters that affect peak-flow characteristics (such as main-channel slope, channel or floodplain conditions, and soil type) that are not adequately reflected in regionalized peak-flow regression equations generated from data collected from the streamgaging network. A statewide effort for rainfall-runoff modeling would help in better characterizing areas where general similarities in peak-flow characteristics might be expected, which would help greatly in defining statewide subregions for developing and applying the regionalized peak-flow regression equations.

9 RESEARCH BENEFITS

The results of this research represent another step forward in addressing the complex peak-flow frequency issues for the Black Hills area. Driscoll and others (2012) presented a qualitative characterization of peak-flow potential for the Black Hills area. The results of this rainfall-runoff modeling research provides a quantitative assessment of peak-flow potential that supports the previous qualitative characterization by Driscoll and others (2012) and is expected to have future applicability in probability analyses for the Black Hills area. In addition, the HEC-HMS model files created as a result of this work will be available to SDDOT and others for infrastructure design purposes.

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11 APPENDIX A

Table 11-1 . Initial and calibrated HEC-HMS parameters for subbasins in basin models

[mi^2, square miles; CN, curve number; Cal, calibration value; T_c, time of concentration; R, storage coefficient]. Initial values estimated using methods described in section 5.2.

Basin (Figure 1)	Element (Figure 2)	Drainage area, mi^2	CN		T_c, hours		R, hours	
			Initial	*Cal*	*Initial*	*Cal*	*Initial*	*Cal*
BATTLE	W150	8.9	61.6	86.1	3.4	7.1	2.3	16.9
BATTLE	W200	1.6	62.9	80.4	0.8	14.8	0.5	0.0
BATTLE	W220	6.8	61.3	78.4	2.5	1.3	1.7	25.5
BATTLE	W240	6.8	62.4	79.8	2.0	0.0	0.9	7.2
BATTLE	W300	15.4	62.2	79.6	6.0	27.8	4.4	21.3
BATTLE	W320	0.3	65.0	83.1	0.4	0.1	0.3	0.4
BATTLE	W340	18.7	61.6	78.8	9.5	21.7	8.5	23.6
BATTLE	W400	7.4	61.7	75.9	3.4	0.1	2.1	33.7
BATTLE	W440	19.7	64.5	79.4	5.6	7.0	3.3	58.6
BATTLE	W480	18.9	71.1	35.1	8.7	0.4	7.9	31.0
BATTLE	W50	2.0	82.1	82.1	2.5	0.2	1.9	89.2
BATTLE	W500	9.2	73.8	73.8	2.3	9.7	1.3	0.4
BATTLE	W520	2.6	75.2	75.2	1.7	4.1	1.4	4.4
BATTLE	W540	4.2	68.3	68.3	2.6	58.6	1.9	237.8
BATTLE	W590	22.4	66.8	46.1	8.0	4.9	6.2	1.0
BATTLE	W630	3.5	69.0	69.0	2.3	0.3	1.7	1.0
BATTLE	W640	20.1	70.3	87.2	9.0	0.5	6.0	1.0
BEAR BUTTE	W100	15.7	63.5	54.4	6.7	11.7	4.4	9.0
BEAR BUTTE	W140	30.2	64.7	50.1	5.7	0.1	2.5	7.9
BEAR BUTTE	W180	24.1	79.7	--	13.0	--	10.7	--
BEAR BUTTE	W230	13.1	66.4	--	4.7	--	2.8	--
BEAR BUTTE	W240	14.3	69.2	--	3.2	--	1.9	--
BEAR BUTTE	W40	52.6	82.3	--	18.5	--	12.9	--
BEAR BUTTE	W50	72.4	80.3	--	16.1	--	10.3	--
BEAVER	W560	6.8	63.4	--	2.6	--	2.3	--
BEAVER	W580	13.5	67.9	--	4.0	--	2.6	--
BEAVER	W630	26.8	62.9	--	10.8	--	7.3	--
BEAVER	W660	10.8	63.0	--	4.3	--	3.5	--
BEAVER	W680	6.7	74.8	--	2.0	--	1.1	--
BEAVER	W700	7.4	69.6	--	3.9	--	3.4	--
BEAVER	W730	0.2	73.0	--	0.5	--	0.4	--
BEAVER	W760	8.0	64.0	--	3.3	--	2.2	--
BEAVER	W770	2.1	74.3	--	1.3	--	0.8	--
BEAVER	W800	9.2	70.2	--	4.3	--	3.5	--
BEAVER	W810	0.5	74.4	--	1.2	--	1.1	--
BEAVER	W850	3.1	82.4	--	2.4	--	1.8	--
BEAVER	W890	5.0	79.4	--	3.4	--	3.1	--
BEAVER	W920	12.4	76.9	--	5.8	--	3.9	--
BEAVER	W940	8.3	81.3	--	3.3	--	1.9	--
BEAVER	W980	4.9	80.2	--	3.0	--	2.2	--
BOXELDER	W110	29.9	64.33	--	4.0	--	1.9	--
BOXELDER	W200	36.9	62.55	--	8.1	--	3.8	--
BOXELDER	W250	13.1	62.14	--	4.0	--	2.1	--
BOXELDER	W290	9.5	65.91	--	7.4	--	7.2	--
BOXELDER	W300	9.7	62.48	--	6.9	--	5.6	--
BOXELDER	W50	27.9	65.47	--	5.3	--	2.5	--
CROW	W100	4.8	72.4	--	3.6	0.0	2.0	419.7
CROW	W110	1.5	71.4	--	1.1	7.2	0.8	1.4
CROW	W120	4.4	73.3	--	2.3	18.9	1.8	925.7
CROW	W140	4.6	63.7	--	1.9	0.0	1.2	256.3
CROW	W160	10.1	61.4	--	2.2	0.5	1.7	256.4
CROW	W170	9.5	62.4	--	2.8	5.3	1.8	24.5
CROW	W80	3.1	72.4	--	1.5	13.3	0.8	0.0

[mi^2, square miles; CN, curve number; Cal, calibration value; T_c, time of concentration; R, storage coefficient]. Initial values estimated using methods described in section 5.2.

Basin (Figure 1)	Element (Figure 2)	Drainage area, mi^2	CN		T_c, hours		R, hours	
			Initial	*Cal*	*Initial*	*Cal*	*Initial*	*Cal*
CROW	W90	3.0	71.3	--	3.1	0.1	2.4	194.6
ELK	W100	30.1	75.0	--	12.2	--	9.1	--
ELK	W110	10.7	82.2	--	7.1	--	5.7	--
ELK	W120	26.1	79.9	--	8.3	--	5.7	--
ELK	W130	0.8	87.4	--	3.1	--	3.8	--
ELK	W140	27.1	64.8	--	10.2	--	7.1	--
ELK	W210	10.6	64.4	--	3.4	--	2.2	--
ELK	W230	10.8	65.9	--	3.8	--	1.9	--
ELK	W270	25.5	62.0	--	5.2	--	3.5	--
ELK	W310	8.9	73.2	--	3.3	--	2.0	--
ELK	W380	5.4	74.4	--	2.3	--	1.4	--
ELK	W420	16.4	62.6	--	8.4	--	6.8	--
ELK	W80	39.2	78.4	--	15.1	--	10.8	--
FALL RIVER	W1010	8.9	76.3	--	2.7	3.4	1.4	2.2
FALL RIVER	W1020	7.3	80.1	--	3.2	4.0	2.1	3.5
FALL RIVER	W610	42.6	68.5	--	13.2	16.0	7.8	13.8
FALL RIVER	W630	15.8	67.5	--	3.6	13.6	1.9	2.5
FALL RIVER	W710	26.4	75.5	--	9.5	10.2	5.9	2.1
FALL RIVER	W720	17.8	75.6	--	3.0	0.1	1.5	2.1
FALL RIVER	W790	17.9	77.1	--	6.3	14.9	3.9	29.1
FALL RIVER	W870	2.3	76.3	--	1.5	0.0	1.0	0.1
FALL RIVER	W930	14.9	76.2	--	8.9	11.6	5.8	1.9
FALL RIVER	W940	9.6	78.6	--	3.7	0.5	2.0	0.3
FALSE BOT	W100	7.0	67.5	--	4.4	--	3.6	--
FALSE BOT	W150	6.9	71.8	--	5.1	--	4.6	--
FALSE BOT	W180	3.2	77.5	--	2.9	--	2.3	--
FALSE BOT	W190	18.4	65.3	--	7.7	--	6.0	--
FALSE BOT	W230	5.2	72.0	--	3.8	--	2.7	--
FALSE BOT	W240	19.6	70.5	--	5.8	--	3.4	--
FALSE BOT	W290	9.5	73.7	--	4.5	--	2.7	--
FALSE BOT	W330	13.5	80.9	--	15.1	--	13.4	--
FALSE BOT	W340	17.1	79.6	--	10.9	--	7.9	--
FRENCH	W240	36.3	62.6	--	9.6	16.0	9.9	1.9
FRENCH	W290	30.4	77.1	--	11.4	26.1	7.9	28.1
FRENCH	W330	35.0	63.8	--	5.9	20.0	3.0	24.9
FRENCH	W340	33.4	64.3	--	11.0	19.9	7.5	17.1
FRENCH	W380	26.2	85.4	--	12.1	27.6	10.3	36.8
FRENCH	W390	40.4	77.2	--	10.8	24.7	8.4	29.9
FRENCH	W60	30.3	85.2	--	10.6	24.2	8.5	30.3
HELLCAN	W100	22.0	78.2	--	8.1	--	6.3	--
HELLCAN	W120	41.7	68.7	--	7.4	--	5.2	--
HELLCAN	W130	49.3	73.4	--	8.9	--	4.4	--
HELLCAN	W70	75.4	72.8	--	14.0	--	7.8	--
HELLCAN	W80	4.8	76.1	--	3.6	--	2.9	--
HELLCAN	W90	38.2	73.4	--	12.0	--	8.2	--
LAME JOHN	W130	6.1	83.0	--	3.2	--	2.0	--
LAME JOHN	W150	17.7	79.5	--	8.4	--	6.0	--
LAME JOHN	W60	26.9	81.1	--	13.2	--	12.4	--
LAME JOHN	W80	22.2	81.8	--	6.1	--	3.8	--
LAME JOHN	W90	28.9	67.8	--	11.0	--	8.2	--
RAPID	W100	35.2	68.0	--	8.6	0.0	4.7	565.7
RAPID	W120	34.8	62.2	--	5.4	19.7	2.8	132.7
RAPID	W150	36.5	63.2	--	11.3	2.0	9.1	85.0
RAPID	W170	37.2	73.1	73.1	8.8	7.5	4.4	96.8
RAPID	W180	42.0	73.0	73.0	8.0	3.2	3.5	61.2
RAPID	W260	79.2	NA - Deerfield Reservoir element					
RAPID	W300	26.7	66.4	--	4.9	0.4	2.6	975.6
RAPID	W320	8.0	73.9	38.4	3.8	5.9	2.4	35.0
RAPID	W350	24.8	62.2	--	5.1	20.0	3.4	52.0

[mi^2, square miles; CN, curve number; Cal, calibration value; T_c, time of concentration; R, storage coefficient].
Initial values estimated using methods described in section 5.2.

Basin (Figure 1)	Element (Figure 2)	Drainage area, mi^2	CN		T_c, hours		R, hours	
			Initial	*Cal*	*Initial*	*Cal*	*Initial*	*Cal*
RAPID	W370	14.3	65.5	--	4.6	0.0	3.1	53.3
RAPID	W410	14.8	67.6	--	6.1	0.0	3.6	67.3
RAPID	W460	5.7	61.6	--	2.6	1.8	1.7	0.3
RAPID	W510	279.8	NA - Pactola Reservoir element					
RAPID	W570	35.7	62.5	--	11.1	3.4	9.4	0.5
RAPID	W690	5.5	62.1	--	1.9	1.6	1.3	2.1
RAPID	W710	6.8	62.4	--	4.5	3.2	3.4	0.0
RAPID	W770	6.0	63.9	--	2.7	0.8	1.9	0.0
RAPID	W810	7.1	64.5	--	5.2	9.3	4.7	2.9
RAPID	W850	43.6	79.5	--	12.2	5.6	6.9	0.9
RAPID	W860	31.6	73.8	--	6.5	0.2	3.0	7.0
RED CANYON	W100	22.5	78.6	--	5.4	--	2.6	--
RED CANYON	W120	41.8	75.2	--	5.7	--	2.8	--
RED CANYON	W170	30.1	65.9	--	5.6	--	2.6	--
RED CANYON	W220	12.9	67.1	--	7.0	--	5.2	--
RED CANYON	W230	36.0	63.5	--	8.9	--	4.9	--
RED CANYON	W70	26.7	74.2	--	13.3	--	11.3	--
RED CANYON	W80	14.6	73.7	--	4.6	--	2.8	--
RED CANYON	W90	25.0	73.0	--	12.5	--	9.3	--
SAND	W420	0.5	72.3	48.0	1.3	2.3	1.1	2.6
SAND	W430	13.4	64.4	42.7	4.9	8.8	5.0	11.7
SAND	W450	3.2	75.6	50.1	1.8	3.1	1.3	3.0
SAND	W460	11.5	72.2	47.9	4.6	8.1	3.9	9.1
SAND	W480	11.3	76.1	50.5	3.2	0.1	1.8	0.2
SAND	W510	14.1	75.0	49.8	4.1	6.3	2.8	0.0
SAND	W520	3.5	74.8	49.6	2.7	7.2	2.5	0.6
SAND	W530	13.3	68.0	45.1	3.0	8.7	2.0	10.2
SAND	W610	29.4	70.1	46.5	4.6	9.4	2.7	7.7
SAND	W620	69.0	73.9	49.1	9.8	9.3	5.7	0.1
SAND	W650	8.9	65.7	43.6	4.3	7.5	3.0	6.7
SAND	W680	25.8	67.4	44.7	5.7	6.5	3.6	3.1
SAND	W730	51.6	71.5	47.5	6.6	20.0	3.7	11.0
SAND	W820	20.2	73.6	48.8	3.7	6.9	1.8	0.4
SAND	W850	24.2	73.6	35.0	3.7	6.1	1.6	18.1
SPEARFISH	W100	28.3	69.8	35.0	6.6	0.0	3.8	125.0
SPEARFISH	W120	10.1	75.2	--	4.0	--	3.3	--
SPEARFISH	W220	21.8	66.9	55.9	2.1	20.0	1.0	32.8
SPEARFISH	W230	28.1	63.6	53.2	4.0	18.3	1.8	78.3
SPEARFISH	W270	8.9	68.2	57.0	2.3	20.0	1.2	2.7
SPEARFISH	W330	3.6	64.1	75.8	1.4	0.6	0.8	46.7
SPEARFISH	W370	7.0	66.5	55.6	1.5	11.7	0.8	2.9
SPEARFISH	W420	2.1	64.7	33.9	1.3	1.3	0.9	0.9
SPEARFISH	W480	17.3	72.1	37.7	5.1	5.2	2.6	2.8
SPEARFISH	W520	17.6	74.3	38.9	2.8	2.8	1.4	1.4
SPEARFISH	W530	29.8	74.2	38.8	8.4	8.6	3.9	4.2
SPEARFISH	W590	4.5	69.0	--	3.2	--	2.8	--
SPEARFISH	W60	6.5	74.9	--	4.7	--	4.1	--
SPEARFISH	W620	5.4	74.7	--	2.6	--	1.9	--
SPEARFISH	W630	17.8	63.9	--	7.6	--	5.8	--
SPRING	W230	17.5	61.9	35.8	10.6	--	8.8	--
SPRING	W250	4.4	58.0	33.6	1.5	--	0.7	--
SPRING	W270	1.7	53.5	31.0	10.6	--	9.6	--
SPRING	W290	12.4	62.5	36.2	4.5	--	2.6	--
SPRING	W330	25.3	62.0	35.9	4.6	--	2.5	--
SPRING	W340	42.3	64.0	37.1	8.1	--	4.0	--
SPRING	W430	8.5	62.0	35.9	4.5	--	3.4	--
SPRING	W450	5.7	62.3	36.1	2.9	--	1.9	--
SPRING	W470	9.4	63.4	36.7	3.2	--	1.8	--
SPRING	W490	8.1	61.5	35.6	3.5	--	2.0	--

[mi^2, square miles; CN, curve number; Cal, calibration value; T_c, time of concentration; R, storage coefficient]. Initial values estimated using methods described in section 5.2.

Basin (Figure 1)	Element (Figure 2)	Drainage area, mi^2	CN		T_c, hours		R, hours	
			Initial	*Cal*	*Initial*	*Cal*	*Initial*	*Cal*
SPRING	W530	6.5	62.0	35.9	2.3	--	1.2	--
SPRING	W550	6.5	62.6	36.3	3.2	--	2.6	--
SPRING	W570	1.0	62.1	36.0	0.7	--	0.5	--
SPRING	W590	13.2	62.5	36.2	3.3	--	1.8	--
SPRING	W680	31.6	75.2	--	12.4	--	10.5	--
SPRING	W690	10.9	65.5	--	4.1	--	3.0	--
STOCKADE B	W100	81.0	70.8	--	18.9	--	14.0	--
STOCKADE B	W110	79.9	70.9	--	16.0	--	11.6	--
STOCKADE B	W120	33.1	79.8	--	19.0	--	21.1	--
STOCKADE B	W130	26.9	75.2	--	6.4	--	4.5	--
STOCKADE B	W140	11.7	86.9	--	5.9	--	4.1	--
STOCKADE B	W160	57.9	69.9	--	8.9	--	4.9	--
STOCKADE B	W210	59.3	71.4	35.2	8.9	11.5	4.8	19.2
STOCKADE B	W230	10.1	73.9	62.4	6.4	16.1	4.7	4.5
STOCKADE B	W90	43.4	75.4	--	11.1	--	8.2	--
WHITEWOOD	W110	24.5	64.2	--	7.6	18.6	4.9	19.2
WHITEWOOD	W130	4.3	62.7	--	1.8	3.7	1.2	24.0
WHITEWOOD	W150	4.9	62.8	77.0	1.9	5.5	1.2	18.9
WHITEWOOD	W200	3.8	67.3	--	1.5	0.4	0.8	6.0
WHITEWOOD	W250	13.5	64.3	--	2.8	0.0	1.8	22.7
WHITEWOOD	W300	16.5	76.3	--	3.2	17.0	1.6	101.2
WHITEWOOD	W340	12.1	79.1	--	6.1	0.0	4.5	8.3
WHITEWOOD	W350	17.9	83.3	--	10.5	4.5	6.6	52.3
WHITEWOOD	W60	6.5	62.4	--	2.5	3.7	1.4	6.5