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Application of HEC-HMS 3.4 in estimating streamflow of the Rio Grande under impacts of climate change

Chi Bui

Chi Mai Bui

Candidate

CIVIL ENGINEERING DEPARTMENT

Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Julie Coonrod	Julie Coonrod, Chairperson
Mark Stone	M Stone
Bruce Thomson	Bruce M Thomson

APPLICATION OF HEC-HMS 3.4 IN ESTIMATING STREAMFLOW OF THE RIO GRANDE UNDER IMPACTS OF CLIMATE CHANGE

BY

CHI MAI BUI

BACHELOR'S DEGREE IN CIVIL ENGINEERING
UNIVERSITY OF NEW MEXICO

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science
Civil Engineering

The University of New Mexico
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ABSTRACT OF THESIS

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ABSTRACT

The Rio Grande originates from the San Juan Mountains of southern Colorado, and flows year-round south through the entire length of New Mexico. It has an approximate drainage area of 1.9 million acres in New Mexico (USGS 1996), and provides habitat for diverse wildlife along the river, including the silvery minnow, an endangered indicator species.

The hydrology of the river is characterized by low flow during the winter months, a snow-induced peak in spring/early summer, and smaller peaks in July and August due to the effect of the monsoon season. In the five recent decades, the Rio Grande has experienced near averages as well as extremes similar to the variability of the climate of the last one-thousand years (Papadopulos 2004). Moreover, many climatic models have generated future climate change scenarios associated with altered temperature and precipitation.

To estimate future average streamflow of the Rio Grande, the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) software was adopted

to simulate streamflow for different climate change scenarios for the Rio Grande watershed above Elephant Butte Dam.

The historical monthly streamflow, precipitation, and temperature of the tributary areas for the Rio Grande from Del Norte, Colorado, to Elephant Butte, New Mexico were collected to calibrate an HEC-HMS hydrologic model for the period of 1971-2000. With the projection for temperature and precipitation associated with future climate change scenarios generated by a climatic General Circulation Model (GCM), the calibrated hydrologic model for the Rio Grande was employed to generate six future climate change hydrographs. The results generated by the calibrated hydrologic model represent the amount of water New Mexico delivers to Texas. The projection of the streamflow under different scenarios of climate change at Elephant Butte outlet were used in conjuction with the projection for the Rio Grande at Otowi bridge to quantify how well New Mexico would meet its obligations to deliver water to Texas under the requirements of the Rio Grande Compact.

A range of modeled streamflow projected total annual volume drops at Elephant Butte from 8.5% to 54.5% as well as one-month earlier arrival of spring induced runoff, resulting in New Mexico straining to meet delivery obligations.

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INTRODUCTION

This thesis has been written as a journal article to be submitted to ASCE Journal of Water Resources Planning and Management. The appendices contain the necessary details to support the journal article and meet the requirements of a thesis.

JOURNAL ARTICLE: APPLICATION OF HEC-HMS 3.4 IN ESTIMATING RESPONSES OF THE RIO GRANDE UNDER IMPACTS OF CLIMATE CHANGE

Abstract

The Rio Grande originates from the San Juan Mountains of southern Colorado, and flows year-round south through the entire length of New Mexico. It has an approximate drainage area of 1.9 million acres in New Mexico (USGS 1996), and provides habitat for diverse wildlife along the river, including the silvery minnow, an endangered indicator species.

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To estimate future average streamflow of the Rio Grande, the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) software was adopted to simulate streamflow for different climate change scenarios for the Rio Grande watershed above Elephant Butte Dam.

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Introduction

The primary water supply for the western United States is from groundwater, and surface water. The significant increase in population in the area coupled with drought conditions within the last twenty years has created chronic water shortages. The use of all near surface water resources has exceeded the sustainable supply for the area (Dettinger et al. 2004). Additionally, the uncertainty of future impacts of global warming has complicated the water scarcity problem in the Desert Southwest.

Variability of Climate Extremes and Streamflows in the West

Climate extremes are not unprecedented in the West. Tree-ring reconstructed streamflow for New Mexico streams for nearly five hunderd years (1525-2000) suggested that the region had experienced a variety of climate extremes. Neither the droughts from the period 2001-2005 nor in the 1950s surpassed the severity of nine driest episodes in the past five hundred years (Woodhouse et al. 2004). Recent studies have documented that recent climate variability in the West are causing significant reduction in natural water storage in snowpack in the Cascade Mountains, the northern Sierra Nevada, and the northern Rocky Mountains (Clow 2010) due to changes in runoff from winter snowpack. The regional Kendal test (RKT), a statistical approach used by Clow (2010), showed that the southern Rocky Mountains also experienced trends of early snowmelt and reduced snow equivalent of snowpack from 1978 to 2007. Hall et al. (2006) applied the statistical decadal mean and monotonic trend methods to the Rio Grande and the Pecos basins in New Mexico from 1960 to 2000 to find that the second half of the period experienced decreased total annual volume as well as exhibited signs of earlier beginning and sooner ending of spring snow induced runoff.

Recent attempts to project snow induced runoff under scenarios of climate change impacts in the West have found that peak streamflows would shift from spring to early spring, and peak evaporation would occur in early summer due to less soil moisture in the summer. Hurd and Coonrod (2008) suggested a one-month shift from May to April for the Upper Rio Grande watershed by the end of the twenty first century. Kang and Ramirez (2007) simulated responses of the South Platte river to climate impact scenarios derived from the second version of the Global Climate Model and Climate Change Scenario (GCM2) for two time periods, 2011-2020 and 2081-2090, using HEC-HMS. The statistical analyses of the modeled outcomes showed that small changes in the trends of rainfall variability could amplify variability of streamflows, because evaporation trends closely correlate to trends in precipitation. Dettinger et al. (2004) simulated and projected the streamflows of the Merced, Carson, and American Rivers in response to climate change scenarios for the time span from 1900 to 2099 by coupling the climate model, Parallel Climate Model (PCM), and the hydrologic model, Precipitation-Runoff Modeling System (PRMS). The results showed that spring snowmelt arrived about one month earlier by 2100 in the business-as-usual scenario in response to increased proportions of rain to snow. These timing changes were accompanied by increased frequency of winter flooding later in the year. Xu and Halldin (1997) calibrated a simple water model from 1981 to 1991 for the Northern Hemisphere Climate-Process Land-Surface Experiment (NOPEX) area. The projected streamflows for the twenty first century showed significant redistributions of monthly discharges, for instance snow induced peaks shifted from April to March, and projected snow accumulations dropped by 50% due to sharp increases of winter runoff.

Hydrologic Modeling with HEC-HMS

Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is public domain software developed by the US Army Corps of Engineers (USACE) (USACE 2009b) to simulate event-based and continuous precipitation-runoff of dendritic watersheds. After new geospatial capabilities were added to HEC-HMS versions 3.0 and later (Olivera 2001; Cunderlik and Simonovic 2004; Kang and Ramirez 2007), it has become more widely used as a versatile tool to model complex watersheds. Olivera (2001) pioneered using HEC-HMS to delineate watersheds into sub-basins and calculate hydrologic parameters, such as sub-basin areas, upstream/downstream reach lengths, and longest flow paths, from the geospatial information of the digital elevation model (DEM). Neary et al. (2004) used hourly Next-Generation Radar (NEXRAD) precipitation in HEC-HMS to model the Cumberland River basin in middle Tennessee from 1997 to 2001. Chu and Steinman (2009) used HEC-HMS to simulate the five-minute hydrologic event model of the Mona Lake, west of Michigan, to estimate parameters for the continuous model from May 2005 to September 2005 at hourly time-steps. Fleming and Harris (2004) developed and calibrated twelve parameters for the soil moisture accounting (SMA) loss method in HEC-HMS based on geographic information systems (GIS) databases. Kang and Ramirez (2007) projected responses of the streamflow of the headwaters of the South Platte River under climate change scenarios using HEC-HMS and hourly NEXRAD precipitation data.

Objective

This paper discusses the calibration of HEC-HMS to create a continuous hydrologic model for the Rio Grande watershed above Elephant Butte Dam (Figure I) for the period 1971-2000 which contains the most complete records, and the wettest years on record (Hurd and Coonrod 2008). With future climatic inputs derived by Smith and Wagner (2006) from the Inter-governmental Panel on Climate Change's Fourth Assessment Report (IPCC 2007), the hydrologic model was used to estimate responses of the streamflow of the Rio Grande above Elephant Butte Dam under near and long term future climate change scenarios. The projections of the streamflow at selected gauges were extracted to analyze New Mexico's performance to fulfill its obligation to deliver water to Texas under the Rio Grande Compact agreements.

Study Site and Stream Gauges

The Rio Grande watershed above the Elephant Butte reservoir is located in two states, New Mexico and Colorado (Figure I).

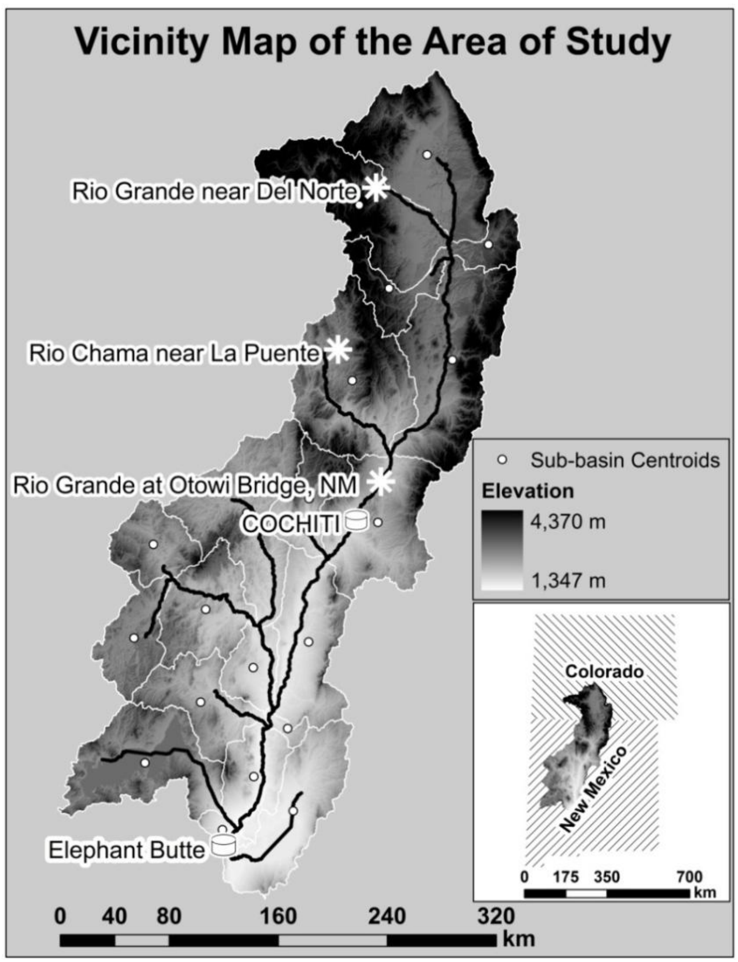


Figure I: The Rio Grande Watershed above Elephant Butte Dam

The headwaters of the Rio Grande originate in the San Juan Mountains in Colorado. The Elephant Butte outlet in New Mexico was selected as the pour point of the watershed. Under the agreements of the Rio Grande Compact, the upstream index gauge at Otowi bridge determines New Mexico's water depletion entitlement and delivery obligation; the downstream index gauge below Elephant Butte Dam measures New Mexico's compliance with the agreements. The model was calibrated against US Geological Survey's (USGS) records of the observed streamflow at Elephant Butte outlet. The projections of the streamflow under different scenarios of climate change at this outlet were used in conjuction with the projection for the Rio Grande at Otowi bridge (Figue I) to project how well New Mexico would meet its obligations to deliver water to Texas under the requirements from the Rio Grande Compact.

Two other gauges upstream from Otowi were used in the verification and validation processes, the Rio Grande near Del Norte and the Rio Chama near La Puente (Figure I), because these reaches are the two largest natural contributors to the streamflow of the Upper Rio Grande based on USGS's database.

Methodology and Data Processing

Calibration of continuous hydrologic models for large scale watersheds requires temporally and spatially fine-scaled observed data which are not always available (Chu and Steinman 2009), for instance, not every sub-basin of a delineated watershed has a stream gauge station, or time-series data measurements are not available for all possible time-intervals and the desired time period of simulation. Using PRISM Climate Group's database does not restrict the size of the watershed, but has limited choices of simulation time-steps. Using temporally fine-scaled NEXRAD climatic data limits the selection of locations, which made it not favorable for this project.

Model Inputs for Calibrated Streamflow

HEC-HMS was the primary modeling tool to synthesize the precipitation-runoff processes for the Rio Grande watershed. In order to start a project in HEC-HMS, a basin model with its hydrologic parameters and elements needs to be created. With publicly available GIS databases, geospatial data of watersheds, such as DEM, soil data from state soil geographic database (STATSGO), temperature, and precipitation from PRISM Climate Group, were pre-processed in ArcGIS to enhance the accuracy in estimating parameters for the HEC-HMS hydrologic model.

1. The 30-arc-second DEM was downloaded from USGS GeoScience Eye Toolkit and processed with ArcGIS geospatial extension HEC-GeoHMS to delineate the watershed into twenty-one sub-basins as seen in Figure I. ArcHydro tool in ArcGIS calculated parameters, such as sub-basin areas, times of concentration, and reach lengths, based on the DEM geospatial information of the watershed (Olivera 2001; Kang and Ramirez 2007).
2. Soil data were downloaded from STATSGO to generate the basin soil map to estimate soil physical parameters for sub-basins (Fleming and Neary 2004; Kang and Ramirez 2007), such as hydraulic conductivity, initial water deficit, and maximum water deficit.
3. Maximum and minimum temperatures were collected from PRISM Climate

Group's database. Monthly average temperatures were obtained by averaging the maximum and the minimum. This method was validated by researchers from University of Dayton (Hurd and Coonrod 2008). The monthly gridded averages were processed with ArcGIS to export into HEC-HMS as twenty-one temperature gauge inputs for the calibrated model.

4. Monthly average gridded precipitation data was collected from PRISM Climate Group's database and processed with ArcGIS to obtain the accumulated monthly precipitation for twenty-one sub-basins that were not compatible with the largest possible one-day time step in HEC-HMS. Deriving data for smaller time steps was adopted from McEnroe's method (McEnroe 2010) to transform the original time interval of gauged precipitation data to the desired fixed time interval by linear interpolation between points. Incremental amounts and intensities of the new time interval were derived from the newly generated accumulated amounts.

Model Inputs for Projected Streamflow

From eighteen climatic models presented in the Inter-governmental Panel on Climate Change's Fourth Assessment Report (IPCC 2007), Smith and Wagner (2006) selected models with the A1B greenhouse gas emission level, also known as the "business as usual" economic activity assumption, to suggest three optimal climate scenarios to best represent the range of outcomes of New Mexico climate: wet, middle, and dry. Smith and Wagner (2006) coupled the three scenarios with two future periods to generate six climate change scenarios:

- Near term: 2030 Dry, 2030 Middle, and 2030 Wet
- Long term: 2080 Dry, 2080 Middle, and 2080 Wet

Future temperature projection (Smith and Wagner 2006) was reported as changes in Celsius degrees with respect to the measurements from 1971 to 2000 as summarized in Table I; future precipitation projection (Smith and Wagner 2006) was reported as percentage changes with respect to the observed data from 1971 to 2000 as summarized in Table II.

Table I: Projection of Temperature Increases for Different Climate Change Scenarios

Δ Temp (°C)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average Change (°C)
2030 Dry	0.84	1.19	1.3	1.07	1.93	3.0	2.59	2.42	1.68	2.07	1.89	1.10	1.8
2080 Dry	2.89	3.56	3.41	4.02	5.49	5.8	4.68	5.07	4.88	5.34	4.12	3.56	4.4
2030 Mid	0.75	0.91	0.98	1.08	1.17	1.45	0.70	1.49	1.12	0.45	0.89	0.44	1.0
2080 Mid	2.85	2.53	2.36	2.68	3.38	4.18	3.14	3.81	3.59	2.74	3.01	2.45	3.1
2030 Wet	1.16	1.59	1.84	1.9	1.74	2	1.62	1.99	2.27	1.81	1.73	1.14	1.7
2080 Wet	2.83	3.08	3.23	3.25	3.24	3.44	3.03	3.43	4.36	3.75	3.27	2.73	3.3

Table II: Projection of Precipitation Changes for Different Climate Change Scenarios

% Change	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average Change (%)
2030 Dry	4.78	1.58	12.11	-9.46	-27.61	-35.06	-27.28	-24.92	-19.25	3.54	-0.97	4.24	-9.86
2080 Dry	-14.25	-7.29	-0.85	-28.2	-53.79	-36.43	-16.69	3.12	-11.8	-3.32	-19.35	1.7	-15.60
2030 Mid	1.69	-8.46	-7.1	-0.16	-9.19	-3.49	13.49	-5.1	13.92	8.23	7.28	-4.58	0.54
2080 Mid	0.88	-6.43	-8.46	-12.61	-24.6	-6.73	-0.46	-15.71	-6.63	-4.06	-18.46	-24.46	-10.64
2030 Wet	4.14	-8.55	-12.18	-6.25	9.32	7	22.23	21.04	8.59	-13.83	-4.73	-5.62	1.76
2080 Wet	0.82	-12.54	-9.64	8.84	17.91	15.99	33.05	55.95	-6.28	-14.22	-15.9	-5.96	5.67

Model Development

Conceptual Model

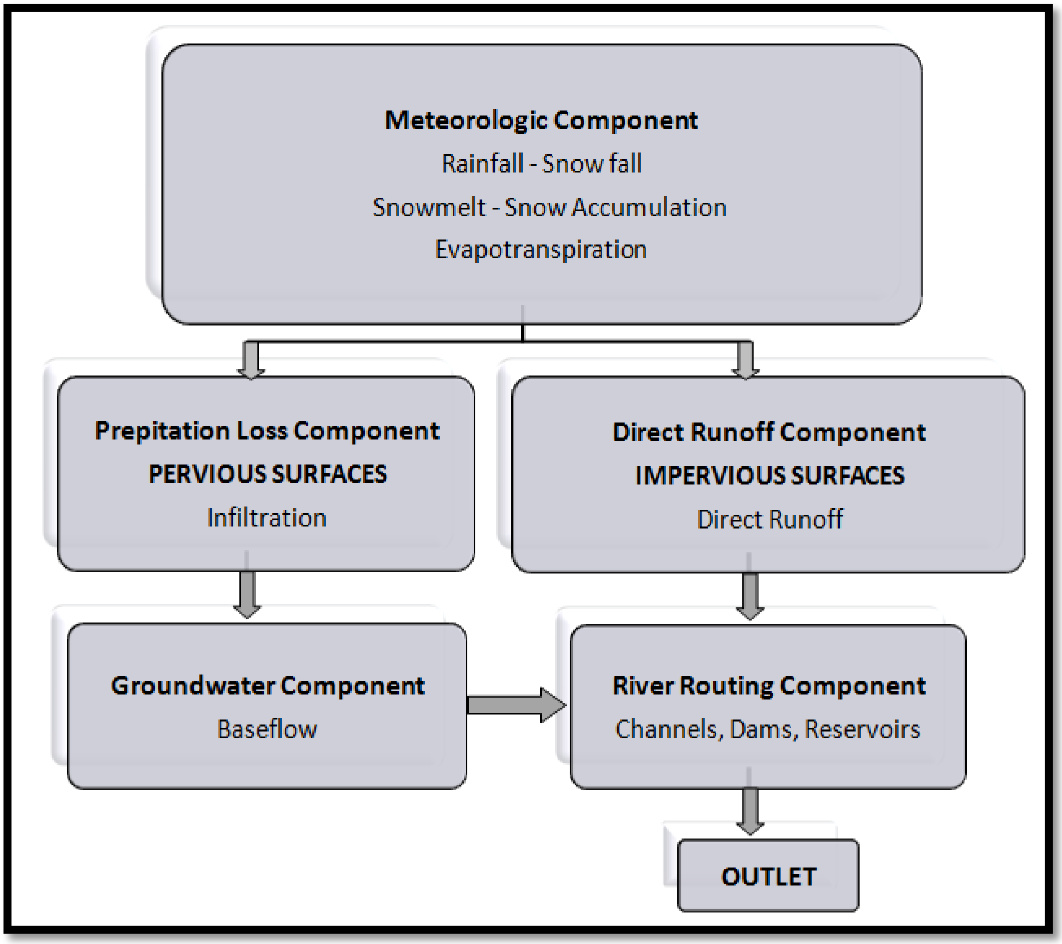


Figure II: Continuous Conceptual Model Diagram in HEC-HMS

A typical continuous model in HEC-HMS consists of six components as seen in Figure II. The meteorologic component uses the temperature and precipitation gauges to model precipitation as rainfall, snowfall, and snow accumulation (USACE 2009b). Precipitation which falls on impervious surfaces will enter the direct runoff component as overland flow. Precipitation which falls on pervious surfaces will undergo losses such as initial abstraction, infiltration, and evapotranspiration of which rates and patterns are defined based on the climate and soil data. The infiltration component of precipitation losses contributes to the direct runoff component and groundwater component. The baseflow and overland flow will enter the river channel component which flows through natural channels and engineered structures such as reservoirs and dams. The basin outlet receives the net runoff from the gross precipitation falling on the watershed (Cunderlik and Simonovic 2004).

Model Component Methods

Hydrologic data of the watershed from January 1971 to December 2000 were used to calibrate an HEC-HMS model at twelve-hour time steps. The Rio Grande is characterized by spring snowmelt induced runoff. Therefore, the ‘Temperature Index’ snowmelt method was incorporated into the meteorologic component to simulate snow accumulation and snowmelt. Unlike event-based modeling that does not require computation of evapotranspiration (ET), a method for ET was needed for continuous simulation (USACE 2009b). ‘Priestley-Taylor’ was selected to calculate ET for the Rio Grande watershed because it has the capability to incorporate climatic data into the model. ‘Deficit and Constant’ is one of two loss methods compatible with the meteorologic method that computes ET. Due to the simplicity to estimate parameters for the ‘Deficit and Constant’ loss method (USACE 2009b), it was selected to calculate infiltration. ‘SCS Unit Hydrograph’ was the transform method because it generates “the standard shape of the unit hydrograph applicable across the United States” (USACE 2009b). ‘Recession baseflow’ and ‘Muskingum’ routing methods were suggested by

Kang and Ramirez (2007) to simulate long-term responses of streamflow to weather variability. The advantages of using these two methods include the capabilities of the 'Recession baseflow' to simulate both event-based and continuous models as well as of the 'Muskingum' routing method to account for streamflow attenuation.

Calibration, Verification, and Validation

Calibration

Calibration was applied to the first year of the 1971-2000 period to replicate the spring snowmelt peak. The calibrated parameters were the snowmelt threshold for the meteorologic model, the recession constants, the peak-to-baseflow ratio method, and the Muskingum X of the routing method which could not be estimated from the preprocessing of the watershed GIS data with HEC-GeoHMS. The parameters of the preliminary calibration were used to expand the model to simulate the first ten years of streamflows. The second round of calibration adjusted the parameters to best represent the ten-year trend from 1971 to 1980. A split sample test, as defined by Refsgaard and Knudsen (1996), suggested three to five years of data dedicated for the calibration and the same length period for the validation process. According to Yapo et al. (1996), a continuous model for eight years or more was a good representation of the long-term trend regardless of the time period of simulation. Once the results of the statistical error analysis on the calibrated model showed accurate reconstruction results, the ten-year calibrated model would be applied to the two following decades in the validation process to assess its effectiveness in making accurate predictions for periods other than the calibration period

(Refsgaard and Knudsen 1996).

Verification

Cunderlik and Simonovic (2004) suggested three statistical objective functions to analyze "goodness-of-fit" measurements of models.

1. Peak-weighted root mean square error (PWRMSE): giving greater weight to simulated errors near peak streamflows.

$$\text{PWRMSE} = \sqrt{\frac{\sum_{t=1}^{n}\left(\frac{Qo\,(t) - Qm\,(t)}{Qo\,(t)}\right)^2 \left(\frac{\mathrm{Qo\,(t)} + \mathrm{Qa}}{2 * \mathrm{Qa}}\right)}{n}}\;; \quad \mathrm{Qa} = \frac{1}{n}\sum_{t=1}^{n}\mathrm{Qo(t)} \qquad (1)$$

Q_O = observed streamflow

Qm = modeled streamflow

Qa = average of observed streamflow

2. Sum of squared residuals (SSR): giving more weight to larger errors and less weight to smaller errors.

$$\text{SSR} = \sqrt{\frac{\sum_{t=1}^{n}\left(\frac{Qo\,(t) - Qm\,(t)}{Qo\,(t)}\right)^2}{n}} \qquad (2)$$

3. Sum of absolute residuals (SAR): giving equal weights to all errors.

$$\text{SAR} = \sum_{t=1}^{n}\left|\frac{\mathrm{Qo\,(t)} - \mathrm{Qm\,(t)}}{\mathrm{Qo\,(t)}}\right| \qquad (3)$$

For event-based simulation, errors smaller than 5% indicate very high performance of models, whereas for continuous modeling, errors smaller than 10% are considered high "goodness-of-fit" measurements (Cunderlik and Simonovic 2004).

Three statistical objective functions were applied in the verification process to determine how the model performed at the Elephant Butte outlet of which observed streamflows were used in the ten-year calibration process. Statistical error analyses were also performed on the reconstructed 1971-1980 streamflows at two verification gauges, the Rio Grande near Del Norte, and the Rio Chama near La Puente, to measure the performance of the model not only at the outlet but also at other primary contributing gauges (Cunderlik and Simonovic 2004). The simulated data that constructed Figures III (a)&(b) were used in the error analyses of the verification process. The statistical results are summarized in Table III.

Table III: Statistical Error Analyses for Verification Process from 1971 to 1980

TABLE III	PWRMSE	SSR	SAR
Del Norte	7.6%	8.6%	2.5%
La Puente	7.2%	8.2%	2.4%
Elephant Butte	7.8%	9.1%	2.6%

At three locations, the unweighted errors (SAR) are smallest. It is intuitive that SAR averages out the large and small errors because they are equally weighted. The peak-weighted errors are slightly smaller than the weighted errors, which indicates there are more large errors elsewhere than in the vicinity of the peak flows.

The overall performance of the model is slightly lower at the Elephant Butte outlet than at the two upstream verification gauges because the streamflow of the Rio

Grande downstream from Cochiti reservoir as illustrated in Figure I is influenced by artificial interferences, such as release rules based on the flood control policy (Roach 2009), the minimum discharge requirement for the silvery minnow, well pumping, and the Albuquerque wastewater treatment plant release as described in USACE's Upper Rio Grande Water Operation Model (URGWOM) (USACE 2009c).

Validation

Validation is the process to assess the ability of the calibrated model to reconstruct measurements from input datasets other than those used for the calibration (Cunderlik and Simonovic 2004; Refsgaard and Knudsen 1996). In the validation process, all calibrated parameters should not be adjusted. The reconstructed streamflows were compared with the observed streamflows to determine the performance of the model outside of the calibration period. In the continuous models generated by Fleming and Neary (2004), and Cunderlik and Simonovic (2004), the time periods equal to or greater than three years were dedicated for calibration and the same time length for the validation. Conservatively, any time period of eight years and above is a good representation of the trend regardless of the selected years (Yapo et al. 1996). Once the ten-year calibration for the Rio Grande watershed proved highly accurate in the validation process, it would be expanded into a thirty-year continuous model to project streamflows outside of the time period of study. Similar statistical error analyses as presented for the verification were conducted for the validation process by applying equations 1, 2, and 3 to the reconstructed and observed discharges. The validation results at Del Norte and La Puente were plotted in Figures III (c), (d), (e), and (f). The statistical error analysis results for the validation process are summarized in Table IV.

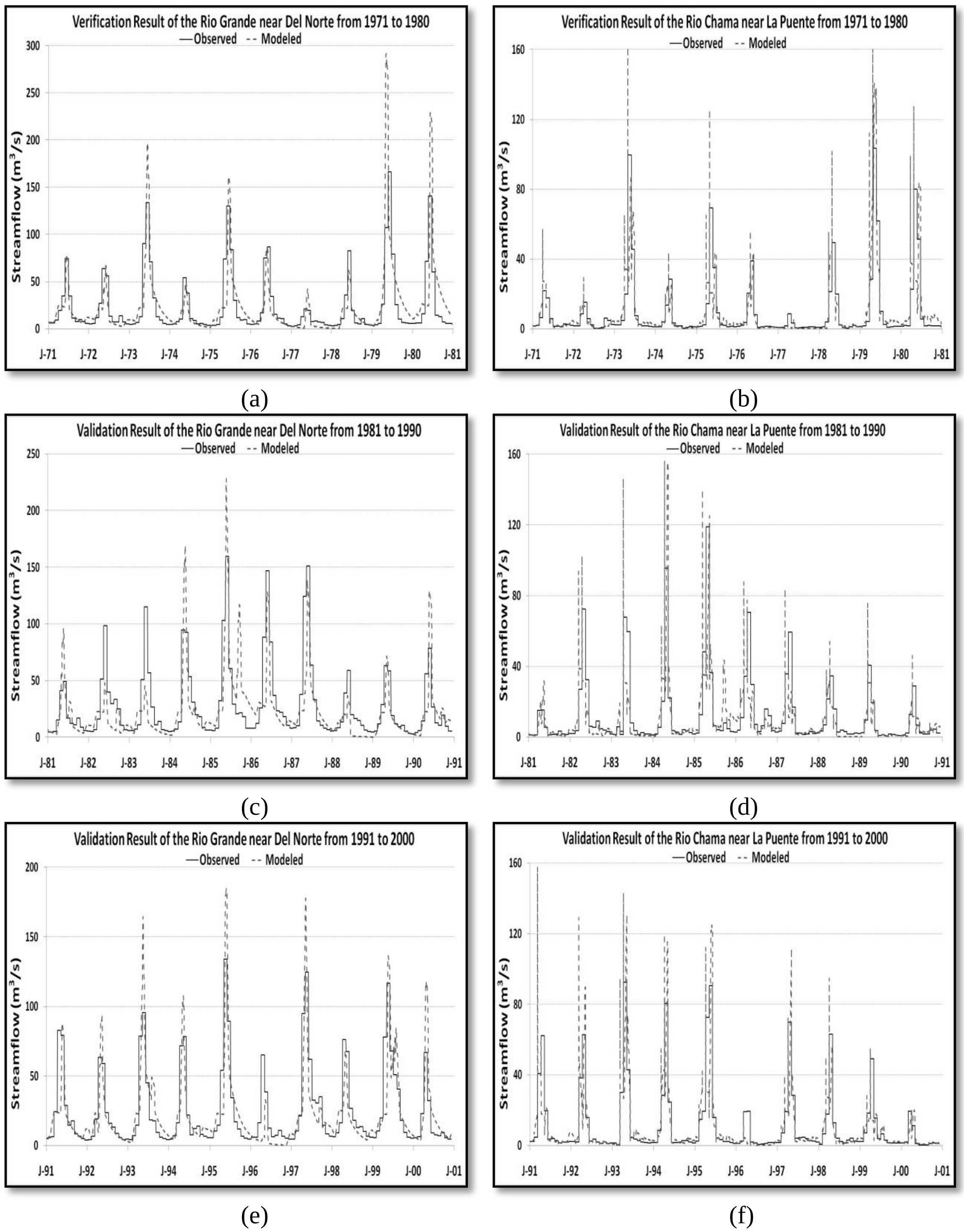


Figure III: Verification and Validation Results at Del Norte and La Puente

Table IV: Statistical Error Analyses for Validation Process

TABLE IV	PWRMSE			SSR			SAR		
	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000
	Calibration	Validation		Calibration	Validation		Calibration	Validation	
Del Norte	7.6%	7.1%	7.5%	8.6%	7.8%	8.6%	2.5%	2.3%	2.5%
La Puente	7.2%	6.7%	9.6%	8.2%	7.6%	11.1%	2.4%	2.2%	3.2%

The results from the last decade are not as strong as the previous one, especially for the La Puente sub-basin. La Puente average streamflow is about half of Del Norte average streamflow. Therefore, the same magnitude of discrepancies generated for the reconstructed streamflows would amplify the errors. Overall, the results of the statistical error analysis prove that the ten-year calibration period is long enough to represent the trend regardless of the selection of the calibration decade.

With statistically reasonable reconstructed results in the validation process, the ten-year model was expanded to the thirty-year model as seen in Figure IV to achieve the ultimate objective of this research which was to project thirty years of Rio Grande streamflow for the near future and long-term future climate change scenarios.

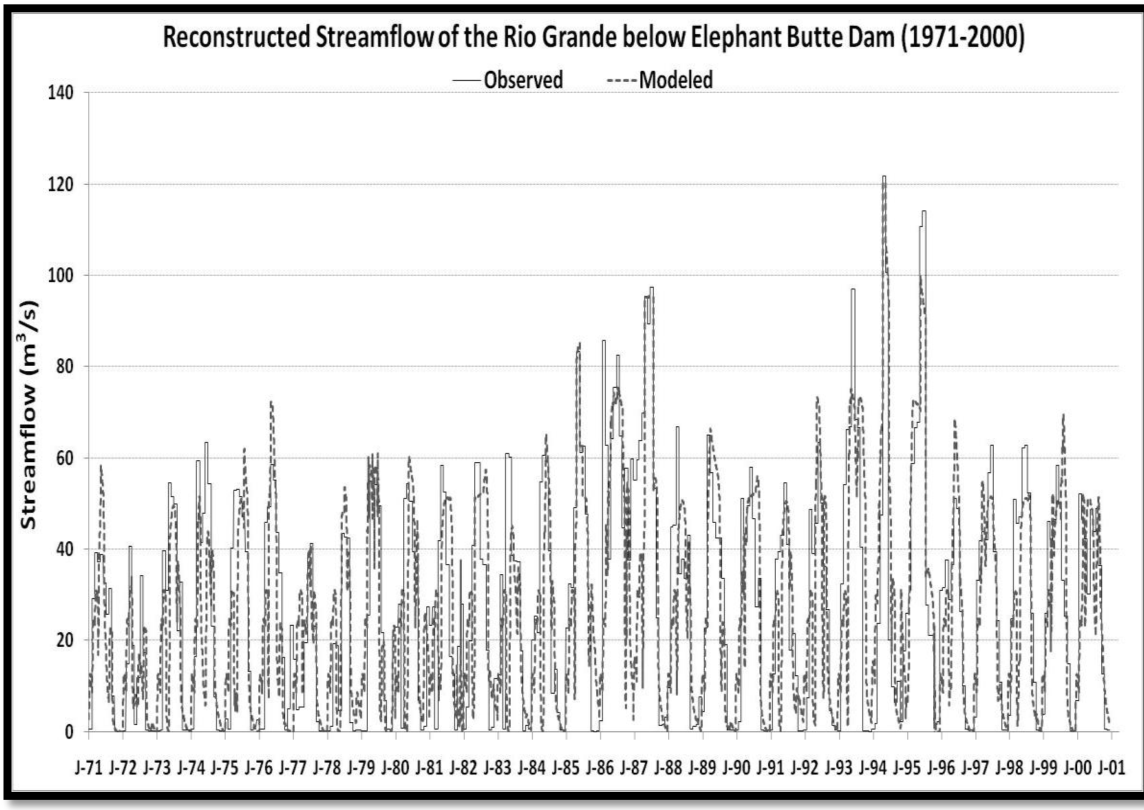


Figure IV: Observed versus Modeled Streamflow at Elephant Butte Outlet

To better visualize the modeled streamflows in Figure IV, the results at Elephant Butte were reported as monthly averages as seen in Figure V. HEC-HMS modeling is strictly the simulation of precipitation-runoff (USACE 2009b). It does not account for water withdrawal for irrigation, inputs from artificial tributary sources, such as the release from the Albuquerque Wastewater Treatment Plant, groundwater pumping, and return of irrigation flow to the Rio Grande (USACE 2009c). The modeled volume represented by the dotted line is lower than the observed volume which is influenced by 2.5 m^3/s wastewater discharge (Glass 2010), and 1971-2000 average groundwater pumping of 4.0 m^3/s for Albuquerque municipal use (USGS 2003). On the falling limb from July to

November, increased water withdrawal for summer irrigation lowers the observed discharge at Elephant Butte represented by the solid line. The transition from November to December of the observed discharge shows an increase in streamflow after irrigation stops in November.

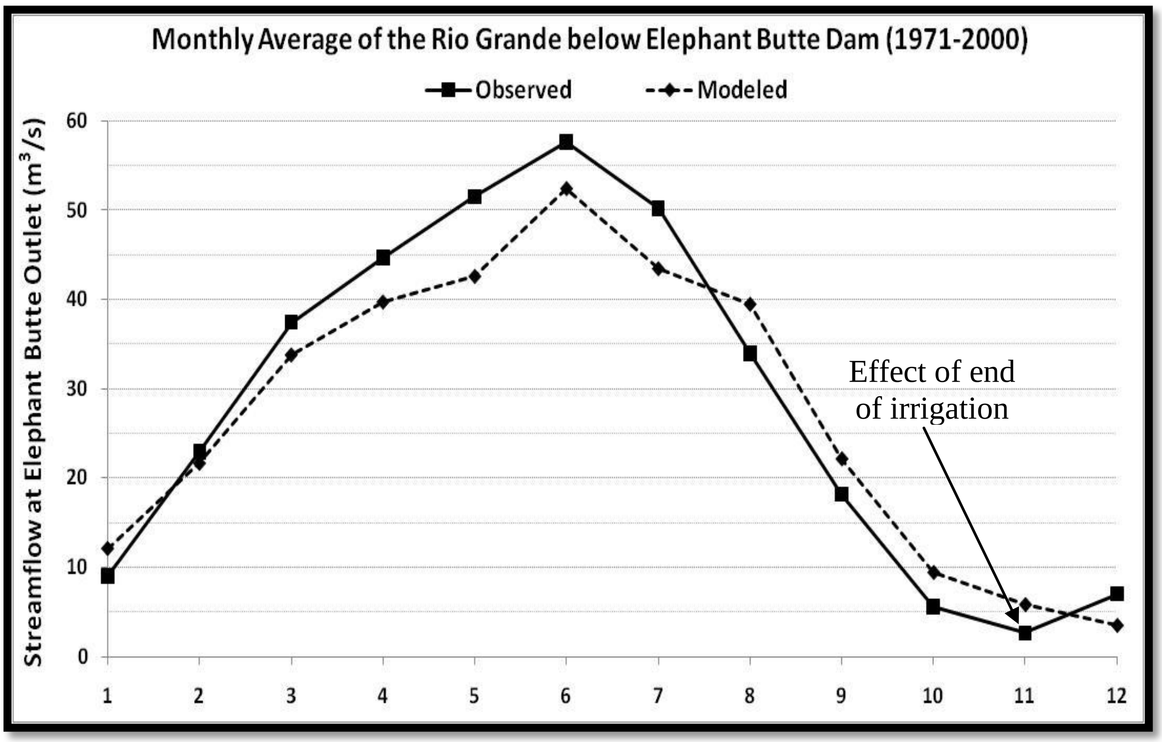


Figure V: Observed versus Modeled Monthly Average Streamflow at Elephant Butte Outlet

Streamflow Projection and Discussion of Results

Early study of the diurnal variations of temperatures in soils by Wollney (1883) and Bouyoucos (1913) indicated that at the depth beyond twenty centimeters, the change of temperatures between day and night of a loam soil during the summer was at most 2 ^{o}C. The maximum increase of temperature for the worst case scenario from Table I is nearly 6 ^{o}C which is approximately one-third of the diurnal variation in temperatures of a summer day. Soil temperatures affect water temperatures in soils, which have an impact on the hydraulic conductivity. As the temperature increases 1 ^{o}C above room temperature, the hydraulic conductivity drops to 98% compared to the value reported at room temperature (Das 2006). Therefore, it can be concluded that the magnitude of temperature changes under six climate impact scenarios do not affect the properties of sub-surface soil layers, and consequently do not impact the behavior of the watershed in the future.

Streamflow Projection

The thirty-year calibrated model used the projected climate change scenarios from Tables I & II to estimate future streamflow of the Rio Grande. The results for Elephant Butte outlet and Otowi gauge were extracted and reported as annual average fractional volume change as summarized in Table V. Based on the results from Table V, the projection for the worst and best case scenarios were reported as monthly averages and plotted in Figure VI. The changes in temperature associated with these two extreme scenarios were plotted above the projected hydrographs to show the direct correlation of the temperature increases with the projected monthly averages.

Table V: Projection of Total Average Annual Fractional Volume

TABLE V	Index Gauge	2030			2080		
		Wet	Middle	Dry	Wet	Middle	Dry
% Volume Change	Elephant Butte	-8.5%	-13.3%	-26.3%	-38.3%	-47.7%	-54.5%
	Otowi Gauge	-10.8%	-14.0%	-25.4%	-17.0%	-32.2%	-35.8%

Discussion

The calibrated HEC-HMS model used the time-series input data from the period 1971-2000 to reconstruct the streamflow of the Rio Grande before it was applied to project the streamflow for different climate change scenarios with the assumption that the watershed would behave simiarly in the future as it did for the period of study. This assumption was validated by early analyses that the hydraulic conductivity of sub-surface soils were not impacted (Wollney 1883; Bouyoucos 1913) by slight changes such as the projected temperature due to global warming in Table I. Secondly, the projected streamflow were the modeled runoff from the watershed based on the projected climatic data from the GCM model. Given the great uncertainty inheritent in climate change scenarios, the range of projected streamflow as summarized in Table V could be used in associated with other models for the Rio Grande as guidelines for future regional water availability assessment.

Table V shows the fractional volume decreases under six climate change scenarios for Elephant Butte oulet and Otowi gauge. The projected changes for the near future scenarios are very similar at two locations. Long-term projected changes at Elephant Butte outlet are more severe than at Otowi. This indicates that the watershed downstream from Otowi will be more sensitive to climate change impacts.

At lower elevation areas in the watershed such as the sub-basins downstream from Otowi, due to warmer temperature projection as described in Table I, there will be more snow-on-rain effects in the winter months, which increases winter runoff and decreases summer reservoir storage (Detting et al. 2004). Warmer temperatures also result in more evapotranspiration in the summer months, which amplifies the projected effect of decreased summer water storage. The delivery obligation does not take into account more severe climate change impacts that the lower half of the Rio Grande watershed will encounter. Therefore, in order to maintain the water supply for its increasing water demand, New Mexico will face significant delivery debt to Texas. However, the cumulative debt cannot exceed the cap which New Mexico encountered during the 1971-2000 period (UFW 1999), the "no-climate-change-impact" baseline. Being able to solve the future water budget problem will be a tough task for New Mexico water management authorities.

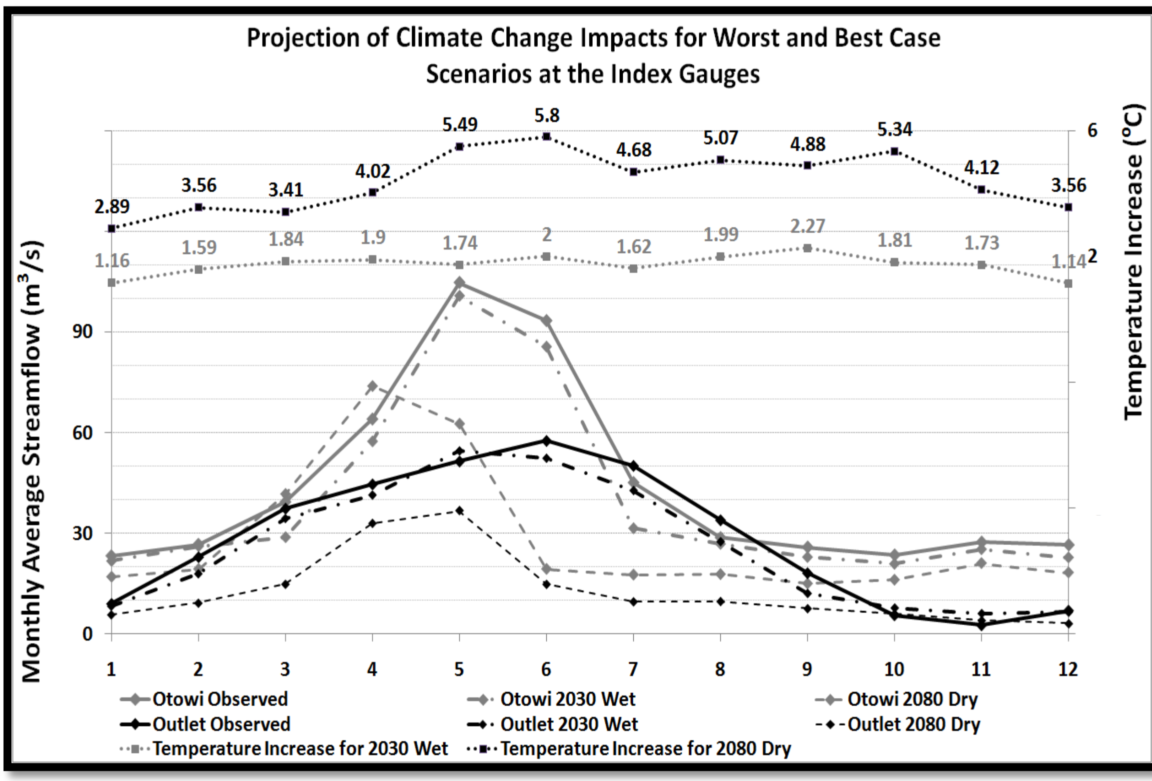


Figure VI: Projection for Worst and Best Case Scenarios at the Index Gauges

Another significant impact of the severely altered climate is the shift of peak streamflows as seen in Figure VI. Consequently, peak evaporation will also shift to early spring due to decreased soil moisture in the summer months (Dettinger et al. 2004). This puts more stresses on native vegetation, which can affect their health and regeneration processes. Other aspects of New Mexico lifestyles will also be interrupted by the peak shift phenomena. Summer river rafting in northern New Mexico will be restricted by low water level in the river; summer irrigation will be limited; declined summer reservoir storgage will have negative impacts on summer water activities. And there are many more hydrologic, economic, cultural, and ecological consequences that cannot be quantified due to limitations of human understanding.

Conclusion

This study explored the continuous modeling capability of HEC-HMS to calibrate a precipitation-runoff model for the Rio Grande watershed stretching from the headwaters above Del Norte, Colorado, to Elephant Butte, New Mexico. The model was then applied to project streamflows of the Rio Grande below Elephant Butte Dam, and of the Rio Grande at Otowi Bridge under different climate change scenarios, the gauges defining New Mexico's delivery according to the Rio Grande Compact. The model helped to project how well New Mexico would comply with the delivery obligation.

New Mexico has had time periods when it exceeded the delivery obligation as well as when it failed to meet the requirement of the Rio Grande Compact (UFW 1999). Projections of significantly decreased water availability during the warmest months of the year when water is needed the most will negatively impact the scarce water supply for human consumptions, agricultural and industrial uses, and ecological sustainability in New Mexico. For the near future projection when the streamflows of the index gauges decline at the similar rates as indicated in Table V, New Mexico will be entitled to less water apportions because New Mexico depletion entitlement is proportional to the incoming streamflow at the upstream index gauge at Otowi. However, the long term projections at Elephant Butte outlet decline more dramatically than those at the upstream index gauge. There is no doubt that New Mexico will not be able to fulfill its delivery obligation based on the six climate change scenarios. The task to allocate water effectively to meet increasing water demands of New Mexico and to ensure the fulfillment of its delivery obligation in the future will be very challenging to the water management authorities.

Acknowledgments

The authors would like to thank US Fish and Wildlife Service in Albuquerque for funding the research on numerical modeling for the streamflow of Bosque Del Apache Wildlife Refuge which laid the foundation for the topic of this study.

APPENDIX A: INTRODUCTION

The primary water supply for the western United States is from groundwater, and surface water. The significant increase in population in the area coupled with regional droughts within the last twenty years has created chronic water shortages. The use of all near surface water resources has exceeded the sustainable supply of the area.

Additionally, the uncertainty of potential impacts of global warming has complicated the issues. Most global climate change scenarios project warmer winters, which results in reduced snowpack and increased winter spills due to rain-on-snow effects. The peak streamflow will shift from spring/early summer to early spring, and peak evaporation will happen in early spring due to less soil moisture in the summer. There will be significant loss in winter precipitation storage in snowpack, subsequently lower reservoir levels in the summer and fall. This substantially affects the scarce water supply in the west for human consumption, agricultural and industrial uses, and ecological sustainability (Dettinger et al., 2004.)

Area of Study

The watershed that drains into the Elephant Butte reservoir, as illustrated in Figure 1, is located in two states, New Mexico and Colorado. The headwaters of the Rio Grande originate in the San Juan Mountains in Colorado. The Elephant Butte outlet in New Mexico was selected as the pour point of the watershed. The results generated by the calibrated hydrologic model at the outlet represents the amount of water New Mexico delivers to Texas. The projection of the streamflow under different scenarios of climate change at this outlet were used in conjuction with the projection for the Rio Grande at Otowi bridge to quantify how well New Mexico would meet its obligations to deliver water to Texas under the requirements from the Rio Grande Compact.

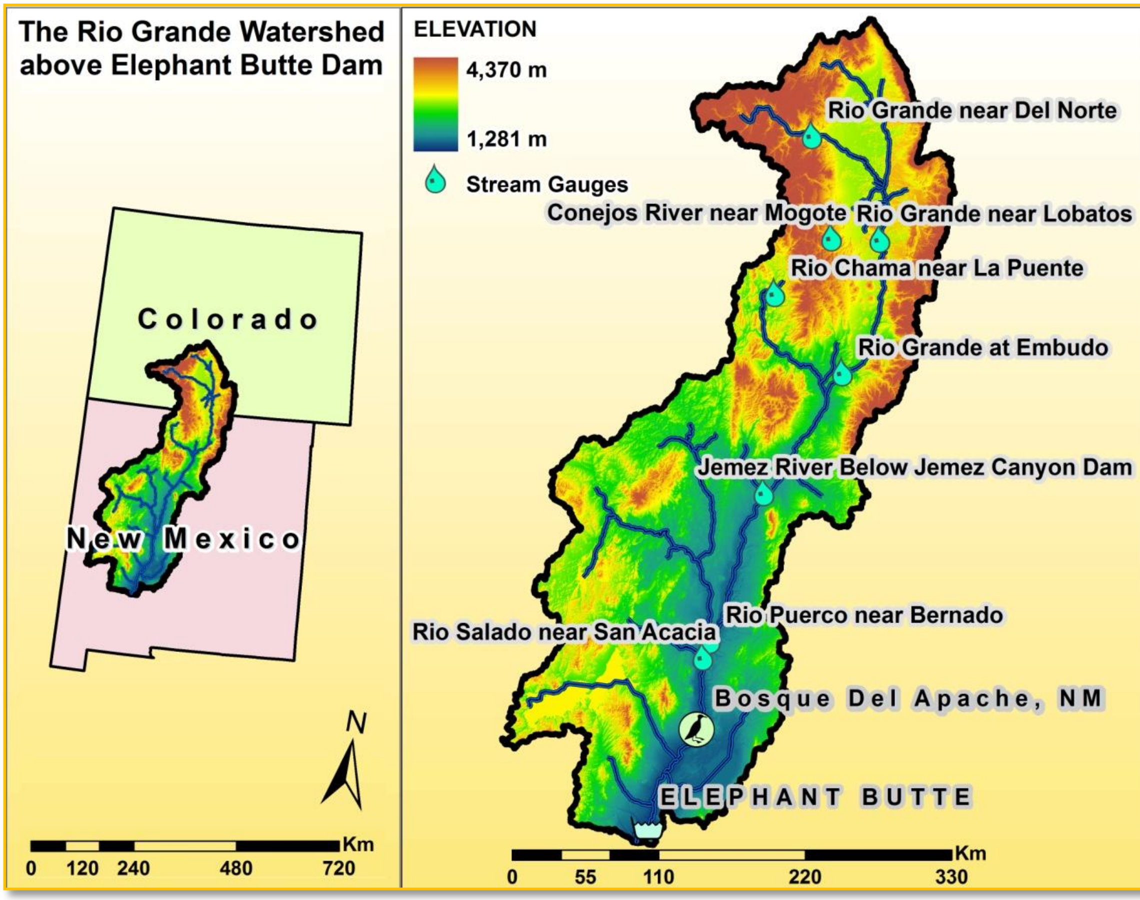


Figure 1: Rio Grande Watershed above Elephant Butte Dam

Climate Variability

Tree-ring reconstructed streamflow for New Mexico streams suggested that the region had experienced a variety of climate extremes. Neither the droughts from the period 2001-2005 nor in the 1950s surpassed the severity of nine driest episodes in the past five hundred years (Hurd and Coonrod, 2008.) In the 1980s, New Mexico has also seen the wettest water years of the most recent five decades.

Climate extremes are not unprecedented in the area. From eighteen climatic models presented in the Inter-governmental Panel on Climate Change's Fourth Assessment Report (IPCC 2007), Smith and Wagner (2006) selected models with the A1B greenhouse gas emission level, also known as the "business as usual" economic activity assumption, to suggest three optimal climate scenarios to best represent the range of outcomes of New Mexico climate: wet, middle, and dry. Smith and Wagner (2006) coupled the three scenarios with two future periods to generate six climate change scenarios:

- Near term: 2030 Dry, 2030 Middle, and 2030 Wet
- Long term: 2080 Dry, 2080 Middle, and 2080 Wet

Table 1 summarizes the projection of precipitation as percentage changes compared to the measurements of the current trend from 1971 to 2000. Table 2 summarizes the projection of temperature as changes in Fahrenheit degrees with respect to the observations from the period of 1971-2000.

Table 1: Projection of Precipitation Changes for Six Climate Change Scenarios

% Change	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average Change (%)
2030 Dry	4.78	1.58	12.11	-9.46	-27.61	-35.06	-27.28	-24.92	-19.25	3.54	-0.97	4.24	-9.86
2080 Dry	-14.25	-7.29	-0.85	-28.2	-53.79	-36.43	-16.69	3.12	-11.8	-3.32	-19.35	1.7	-15.60
2030 Mid	1.69	-8.46	-7.1	-0.16	-9.19	-3.49	13.49	-5.1	13.92	8.23	7.28	-4.58	0.54
2080 Mid	0.88	-6.43	-8.46	-12.61	-24.6	-6.73	-0.46	-15.71	-6.63	-4.06	-18.46	-24.46	-10.64
2030 Wet	4.14	-8.55	-12.18	-6.25	9.32	7	22.23	21.04	8.59	-13.83	-4.73	-5.62	1.76
2080 Wet	0.82	-12.54	-9.64	8.84	17.91	15.99	33.05	55.95	-6.28	-14.22	-15.9	-5.96	5.67

Table 2: Projection of Temperature Increases for Six Climate Change Scenarios

Δ Temp (F)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average Change (F)
2030 Dry	1.5	2.1	2.3	1.9	3.5	5.4	4.7	4.4	3.0	3.7	3.4	2.0	3.2
2080 Dry	5.2	6.4	6.1	7.2	9.9	10.4	8.4	9.1	8.8	9.6	7.4	6.4	7.9
2030 Mid	1.4	1.6	1.8	1.9	2.1	2.6	1.3	2.7	2.0	0.8	1.6	0.8	1.7
2080 Mid	5.1	4.6	4.2	4.8	6.1	7.5	5.7	6.9	6.5	4.9	5.4	4.4	5.5
2030 Wet	2.1	2.9	3.3	3.4	3.1	3.6	2.9	3.6	4.1	3.3	3.1	2.1	3.1
2080 Wet	5.1	5.5	5.8	5.9	5.8	6.2	5.5	6.2	7.8	6.8	5.9	4.9	5.9

Research Objectives

The 2080 Dry scenario from Table 1 and Table 2 indicates the most drop in precipitation which is worsened by the most increase in temperature. How does the long term Dry scenario complicate the current water scarcity issue in the region? The 2080 Wet scenario suggests the second highest increase in temperature. Does the increase in precipitation for 2080 Wet projection offset the evapotranspiration rate to minimize changes in streamflow of the Rio Grande? Does the projection for 2030 Middle scenario with the least increase in temperature and slightly increase in precipitation help to ease the regional water shortage? And how do the temporal and spatial aspects of hydrologic modeling affect the overall outcomes?

HEC-HMS 3.4, a rainfall-runoff modeling approach developed by the US Army Corps of Engineers, was employed to find answers for possible responses of the streamflow of the Rio Grande under six climate change scenarios suggested in Table 1 and Table 2. The period of study was selected from 1971 to 2000 to capture the variability of New Mexico climate as seen in Table 3. The averages of the 1942-2010 period streamflows of four gauges, the Rio Grande near Del Norte, the Rio Grande at

Otowi Bridge, the Rio Grande at Albuquerque, and the Rio Grande below Elephant Butte Dam, were compared with the means from three decades, 1971-1980, 1981-1990, and 1991-2000. The 1971-1980 decade exhibited the dry trend by significant repeated drops of streamflow averages. The 1981-1990 decade represented the wet trend by continuous large increases of streamflow averages.

Table 3: Variability of Streamflow of the 1971-2000 Period

TABLE 3	% Streamflow Change of Rio Grande near Del Norte, CO			% Streamflow Change of Rio Grande at Otowi Bridge, NM			% Streamflow Change of Rio Grande at Albuquerque, NM			% Streamflow Change of Rio Grande below Elephant Butte Dam, NM		
	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000
Jan	-5.0%	18.3%	7.3%	-1.3%	22.1%	23.9%	1.8%	34.8%	26.2%	-55.1%	54.4%	-22.7%
Feb	-5.0%	16.3%	4.1%	-18.7%	32.3%	17.6%	-14.2%	52.3%	8.9%	-55.4%	57.7%	17.3%
Mar	-3.6%	14.2%	11.8%	-10.8%	41.7%	20.6%	-5.9%	58.1%	23.5%	-10.8%	2.2%	25.9%
Apr	-18.4%	2.9%	-7.7%	-22.0%	50.1%	10.9%	-23.7%	42.4%	13.5%	-11.4%	27.8%	13.0%
May	-10.1%	1.9%	4.8%	-8.2%	25.8%	14.9%	-2.7%	9.0%	13.4%	-10.1%	41.9%	27.2%
Jun	9.8%	19.4%	-2.2%	7.7%	27.5%	21.7%	2.6%	16.7%	33.8%	-9.5%	14.6%	40.5%
Jul	12.6%	19.5%	5.1%	25.3%	19.8%	27.1%	43.0%	65.0%	27.6%	-7.7%	11.6%	21.4%
Aug	-18.8%	22.1%	5.5%	-10.5%	-2.0%	28.7%	-22.2%	26.3%	37.0%	-15.0%	7.1%	4.1%
Sep	-29.3%	29.8%	36.3%	-16.4%	21.7%	53.7%	-28.5%	46.8%	73.5%	-42.3%	27.3%	43.1%
Oct	-24.5%	42.6%	17.7%	-4.7%	33.0%	46.7%	-31.7%	45.8%	74.2%	-95.6%	-3.6%	44.3%
Nov	-16.4%	39.6%	10.6%	4.8%	16.1%	1.0%	13.7%	7.8%	13.3%	-79.8%	42.7%	-83.8%
Dec	-11.3%	21.5%	8.4%	21.0%	11.6%	4.4%	19.0%	17.1%	8.3%	16.7%	70.1%	-66.8%

From the data for precipitation and temperature from the period of 1971-2000, the model was first calibrated against the observed streamflow at the Elephant Butte outlet. With the inputs from the potential temperature and precipitation for six climate change scenarios, HEC-HMS generated the hydrographs that represented plausible projected streamflows for the area of study. The projected hydrographs would be used in conjunction with the projection at Otowi to measure how well New Mexico would fulfill its delivery obligation to Texas.

APPENDIX B: LITERATURE REVIEW

Climate Change and Its Implication for New Mexico's Water Resources and Economic Opportunities by Hurd and Coonrod, 2008

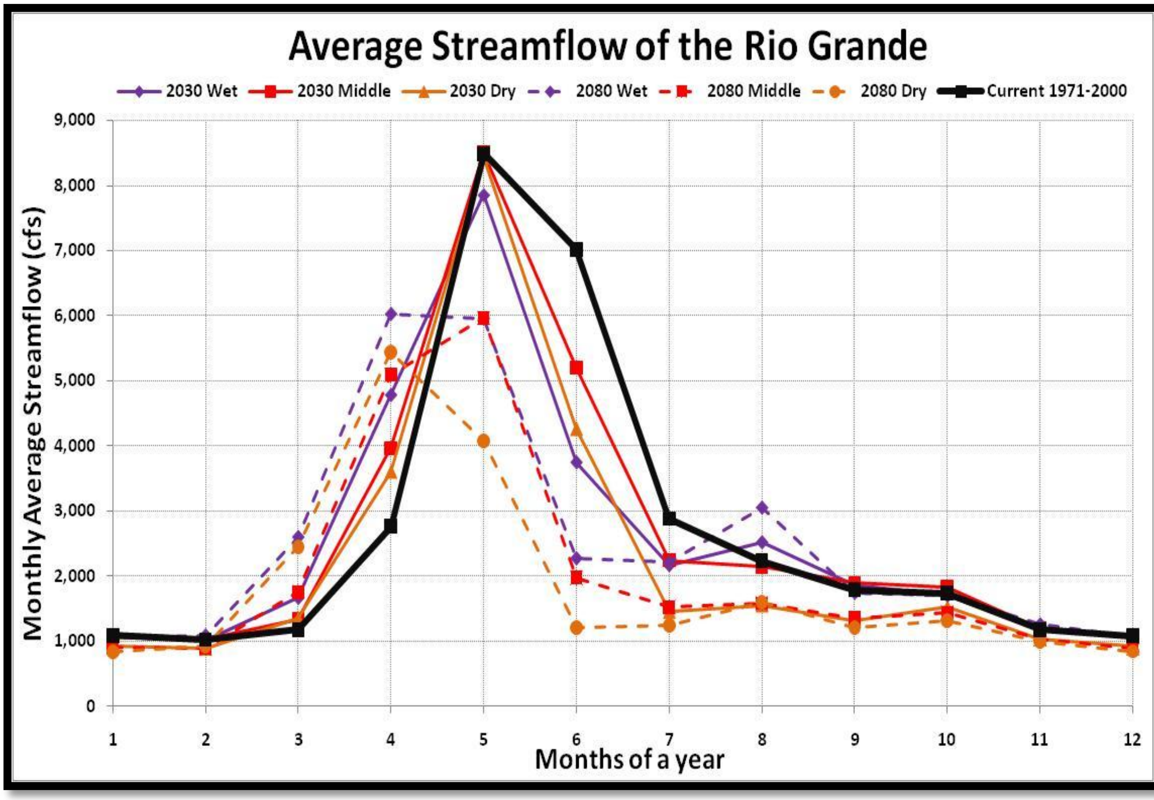


Figure 2: Projected Streamflows for the Rio Grande

With the desire to generate the streamflow inputs for the hydro-economic model for New Mexico, WATBAL, a computational approach to study the impact of a potentially altered climate on river basin runoff (Yates D., 1996) was adopted to simulate the streamflow of the Rio Grande above Elephant Butte. Thirty years of monthly average streamflow, and spatially averaged temperature and precipitation data from eight gauged tributary watersheds to the Rio Grande above Bosque Del Apache National Wildlife

Refuge were collected to calibrate eight individual WATBAL models. With the inputs as potential temperature and precipitation for each climate change scenario suggested by Smith and Wagner (2006), the WATBAL calibrated models were used to project streamflows for six different climate change scenarios. The results were reported as monthly average streamflow as seen in Figure 2 which shows significant drops in projected total annual volumes and one-month peak shift under all climate change scenarios.

Calibration, Verification, and Sensitivity Analysis of the HEC-HMS Hydrologic Model by Cunderlik J. and Simonovic S., 2004

The study by Cunderlik and Simonovic presented the calibration and verification of the HEC-HMS models for the event-based and continuous hydrologic simulation for the ***gauged*** Upper Thames River basin (UTRb.)

For each model, a river basin was created. It included sub-basins, reaches, reservoirs, junctions, diversions, sources and sinks in a hydrologic order specified by the project. The appropriate methods for loss, transform, and baseflow were selected for each basin based on the characteristics of the basin. An important process of their project was to create a meteorologic model which modeled precipitation as rainfall or snowmelt and evapotranspiration. The inputs for the meteorologic model were created from time-series data from rain gauges, temperature gauges, solar radiation gauges, and stream gauges. The paired-data component was created to define the snowmelt rate which closely represented the snowmelt process of the watershed. The only difference between the event-based and the continuous simulation was the time periods (control specifications) over which the models were run.

The calibration was performed for the period of 1979 to 1988. The calibrated model was used for the period 1988 to 1997 to verify how closely the modeled results represented the observed streamflow from the stream gauges defined in the time-series data component. Adjustments were made for different parameters initially used in the models until the modeled streamflow was a good representation of the observed data.

The calibration and verification results presented in their study were used in another task to assist the case study to assess risks and vulnerability of UTRb.

Hydrological Study for a Mini-hydropower Plant in the Pyrenees by Colombie M., 2007

This study focused on the ***ungauged*** watersheds, Le Moulin and Le Siouré, in the Pyrenees to analyze the feasibility of a power plant. Ten kilometers upstream from Le Moulin and Le Siouré, L’Artigue River has historical daily streamflow for forty years which was used to generate streamflows for the area of study.

Two approaches were introduced: statistical, and numerical using HEC-HMS. The research team surveyed the two streams in the area of study to take measurements of the streamflows and correlated them with the gauged upstream flow of L’Artigue River. The hydrographs from HEC-HMS were calibrated against the statistical results.

Because the soil cover of the area of study was unknown, the calibration results did not well represent the streamflows by the statistical approach which was more appropriate for ungauged watersheds.

New Modeling Capabilities in HEC-HMS Applied to Mill Creek Basin by Fleming M. and Harris J., 2006

The scope of the project was to perform event-based and continuous hydrologic analysis to evaluate the existing flood control system, and the feasibility to implement environmental restoration for the Mill Creek Basin in Nashville, Tennessee. Another requirement of the project was to minimize the area of the sub-basins to be less than or equal to 1.3 square miles.

HEC-HMS was adopted to perform the analysis. Radar precipitation and historical streamflow data were used to calibrate the event-based and continuous models. With the GIS tools newly developed for HEC-HMS of version 3.0 and later, HEC-GeoHMS, it is capable of building ***gridded*** hydrologic models. For instance, instead of averaging the precipitation for the sub-basin, each grid cell carries its own value, which increases the level of detail and accuracy of the analysis.

The soil data from State Soil Geographic Database (STATSGO) was used to build a gridded soil cover file. Another new capability of HEC-HMS is the gridded and deficit loss method, which tracks the moisture state in each cell. The gridded Priestly-Taylor evapotranspiration method, also a new tool in HEC-HMS, is an alternative for the monthly constant values method which does not capture the fluctuation of future projected temperatures that can alter the evapotranspiration rate and the water balance for the watershed.

New capabilities added to HEC-HMS, for instance applying advanced gridded basin models versus lumped models, provided more flexibility in using GIS input data to more accurately simulate continuous hydrologic models.

Recent Variations in Temperature, Precipitation, and Streamflow in the Rio Grande and Pecos River Basins of New Mexico and Colorado by Hall A. et al, 2006

Daily temperature and precipitation data were collected for the Rio Grande and Pecos River from the National Oceanic and Atmospheric Administration’s (NOAA) National Climate Data Center (NCDC). The period of analysis was from 1960 to 2000 with nearly complete records. Two statistical analysis approaches were used to analyze climatic and hydrologic trends of the two basins. Decadal means from two periods of 1976-1985 and 1986-1995 were calculated to evaluate the significance of differences. The other statistical approach was to describe the monotonic trends of the entire time-series from 1960 to 2000.

From a cross reference in the work from Hall et al. (2006), the trend of warming in the continental US from 1950 to 1999 was associated with change of land use. However, they did not find any consistent association between population centers and temperature increase.

The precipitation stations were grouped into four clusters based on the trends monthly precipitation changed in the period of analysis. A lot of clusters showed moderate to strong increases in precipitation from January through March. The precipitation from June through September showed decreases ranging from weak to moderate confidence levels.

The streamflow at different stations were plotted to detect the peak shifts and volume changes. The first half of the time-series records had more annual volume than the second half. The second half of the period also exhibited spring runoff starting sooner and ending earlier. Two decadal records of 1976-1985 and 1986-1995 were analyzed to detect their streamflow patterns. The second decadal plot showed shifts in magnitude and timing of spring runoff, though the maximum flow rate did not significantly decrease.

Response of Streamflow to Weather Variability under Climate Change in the Colorado Rockies by Boosik Kang and Jorge A. Ramírez, 2007

The South Platte River basin is located in three states, Colorado, Wyoming, and Nebraska. The area of study was one of the nineteen sub-basins of the watershed, the headwaters sub-basin at the upstream end of the river system.

The model used the downscaled climate outputs from the second version of the Global Climate Model and Climate Change Scenario (CGCM2) to generate precipitation gridded datasets under different climate change scenarios. HEC-HMS and the ArcGIS® geospatial extension were used to delineate the area of study. The gridded soil moisture accounting method computed infiltration. The transform method was ModClark. The calibration was for three months in 1997, June, July, and August. The simulation was run for two time windows, 2011-2020 and 2081-2090.

The average modeled runoff decreased by 15.4%. However, more important than the total volume decrease, the statistical analyses of the modeled outcomes showed that small changes in the trends or variability of rainfall can result in amplified variability of streamflows, because those precipitation trends closely correlate to trends in evaporation.

Though precipitation is the primary input for any rainfall-runoff simulation, impacts of climate change scenarios that can alter other variables of the water balance equation such as evaporation and soil moisture storage could greatly affect runoff and water availability.

Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming by David Clow, 2010

The western United States receives little precipitation in the summer months. The area relies mostly on winter and early spring snowfall that can be stored for agricultural, industrial, environmental, and human consumption. Recent studies in the West have found consistent decrease in snowpack accumulation and natural water storage. This work used a statistical approach, the regional Kendall test (RKT), to detect the trend in timing of snowmelt and associated runoff by combining data from different stations in Colorado for the period of 1978-2007. The elevation of the SNOTEL stations ranged from 2,560 m to 3,526 m.

The Snow Water Equivalent data for SNOTEL sites were used as input data to assess the timing of snowmelt. These SNOTEL stations also provided data on temperatures to analyze the warming trend. Daily streamflow from 58 headwaters in

Colorado were taken from USGS database as input data to evaluate the timing of runoff associated with snowmelt.

Unlike previous studies which used regression methods to detect trends of snowmelt and runoff associated with climate variability, the RKT test is a non-parametric method which is resistant to missing data and outliers. Besides, the method performs very well in grouping data in a region, therefore, possesses more power to detect trends in short datasets.

The results showed that snowmelt occurred 4.8 days/decade earlier, and half of the snowpack melted 4.5 days/decade earlier. The temperatures from November to May increased 0.9 ^{o}C/decade, and snow water equivalent amount dropped 4.0 cm/decade.

The study sent out a strong message to water resource management authorities that high-elevation mountains in Colorado would not be exempt from impacts of climate change scenarios that would decrease natural water storage for the Western United States.

The Effect of Climate Change on River Flow and Snow Cover in the NOPEX Area Simulated by a Simple Water Balance Model by Xu C. and Halldin S., 1997

The increase in CO_2 concentration in the atmosphere causes changes in global temperatures and precipitation. With the plausible assumption of double CO_2 emission by the end of the 21st century due to exponential economic and population growth, temperatures in the northern hemisphere could increase from 3 ^{o}C to 5 ^{o}C by 2100 which are associated with 15% change in precipitation. This would greatly impact every aspect of human well being, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management.

From four original climate scenarios ranging from 1 ^{o}C to 4 ^{o}C increases in temperature and 10% to 20 % increases in precipitation, eight different combinations of climate change scenarios were developed for the model which was based on the monthly water balance principle. Inputs of the model were monthly values of areal precipitation, long-term average potential evapotranspiration and air temperature. Outputs of the models were river flow and other water balance components, such as evapotranspiration, soil-moisture storage, accumulation of snowpack, etc. Observed streamflows in the area were available for eleven years from 1981 to 1991 for calibration of the model.

The study analyzed modeled annual and monthly average discharges. The annual increase in runoff were directly associated with increase of precipitation. The monthly modeled streamflows showed significant redistribution of monthly discharges. Sharp increases in runoff of the winter months led to decrease in snow accumulation by 50%. Warmer temperature trends resulted in spring runoff occurring one month sooner, from April to March. Streamflows of the summer months were not significantly affected because increased evaporation offset increased precipitation.

APPENDIX C: RESEARCH APPROACH

Data Collection

The surface data included terrain, soils, and land cover. The most common terrain data come in the form of digital elevation model (DEM) which could be downloaded from the USGS GeoScience Eye Toolkit.

http://cumulus.cr.usgs.gov/GS_Toolkit/

The source of soils and land use data were from the State Soil Geographic Database (STATSGO). The data could be extracted based on the latitude and longitude boundaries of the area of interest.

http://www.soils.usda.gov/survey/geography/statsgo/

The period for time-series data collection was selected from 1971 to 2000, since it captured the variable climate extremes of New Mexico as illustrated in Table 3. The historical monthly streamflow data for gauges of interest were collected from the United States Geological Survey (USGS) database.

http://waterwatch.usgs.gov/?m=real&r=nm&w=map

Unlike the streamflow data which are measured for specific locations, the monthly precipitation and temperature data from PRISM Climate Group's website are continuous surfaces for the entire United States. They were downloaded as a whole for

360 months, and processed in ArcGIS® to reduce to the size of the area of interest.

HEC-HMS 3.4, Hydrologic Modeling System

HEC-HMS 3.5 is the latest version of the hydrologic modeling system developed by the US Army Corps of Engineers. However, the research started before HEC-HMS 3.5 was developed. Therefore, HEC-HMS 3.4 was the primary computational models for this research to simulate and project streamflows in the study area under the impacts of climate change as described in Table 1 and Table 2. Two geospatial tools, ArcGIS® 9 and its associated hydrologic modeling extension, HEC-GeoHMS, helped to generate the basin background maps and to perform calculations and transformation of gridded time-series data.

Structure of a Project in HEC-HMS 3.4

To start a project, a basin has to be created. Seven possible hydrologic elements of a basin model include: sub-basins, reaches, reservoirs, junctions, diversions, sources, and sinks. However, it is not necessary to have all seven elements in a basin model. The delineation of the basin into sub-basins and the creation of the stream network can be performed with ArcGIS® spatial analyst tool. The delineated map of the basin and the stream network can be imported from ArcGIS® for better visualization of the locations of all basin elements and their hydrologic orders. The screen capture of a basin model is illustrated in Figure 3.

For every hydrologic element, there are some properties that are required in order to perform the hydrologic simulation, and there are some other optional properties that can help in the calibration process. Examples of required properties are the area for a sub-basin, the Muskingum K and X values for the selected Muskingum reach routing method of a reach, and the storage discharge function as well as the elevation storage function for a reservoir. Examples of optional properties are the observed streamflow time-series data for a sub-basin, a reach, and a reservoir to validate the modeled streamflow.

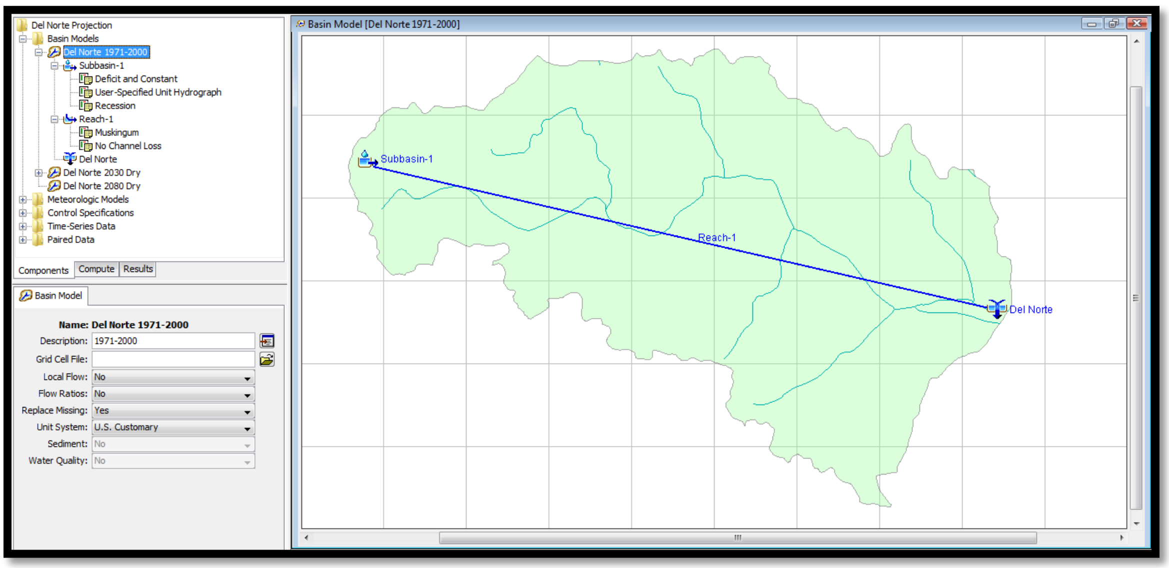


Figure 3: Interface of a Basin Model in HEC-HMS 3.4

After the basin is created, the meteorologic model (illustrated in Figure 4) has to be defined to replicate the weather condition of the basin. Three elements of a meteorologic model include precipitation, evapotranspiration, and snowmelt of which measured or projected time-series data are created in Time-Series Data Manager and Paired Data Manager. Examples of time-series data created in Time Series Data Manager are precipitation and temperature gridded data. Examples of time-series data created in Paired Data Manager are gauges or users' specified unit hydrographs, snowmelt rate functions, and elevation storage functions as well as storage discharge functions. There are several methods for each meteorologic element; however, there are some restrictions on combining them with some properties of some basin model elements. For instance the deficit and constant, gridded deficit and constant, soil moisture accounting, and gridded soil moisture accounting loss methods of a basin should be used in combination with a meteorologic method that computes evapotranspiration (US Army Corps of Engineers, HEC-HMS 3.4, Hydrologic Modeling System.)

A hydrologic simulation run cannot be accomplished without the time period over which the model is run. The control specifications (illustrated in Figure 4) dictate when the simulation starts and stops as well as the time interval. If the time-series data do not have the same time interval as the control specifications, the data will be interpolated linearly. The maximum possible time interval value is one day, and the minimum possible time interval value is one minute. The time-series results will have the same time interval with the control specification.

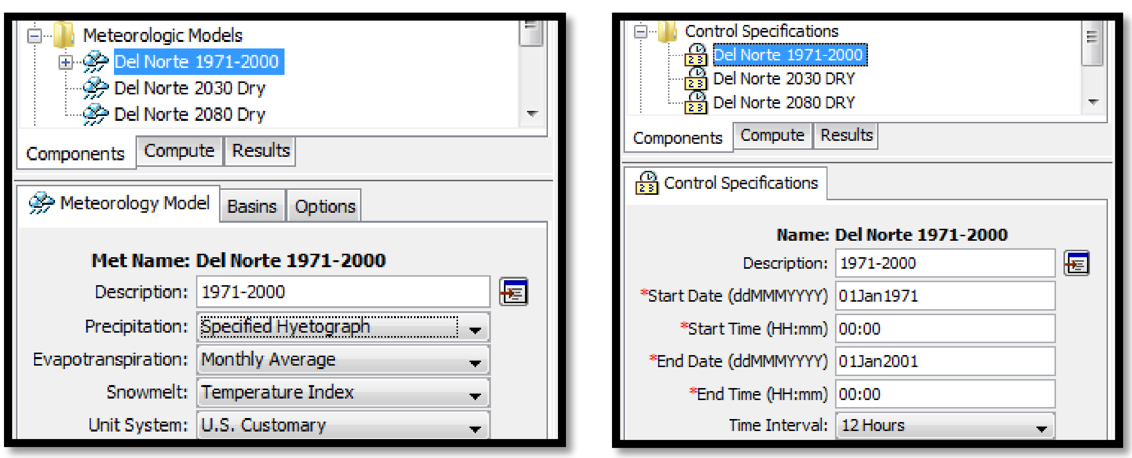


Figure 4: Examples of a Meteorologic Model and the Control Specifications

Model Diagram

The continuous model in HEC-HMS 3.4 consists of six components as seen in Figure 5. The meteorologic component uses the temperature gauges and the precipitation gauges or gridded data to spatially and temporally model precipitation. The temperature gauges and the temperature index of the meteorologic component separate rainfall and snowfall. Snow accumulation and snowmelt are computed by the melt rate function of the meteorologic component.

Precipitation which falls on impervious surfaces will enter the direct runoff component in the form of overland flow. Precipitation falls on pervious surfaces will undergo losses such as initial abstraction, infiltration, and evapotranspiration of which rates and patterns were defined based on the temperature and soil gridded data. The infiltration component of precipitation losses contributes to the direct runoff component and groundwater component.

The baseflow and overland flow will enter the river channel component which flows through natural channels and engineered structures such as reservoirs and dams. The basin outlet receives the net runoff from the gross precipitation falling on the watershed.

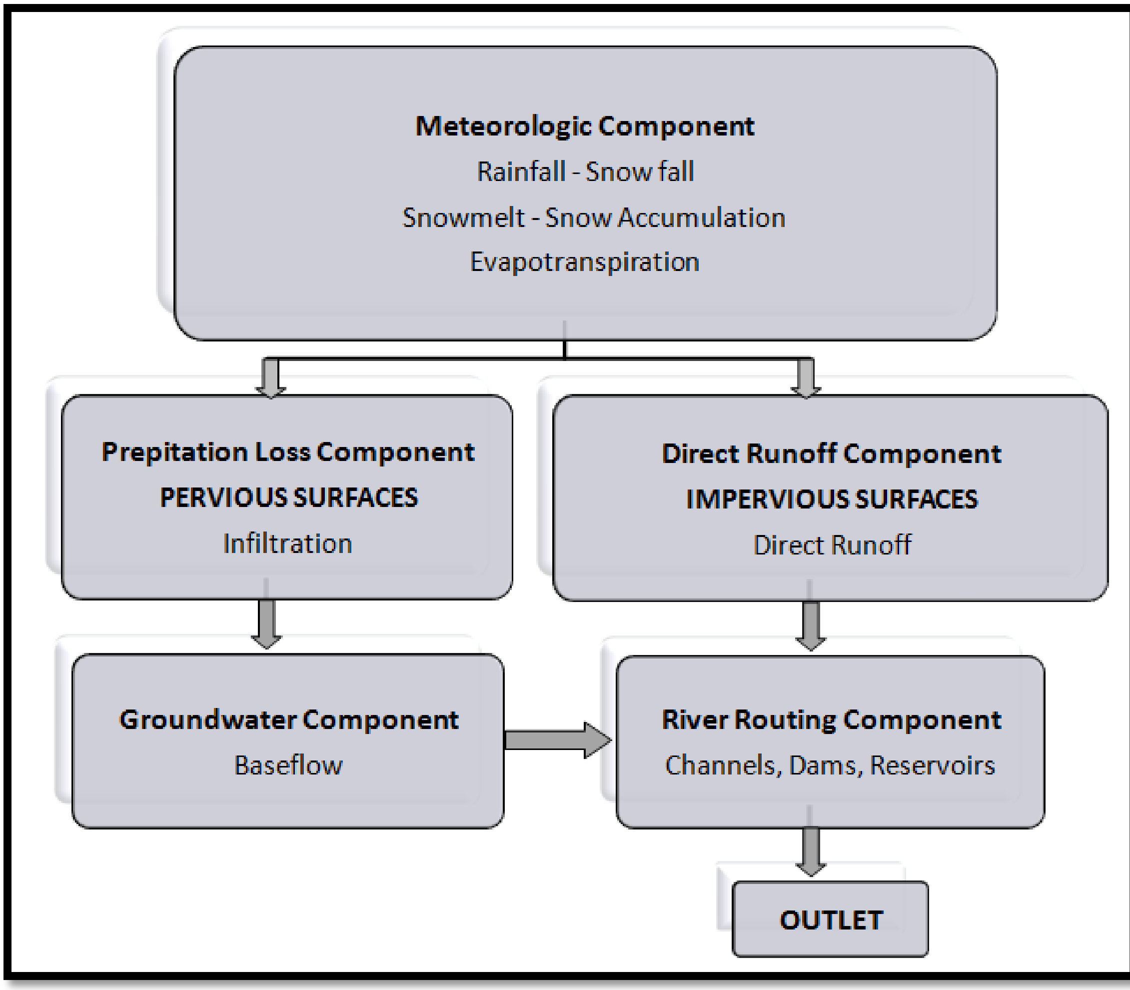


Figure 5: Continuous Model Diagram

Expected Results

The maximum possible time interval for the control specifications of an HEC-HMS model is one day. Therefore, for a thirty-year period, the results with one-day time steps will have at least eleven-thousand data points. Cunderlik and Simonovic (2004) initially suggested 1-day time steps for continuous modeling. However, because of the time of concentration of several sub-basins of the UTRb watershed were less than one day and greater than six hours, the 6-hr time steps were selected for their research. 12-hour time steps are suitable for the Rio Grande watershed based on the restriction of the smallest time of concentration.

One of many effective ways to view the results is to average the data of each month, which reduces the number of data points to three-hundred-sixty. To reduce even more the size of the modeled streamflow dataset, the averages of January, February, March, etc, would be computed to generate an average streamflow plot of the Rio Grande as illustrated in Figure 2.

The models was calibrated against the observed streamflow at Elephant Butte outlet from 1971-2000. The projected streamflow generated by HEC-HMS 3.4 would be used in conjunction with the streamflow projection at Otowi gauge to quantify how well New Mexico would meet its delivery obligations to Texas.

The models built in HEC-HMS 3.4 with proper calibration should generate lower peaks for near term 2030 and long term 2080 projection. The peaks for long term 2080 projection should shift from spring/early summer to early spring. There should be more winter runoff due to rain-on-snow spills. The total annual volume should drop significantly for the long term Dry scenario projection.

APPENDIX D: SPATIAL AND TEMPORAL COMPONENTS OF HYDROLOGIC MODELING

HEC-HMS is the tool to simulate precipitation-runoff. The principle behind the software is simply water budget accounting to compute the net runoff based on the water balance equation:

Precipitation – Initial Abstraction – Evapotranspiration – Infiltration = Runoff (1)

The precision of modeled discharge depends on four inputs. Some can be measured such as precipitation, and some can be estimated based on the characteristics of the watershed. Though precipitation can be measured, how fine the resolution of the precipitation data points is? How well does the precipitation gauge located at Sunport Airport in Albuquerque reflect the rainfall trend of Albuquerque where people on different directions of the I-40 freeway may experience rainfall walls locally separating the Eastbound and Westbound lanes? And even when the area of study is small enough to neglect any significant change in rainfall pattern, the geometry and the topography of the watershed dictates the path a water drop will take to travel to the outlet, which affects the time it starts contributing to runoff. Being able to resolve the spatial and temporal components of hydrologic modeling is the key to more realistic models.

Spatial Aspects

San Acacia is located approximately one-quarter length of the stretch of the Rio Grande in the area of interest towards the Elephant Butte outlet as seen in Figure 6.

Because to its downstream location, San Acacia has a large contributing area within the watershed of interest. Therefore, San Acacia was selected to study the spatial effects of hydrologic modeling of the area of study.

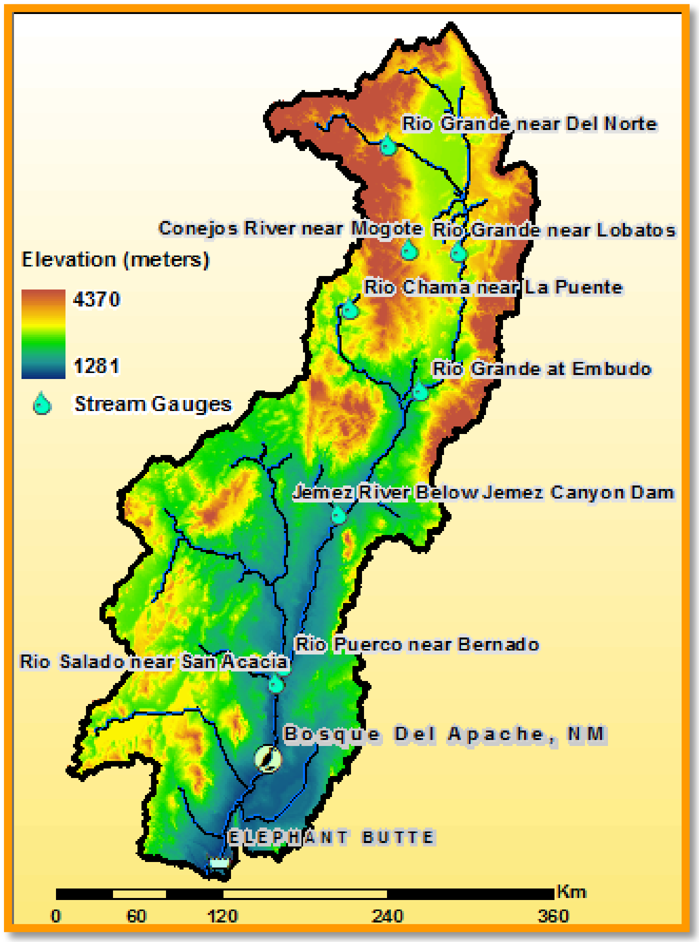


Figure 6: Stream Gauges of the Tributary Areas to the Rio Grande

From the elevation color ramp, San Acacia resides in the lowest area in the watershed. There are three streamflow gauges in the San Acacia vicinity:

- Rio Grande Conveyance Channel at San Acacia, USGS gauge 08354800
- Rio Grande Floodway at San Acacia, USGS gauge 08354900

* Rio Grande at San Acacia NM, USGS gauge 08355000

Based on the lattitudes and longitudes of the local stream gauges, their local precipitation and temperature data for 360 months from 1971 to 2000 were extracted from PRISM climate database and averaged to represent the precipitation and temperature of San Acacia. On the other hand, from Hurd's and Coonrod's work in 2008, the precipitation data were extracted for the entire watershed above San Acacia and spatially averaged for the same period. The locally averaged and spatially averaged data were plotted as seen in Figure 7 on a one-to-one basis. The differences between the locally average and spatially average precipitation data vary greatly, from two folds to orders of magnitude as illustrated in Figure 7.

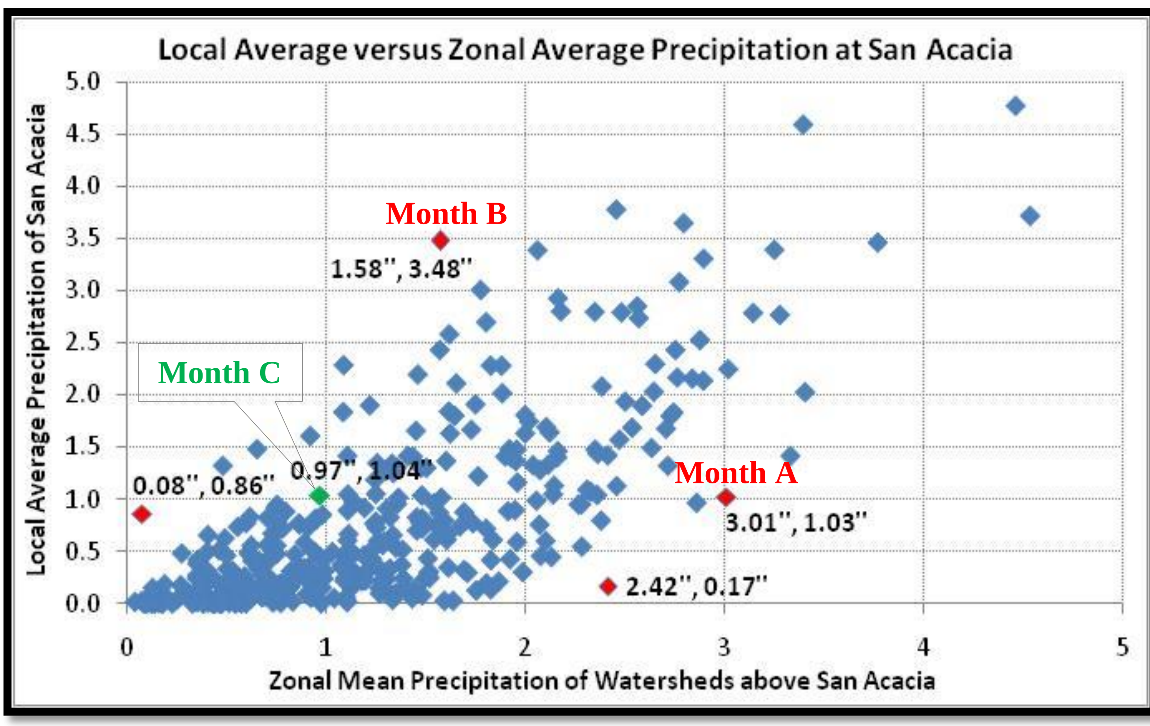


Figure 7: Locally Averaged versus Spatially Averaged Precipitation

To model the streamflow of the Rio Grande passing San Acacia, if the locally monthly averaged precipitation for “month A” as seen in Figure 7 at San Acacia is used, it is assumed that the entire watershed above San Acacia receives the same amount of precipitation, which underestimates runoff. On the other hand, if the spatially monthly averaged precipitation for “month B” is used, it will not capture the peak caused by much higher precipitation near the outlet at San Acacia. Even when “month C” seems to have a one-to-one correlation beween the two averages, 0.07 inch of rainfall difference over a large basin like this area of study is approximately equivalent to 170 kAF of water for one month period.

The spatially distributed precipitation over a large basin varying significantly in elevation poses another challenge in hydrologic modeling. If “month C” happens to be one of the winter months, approximatly half of the precipitation falling on the watershed could be snowfall which does not immediately contribute to runoff at San Acacia. This emphasizes the important role of the other factor in hydrologic modeling, the temporal component.

Temporal Aspects

Several aspects of the temporal component can affect the overall runoff of the watershed, such as rainfall intensity, and the timing of precipitation. One inch of precipitation in an hour and one inch of precipitation in six hours over the same watershed have the same volume of precipitation; however, the watershed responds differently in these two scenarios. Deep well-drained sands and gravel can infiltrate approximately 0.3 inch of water per hour. The rainfall intensity of 1 in/hr greatly surpasses the infiltration capacity of watersheds with soil types of sands and gravel. The excess precipitation that cannot be taken in by the soil will pond on the surface and eventually become runoff. On the other hand, sandy soils can take in all water from the 1-inch 6-hour storm without leaving any excess precipitation for runoff.

Timing of precipitation events has a great effect on when runoff starts. Precipitation during winter months at high elevation does not immediately contribute to runoff at the outlet. Rainfall events occur on soils with antecedent moisture from recent storms will likely have less time to infiltrate, which accelerates surface ponding and runoff. Not only do consecutive storms affect the infiltrability of soils, they also reduce evapotranspiration because there is not enough water pressure gradient between the atmosphere and the soil surface. From the water balance equation, when precipitation input stays constant and all other terms on the left side decrease, runoff increases.

PRISM Climate Group's database provides monthly total precipitation and average temperature data for single points and large regions in the United States. The data can be extracted in the tabular format for points, and 4-km resolution grid cells. There is no limitation on the start and stop years to be extracted for single points. However, there is no option to extract more than one months of gridded climate data. Due to the special structure of GIS raster data which include the geospatial and temporal details, single-month gridded climate data cannot be stacked on top of each other to create a continuous surface of time-series data for the entire period of study.

DayMET U.S. Data Center provides access to daily temperature and precipitation data for single points in the cotermious United States from 1980 to 1997. There is no option to extract continous daily time-series surfaces.

Monthly total precipiation does not reveal daily rainfall trends and significant events that can affect the shape of the hydrograph. Even daily precipitation data do not reflect rainfall patterns of semi-arid regions like New Mexico where intense and quick storms dominate. The limitation of DayMET and PRISM data availability poses difficulty in incorporating the temporal and spatial components into the hydrologic modeling process for this research.

For this research, to minimize the effect of the limitations of gridded data availability, the watershed was delineated into twenty-one small sub-basins. The monthly gridded data were spatially averaged at the centroid of each sub-basin to represent the time-series data for that sub-basin.

APPENDIX E: DATA PROCESSING

Watershed Delineation

The HEC-GeoHMS, an extension of ArcGIS®, was used to delineate the watershed in Figure 1 into twenty-one sub-basins and exported into HEC-HMS as the background map as shown in Figure 8. Steps to delineate the watershed using HEC-GeoHMS are summarized in Appendix J. Based on the geospatial data from the DEM of the watershed, the hydrologic and hydraulic parameters of the sub-basins were computed with ArcHydro tools in ArcGIS® and summarized in Table 4.

Table 4: Hydrologic and Hydraulic Parameters computed with ArcHydro

WATERSHED DELINEATION FROM DEM							
River Name	River Length (mi)	Longest Flow Path (mi)	Elevation Upstream (ft)	Elevation Downstream (ft)	River Slope	Sub-basin	Sub-basin Area (mi^2)
R20	49.8	127.2	7,547	7,510	0.0141%	W230	3,024.6
R30	105.9	164.0	8,573	7,510	0.1894%	W240	2,613.7
R40	8.1	51.9	7,510	7,494	0.0363%	W250	581.6
The Conejos	18.4	98.2	7,637	7,494	0.1473%	W260	3,260.9
R60	81.0	154.8	6,913	5,610	0.3045%	W270	766.0
R70	120.3	135.2	7,494	5,610	0.2966%	W280	3,157.6
R80	22.8	147.3	5,423	5,063	0.2972%	W290	2,501.8
The Rio Chama	67.1	95.4	5,610	5,063	0.1546%	W300	2,736.2
The Jemez	9.7	79.1	6,529	6,388	0.2747%	W310	1,033.3
R110	93.8	101.2	6,230	5,079	0.2326%	W320	2,068.3
R120	70.0	59.5	6,388	5,079	0.3541%	W330	1,046.6
R130	35.5	66.4	7,124	6,388	0.3922%	W340	1,123.5
R140	52.3	96.7	5,079	4,712	0.1329%	W350	1,633.2
R150	85.3	75.2	5,063	4,712	0.0779%	W360	752.2
The Rio Pueco	42.0	42.8	5,778	4,677	0.4957%	W370	1,394.4
R170	10.5	118.1	4,712	4,677	0.0615%	W380	156.0
R180	95.6	100.0	7,078	4,450	0.5211%	W390	1,117.3
R190	62.9	79.0	4,677	4,450	0.0684%	W400	2,414.5
R200	12.0	27.6	4,450	4,419	0.0498%	W410	2,060.2
R210	0.10	154.4	4,419	4,418	0.0666%	W420	207.6
R220	66.3	0.26	4,993	4,419	0.1639%	W430	0.012

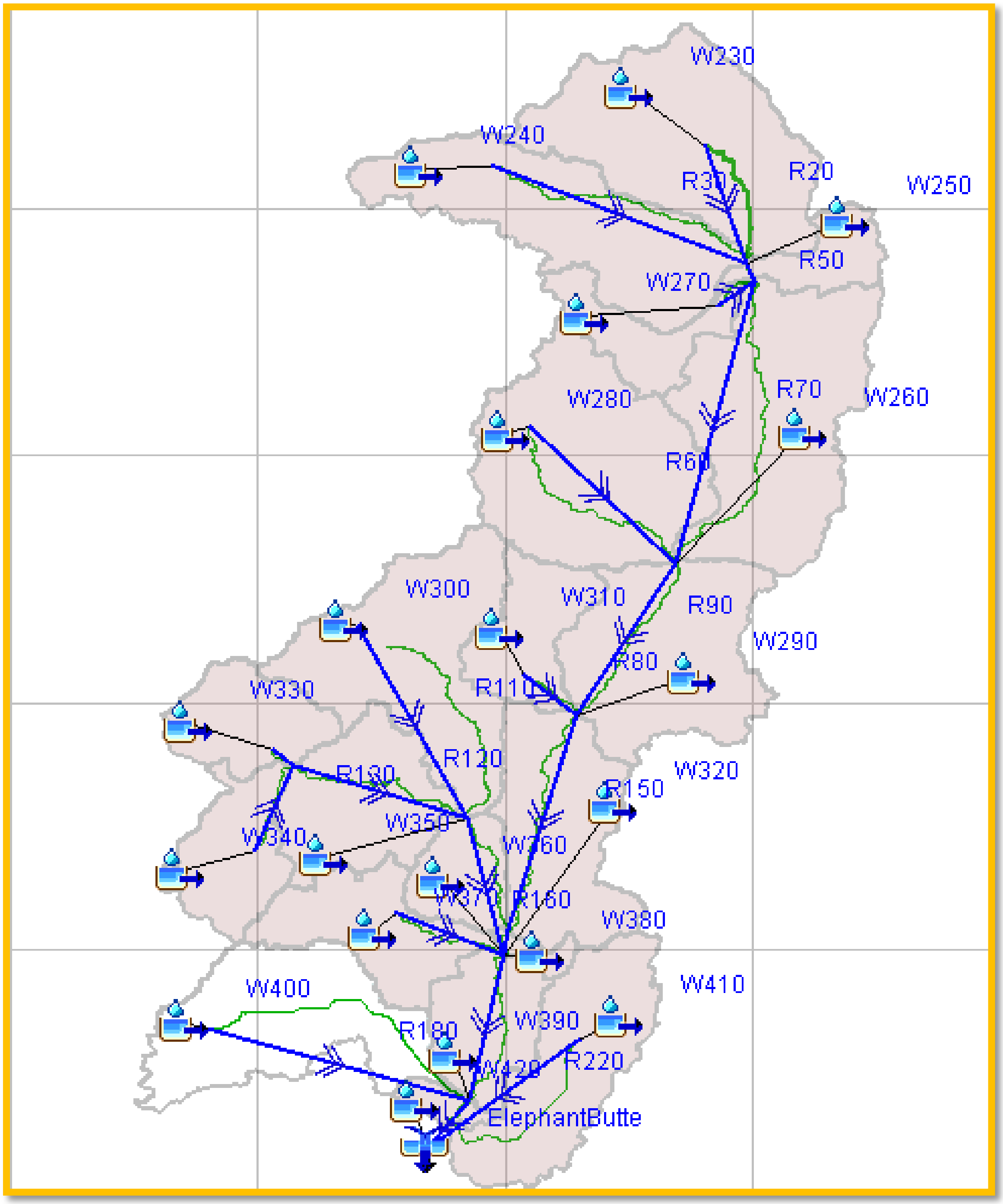


Figure 8: Watershed Delineation using HEC-GeoHMS

Land Use Land Cover Data

The land use data for New Mexico and Colorado from 2001 database were obtained in the raster form from STATSGO and processed with ArcGIS®. Raster-form datasets are universal data type to hold geospatial information. They are matrices of cells with discrete values such as elevation to represent the geographic features.

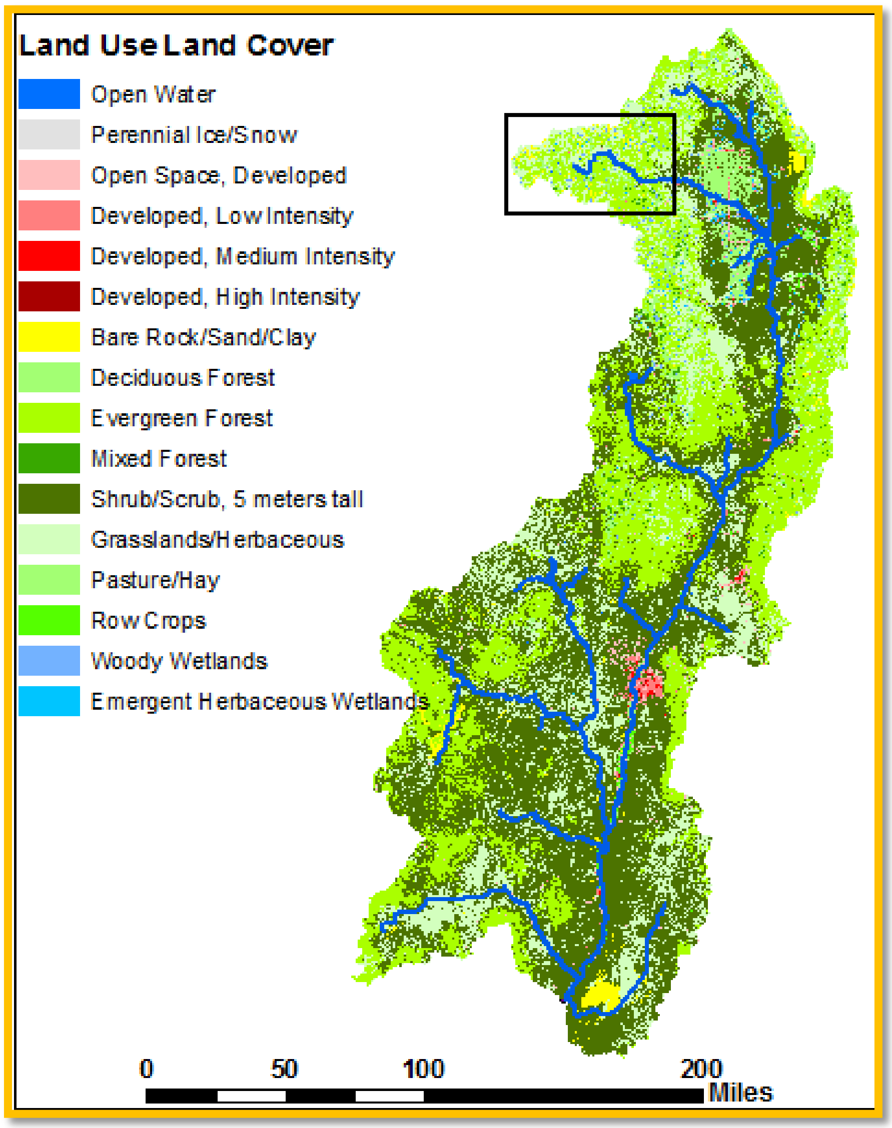


Figure 9: Land Cover Data for the Delineated Watershed

Based on raster calculation in ArcGIS®, the land use of four levels of development intensity is 1.8% of the total area. The medium intensity and the high intensity areas make up only 0.19% of the total watershed area. The projection of population of the Rio Grande watershed for the near future 2030 was 45.7% and for the long-term future 2080 was 75.7% (Hurd and Coonrod, 2008). Therefore, it could be assumed that the land use data would not change for the future projection scenarios.

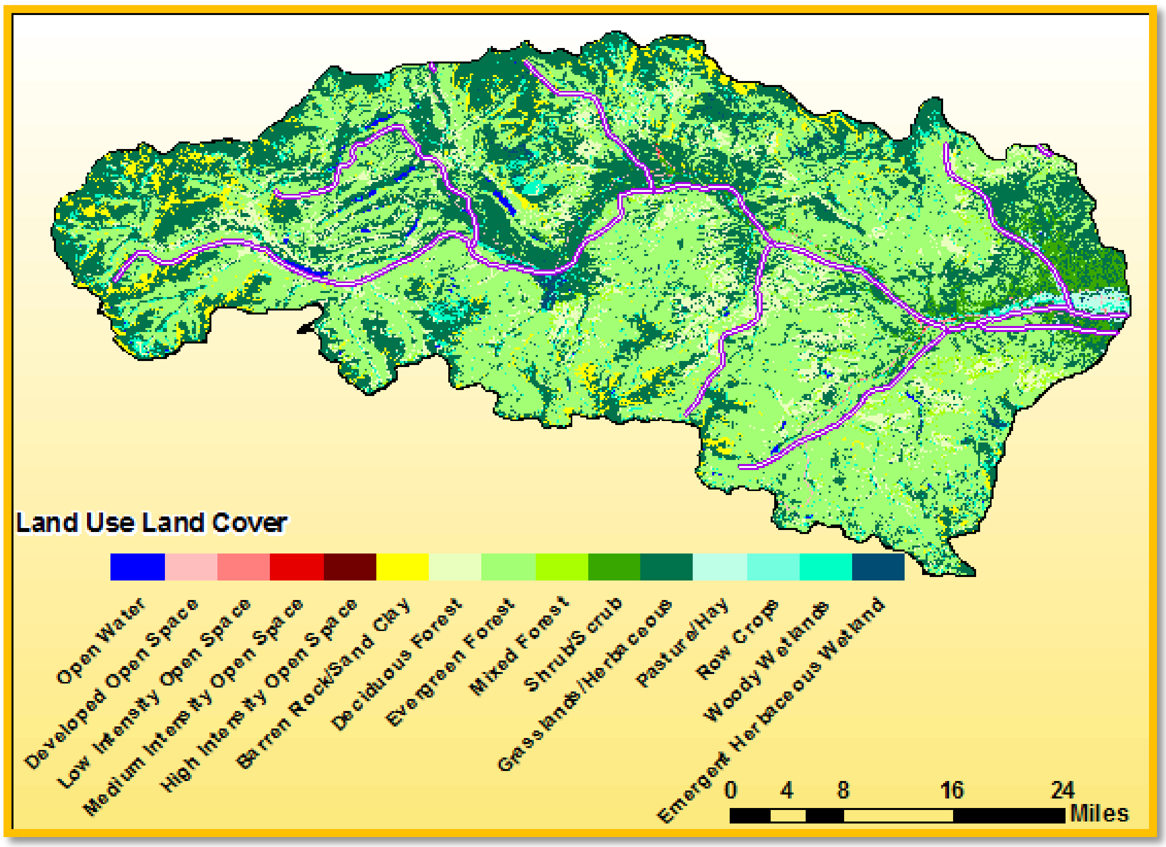


Figure 10: Land Cover Map of Del Norte, Colorado

The land use data for two states were connected by the Append tool to avoid unnecessary similar fields being created in the attribute tables of the original data. The boundary of the delineated watershed was used to clip the land use into the size and shape of the area of study. The raster-form land use was converted into polygons by the vectorization process in ArcGIS® for later processing with the soil data which are in the feature polygon format. There were sixteen number-coded categories of land use which were manually labeled correctly based on the National Land Cover Database as seen in Figure 9. A close-up view of the Del Norte land cover is shown in Figure 10.

Soils Data

The soil data for New Mexico and Colorado were obtained in the form of ESRI features from STATSGO and processed with ArcGIS®. The Microsoft Access empty database file also came with the soil data for each state to convert numerous soil tables into the tabular form that can be read by ArcGIS®. There are four most common feature types in ArcGIS®: points, lines, polygons, and map annotations. The soil data have discrete boundaries to embrace polygons of different soil types. Each polygon reflects not only a soil type but also other geographic data such as the soil layer depth, locations, map unit codes, chemical contents, etc. The soil information can only be extracted through the Access empty database file that comes with the soil map.

The original attribute table of the soil data was joined with that of the component table to extract information on the types of soil and their components for each soil polygon. Additional fields on the percentage of each soil type were manually created in the attribute table based on the presence of that particular soil on a polygon.

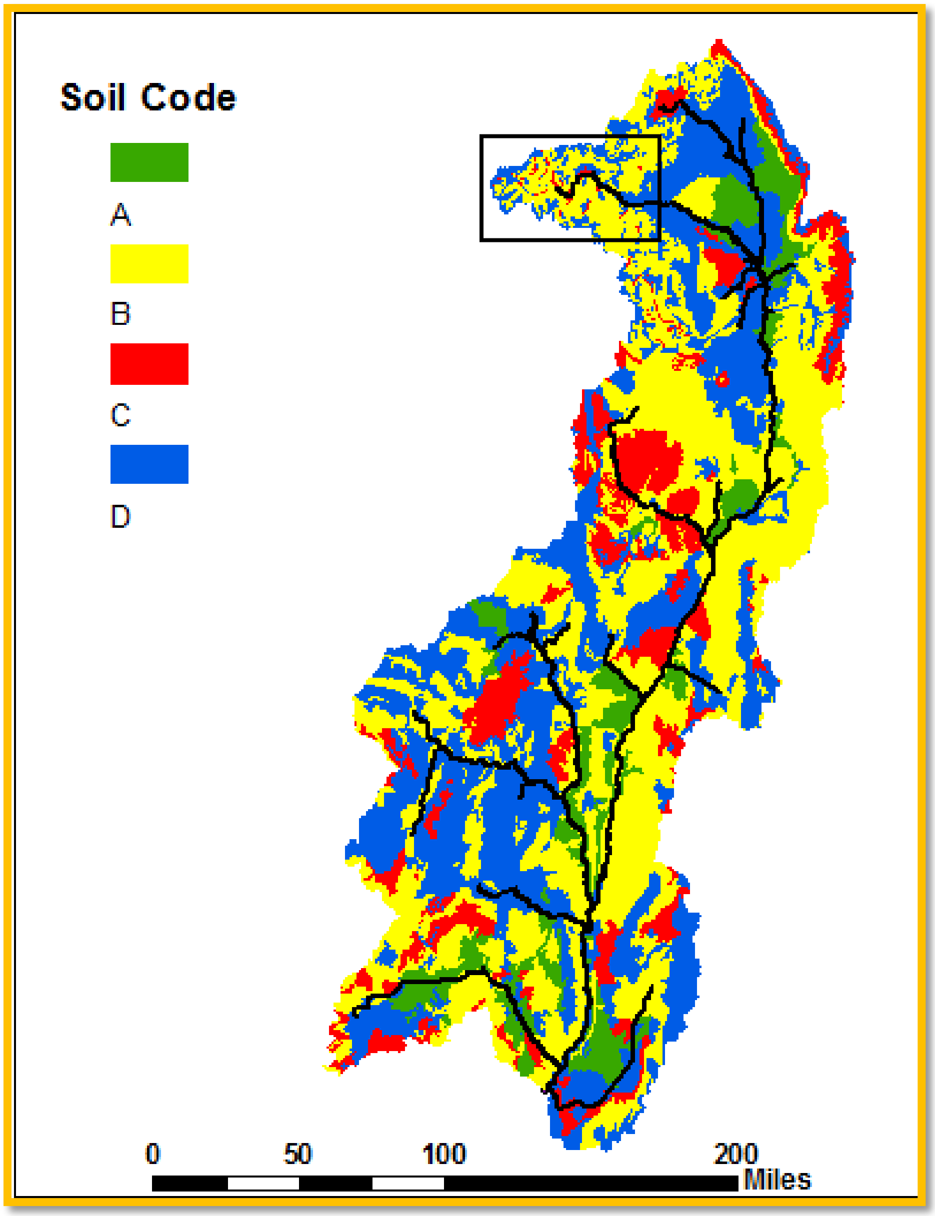


Figure 11: Soil Types of the Delineated Watershed

The soil data for New Mexico and Colorado were appended and trimmed into the size and shape of the delineated watershed as seen in Figure 11. The original DEM did not have a projection coordinate system. The geographic coordinate system of the raw DEM was NAD 1983. In the process to compute basin hydrologic and hydraulic parameters a projection coordinate was required to obtain a “z value” for every point on the map. Albers Equal Area Conic projection coordinate system was applied to the data frame to fulfill the “z value” requirement. A close-up view of the soil map for Del Norte is illustrated in Figure 12.

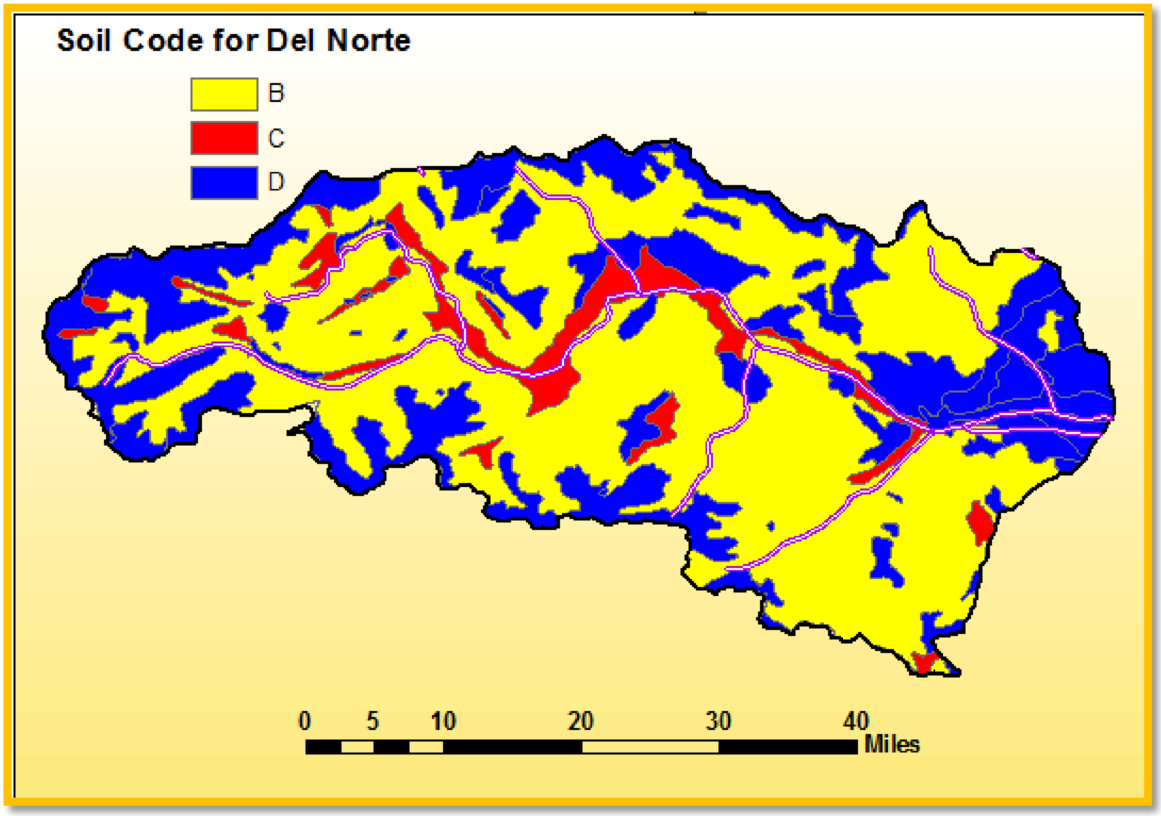


Figure 12: Soil Map of Del Norte, Colorado

The soil and land use datasets were merged together to create a mesh to compute the infiltration capacity and the runoff potential of the watershed. From four types of soil and sixteen categories of land use, there are sixty-four different combinations of land use and soil that each polygon can have. Based on the SCS TR55 manual, software for stormdrain management, each combination of soil and land use was assigned a curve number from thirty to one-hundred according to the infiltration capacity and runoff potential of each polygon. With the input files being the watershed filled DEM, the curve number matrix, and the merged soil-land-use map, the gridded curve number was created with HEC-GeoHMS for the watershed as seen in Figure 13.

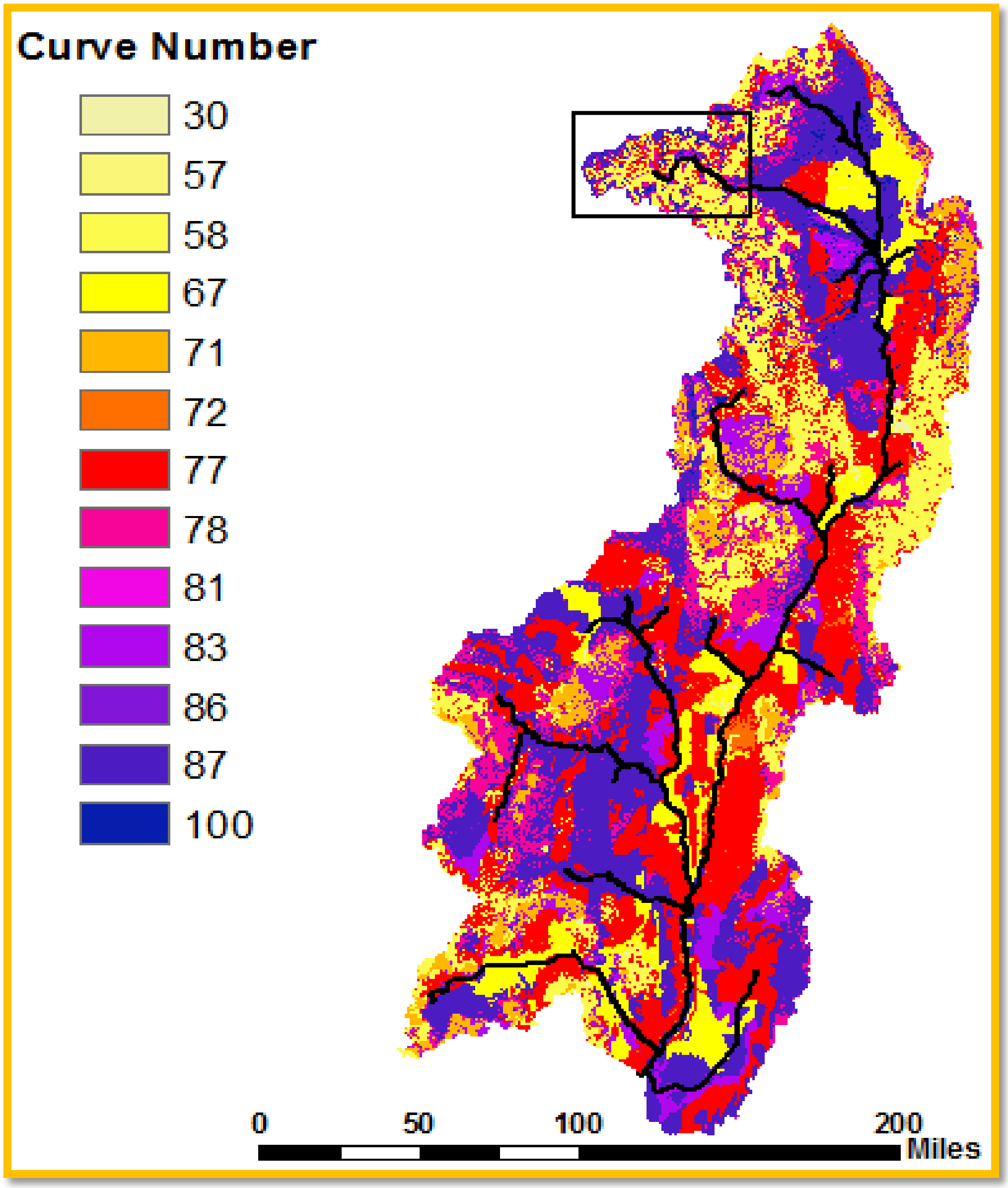


Figure 13: Gridded Curve Number of the Delineated Watershed

This curve number grid can be used in HEC-HMS as a computational tool to perform soil moisture accounting to dry out the soils between events on a cell-by-cell basis (Fleming and Neary, 2004). However, the curve number loss method is not compatible with continuous modeling in HEC-HMS. Therefore, only the soil grid map was used in HEC-HMS to estimate the soil parameters for the loss method such as initial deficit, maximum deficit and conductivity. A close-up view of the curve number grid for Del Norte is shown in Figure 14.

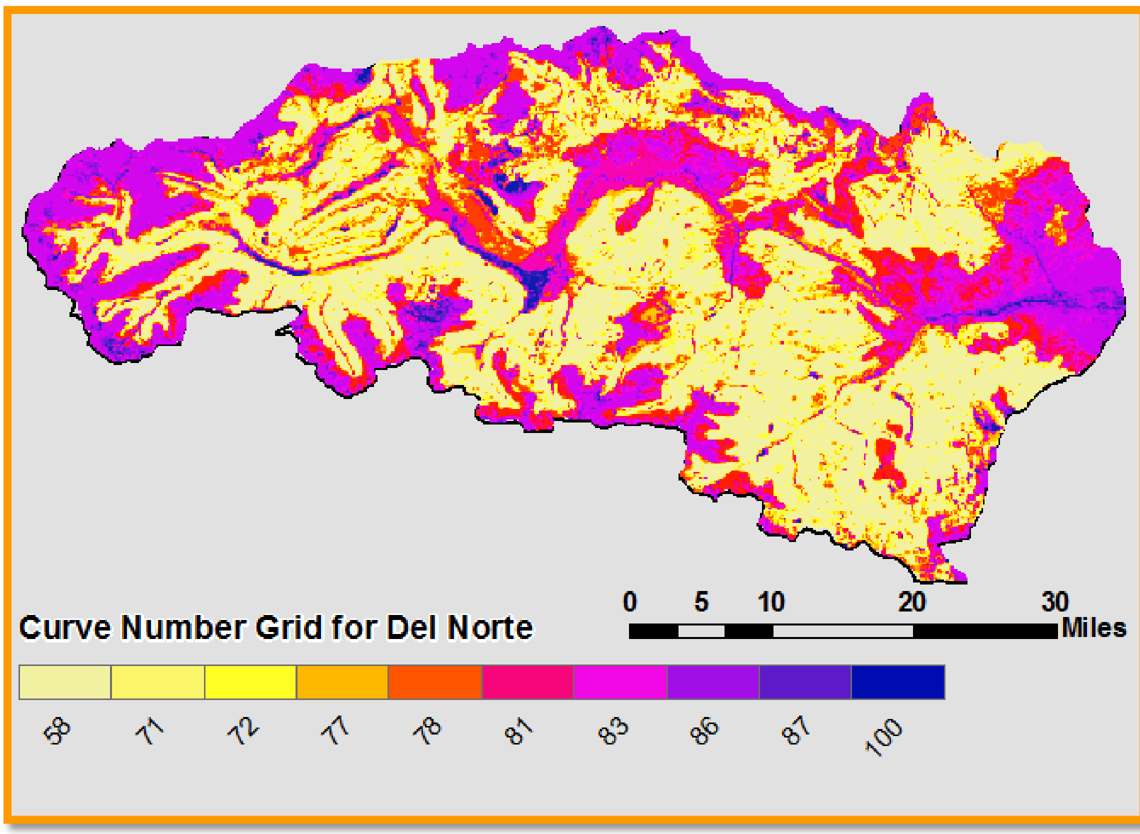


Figure 14: Curve Number Grid for Del Norte, Colorado

Time-series Data

Streamflow

Monthly statistics streamflow data from USGS database were used for calibration and verification of the hydrologic models in this research. There were twenty-one sub-basins in the area of study. Optimally, there should be twenty-one observed streamflow gauges to monitor how well the model reconstructs the streamflow at each gauge. The simulation used 12-hr time steps for the 30-year period; therefore, there were almost 22,000 data points for each time-series brought into HEC-HMS.

Observed streamflow data are optional in HEC-HMS whereas temperature and precipitation were the mandatory inputs. After the observed streamflow measurements for Del Norte and Elephant Butte were imported, HEC-HMS showed signs of frequent crashes. Due to the limitation of the available computational power, bringing in more than three observed streamflow gauges for the 30-year period were not practical. Besides, not all delineated sub-basins had gauged streamflow measurements. Therefore, three locations were selected as the verification points of the models as seen in Figure 15:

- Upstream control gauge: Rio Grande near Del Norte, USGS 08220000
- Middle control gauge: Rio Chama near La Puente, USGS 08284100
- Downstream control gauge: Rio Grande below Elephant Butte Dam, USGS 08361000

Monthly statistics streamflow for the period 1971-2000 were monthly average single values for individual stream gauges in the tabular format. The data were processed in MATLAB with logical functions to convert 360 months into 22,000 data points. Special considerations in writing the MATLAB codes for this task were the varying numbers of days in a month as well as of the February month of a leap year.

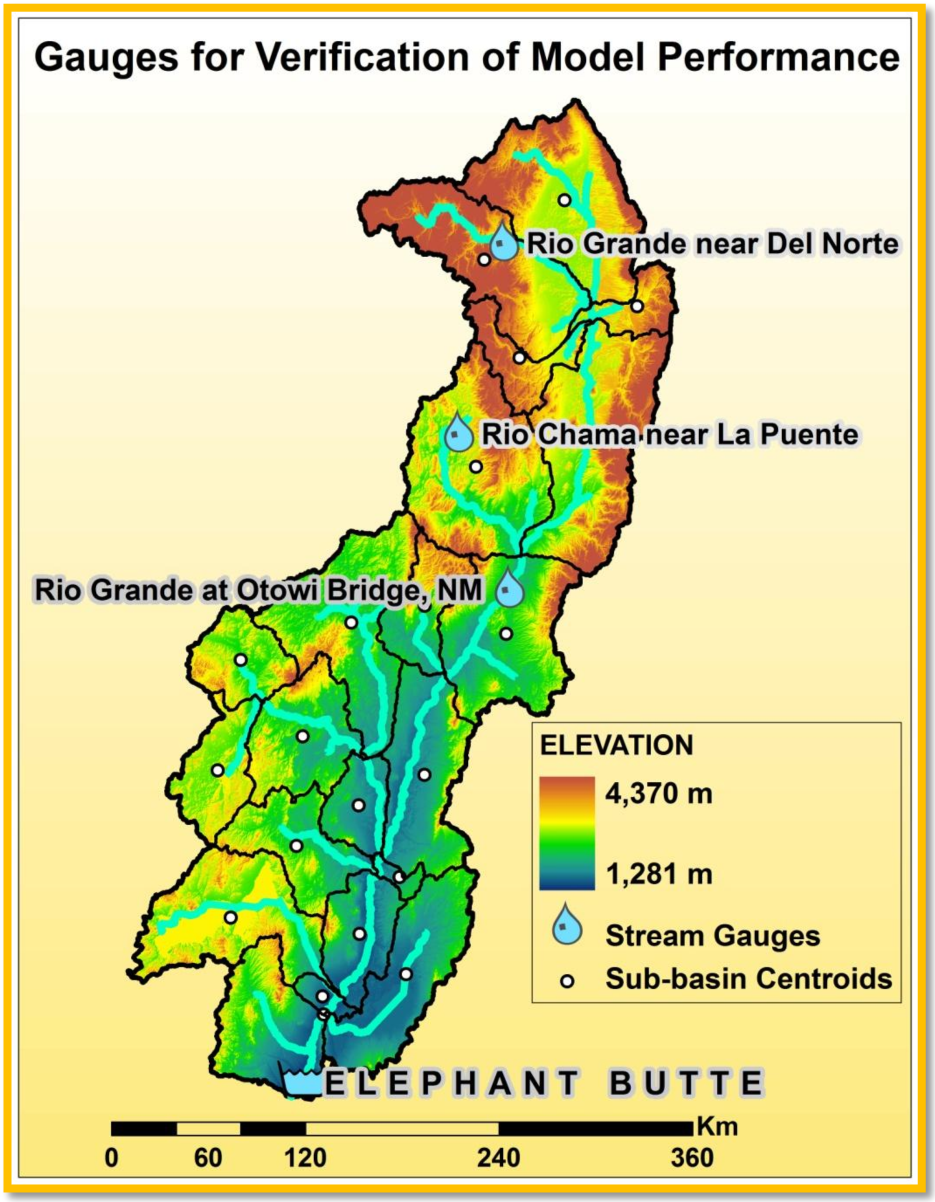


Figure 15: Control Gauges

Precipitation and Temperature

Precipitation

PRISM Climate Group's database was the primary source of precipitation and temperature gridded data. 360 continous surfaces of total monthly precipitation for the United States were extracted. With the boundary of the watershed, the precipitation data were trimmed down to the size and shape of the area of study by ArcGIS®. For every sub-basin, the precipitation was spatially averaged at its sub-basin centroid and exported into files with the dbf-extension. Using Excel, the data were compiled for each sub-basin.

Daily precipitation time-series were required because the maximum time-steps in HEC-HMS simulation is one day. The selected time-steps should be smaller than the smallest time of concentration of the sub-bains (Cunderlik and Simonovic, 2004). Therefore, 12-hour time steps were suitable for this project because the smallest time of concentration was 13.5 hours. 12-hr time step simulations require approximately 22,000 data points for each time-series from every sub-basin. A slighly different procedure in MATLAB to convert 360 points into 22,000 data points was applied to import the precipitation data into HEC-HMS. PRISM database only provides total monthly precipitation data.

Similar work with the requirement to convert available monthly average precipitation into hourly time steps was conducted for the continuous simulation of streamflow of the Johnson County, Kansas (McEnroe, 2010). From a table of accumulated rainfall versus time, the gauge data were converted from the original time interval to the desired fixed time interval by linear interpolation between points. Incremental amounts and intensities of the new time interval were derived from the newly generated accumulated amounts. An example of this procedure is illustrated as following:

Given intervals	After 0 hour	After 6 hours	After 12 hours
Accumulated data (in)	0	1.5	2.5

New intervals	After 0 hour	After 3 hours	After 6 hours	After 9 hours	After 12 hours
Accumulated data (in)	0	0.75	1.5	2	2.5
Incremental increase (in)	0	0.75	0.75	0.5	0.5
Intensity (in)	0	0.25	0.25	0.17	0.17

For this research, the total monthly precipitation data were divided into three equal amounts and assigned ten days apart. Initially, the five-day interval was used to calibrate the model, however, it did not respond to evapotranspiration because the soil did not have enough time to dry after five days. Using the ten-day interval worked well for the model to capture evapotranspiraiton. The precipitation data prepared above were the inputs of the model to calibrate the simulated discharge against the observed streamflow from 1971 to 2000.

Precipitation inputs for future projection come from Table 1 which computes the future precipitation data as the percentage changes compared to the current dataset.

Temperature

Unlike precipitation, daily temperatures vary between nights and days. 720 continuous minimum and maximum temperature surfaces were downloaded and processed in ArcGIS® into the shape and size of the watershed. The monthly average temperatures were computed by averaging the monthly maximum and minimum gridded data. This method was validated by the work from researchers at the University of Dayton after they analyzed 53,004 daily temperature records (Hurd and Coonrod, 2008). The source was taken from http://www.engr.udayton.edu/weather/source.htm.

> *"We compared average daily temperatures calculated from 24 hourly readings, T24, to average daily temperatures calculated as the average of the daily minimum and maximum temperature, Tminmax… the average bias is less than the precision of the source data, and we conclude that the bias between T24 and Tminmax is not statistically significant… Thus, use of either T24 or Tminmax "average" daily temperatures should give similar results."*

The temperature data were spatially averaged at the centroid of each sub-basin just like the procedure for precipitation data. ArcGIS® Extract Tool and the MATLAB codes helped to import the temperature data into HEC-HMS for all sub-basins. The temperature data prepared above were the inputs for the model to calibrate the simulated discharge against the observed streamflow from 1971 to 2000.

Temperature inputs for future projection come from Table 2 which computes the future temperature data as increases or decreases in Fahrenheit degrees compared to the current dataset.

APPENDIX F: SELECTION OF MODEL PARAMETERS

The selection of model methods was based on the consideration of their compatibility in HEC-HMS and the requirement for continuous modeling.

Meteorologic Model

The meteorologic model is the primary computational tool in HEC-HMS. It defines the climatic boundaries of the watershed and performs the computation of the water balance from total incoming precipitation, such as evapotranspiration, infiltration, snow accumulation, snow melt and runoff.

Precipitation Method

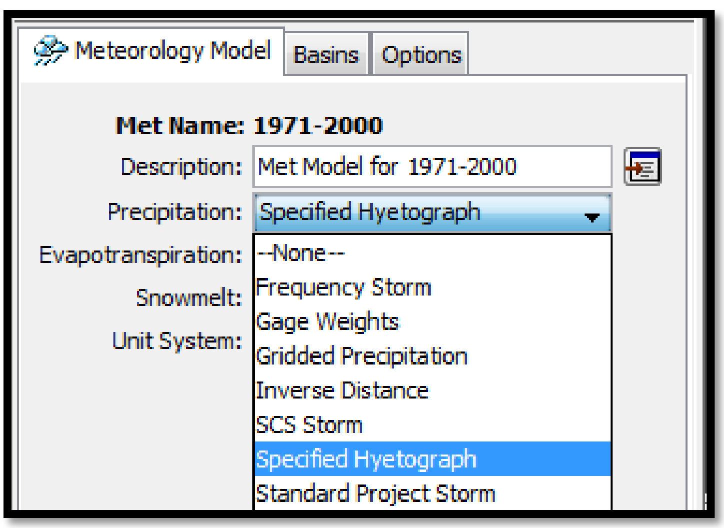


Figure 16: Precipitation Methods

There are five methods for the total incoming precipitation as shown in Figure 16. Ideally gridded precipitation data are preferred to other methods since they include both the temporal and spatial factors. They are used in conjunction of other compatible gridded methods, such as the gridded Priestly Taylor, the Gridded Temperature Index, and the gridded soil moisture accounting. However, due to the limitation of the data availability from PRISM database, individual monthly gridded precipitation could not be stacked on top of each other to create a continous surface for the entire time period. Specified Hyetograph method was used as an alternative. This method required twenty one precipitation gauges for all sub-basins which were defined in the time-series manager menu. Precipitation data were spatially averaged data for each sub-basin.

Evapotranspiration Method

There is an option to include evapotranspiration in the hydrologic modeling process in HEC-HMS. Event-based simulations do not need evapotranspiration because there is no pressure gradient between the atmosphere and the soil surface during rainfall events. For long term simulations, evapotranspiration plays an important role in the water balance equation and should be included.

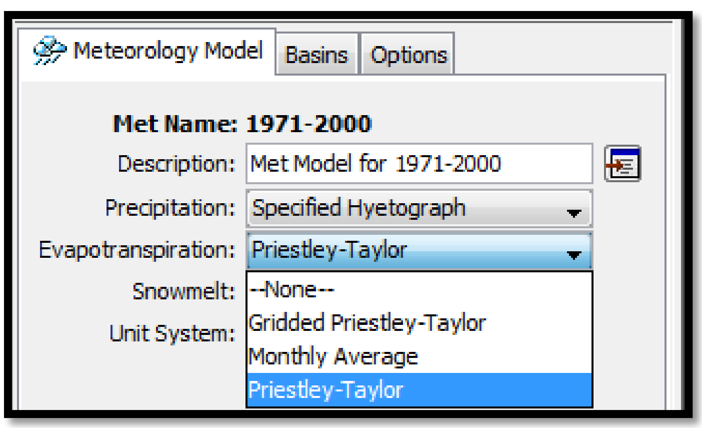


Figure 17: Evapotranspiration Methods

Gridded Priesley-Taylor method accurately accounts for the temporal and spatial factors in hydrologic modeling on a cell-by-cell basis (Fleming and Harris, 2004). Again due to the limitation of PRISM gridded climatic data, Priestly Taylor method was selected. The inputs for this method were the temperature gauges which were defined in the time-series manager menu. Temperature data were spatially averaged data for each sub-basin.

Snowmelt Method

Though there are four choices for Snowmelt method as seen in Figure 18, Energy Budget and Gridded Energy Budget are not available for selection. If either of them is highlighted, “None” will appear in the box where the drop down arrow for snowmelt is. The help menu from HEC-HMS does not provide any information on either of them. HEC-HMS 3.5 took out two unworkable snowmelt methods.

Between the two remaining choices, Temperature Index was selected because of the same reason encountered for the precipitation and evapotranspiration methods. There are ten different parameters that are required for the Temperature Index, which is illustrated in Figure 19. A lot of the parameter selections were the recommended values from the HEC-HMS 3.4 help menu. Some other parameters were adopted from the work of Colombie M. in 2007 to project the hydrographs of two ungauged watersheds for the feasibility study of a small hydropower plant in the Pyrenees mountains, France. A couple of parameters were achieved through the calibration process.

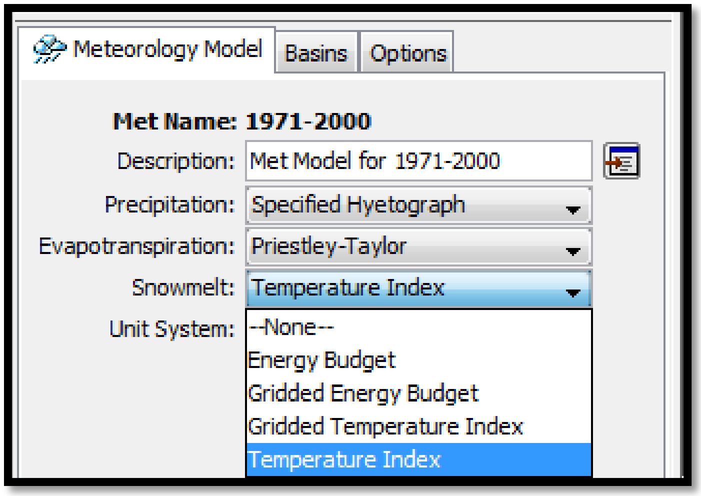


Figure 18: Snowmelt Methods

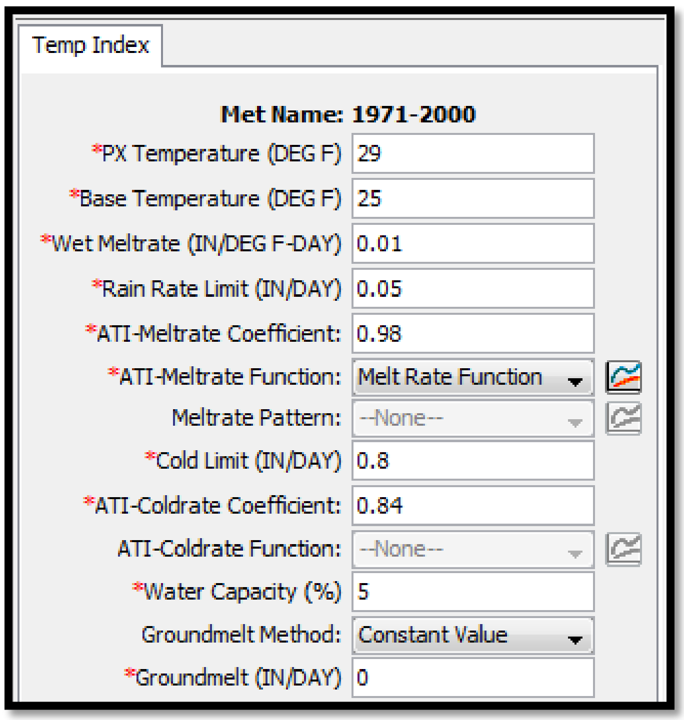


Figure 19: Selection of Temperature Index Parameters

- PX Temperature: to determine if the incoming precipitation is rainfall or snowfall. This parameter was achieved by the calibration process.
- Base Temperature: to compute snowmelt. This value was achieved by calibration.

The range from Base Temperature to PX Temperature is known as snowmelt threshold. The difference between one value from the temperature gauges and the base temperature defines the temperature index. From the melt rate function created from the Paired Data Manager menue, snowmelt is the product of the temperature index and the melt rate value.

- Wet melt rate: to model the effect of rain-on-snow spill. This value was adopted from Colombie's model (2007). If the rainfall rate is greater than the rain rate limit defined in the next box from Figure 19, wet melt rate represents the rate the snowpack melts. This rate is greater than the rate defined in the melt rate function.
- Rain rate limit: to distinguish between wet melt and dry melt. This value was adopted from Colombie's work (2007).
- ATI (antecedent temperature index) melt rate coefficient: 0.98 is HEC-HMS recommended value. It is an intermediate value that is used to update the antecedent melt rate index from one time interval to the next.
- ATI melt rate function: this function needs to be defined in the Paired Data Manager menu beforehand. The function was adopted from Colombie's work (2007).
- Cold limit: to account for temperature changes during high precipitation rates. HEC-HMS recommended value is 0.8 in/day.
- ATI cold rate coefficient: 0.84 is HEC-HMS's recommended value. It is an intermediate value that is used to update the antecedent cold content index from one interval to the next.
- Water capacity: HEC-HMS recommended values are from 3% to 5%. It

represents the amount of melted water accumulated in the snowpack before any liquid water at the soil surface available for infiltration or runoff. This range of the initial values for water capacity does not impact the overall outcomes of the model because of the long run simulation period.

- Groundmelt method and ground melt: there are two options for groundmelt methods which are annual pattern or constant. The "constant" method was selected and the constant value was 0. It is reasonable to assume that there is no heat from the ground that can melt the snowpack.

Sub-basins

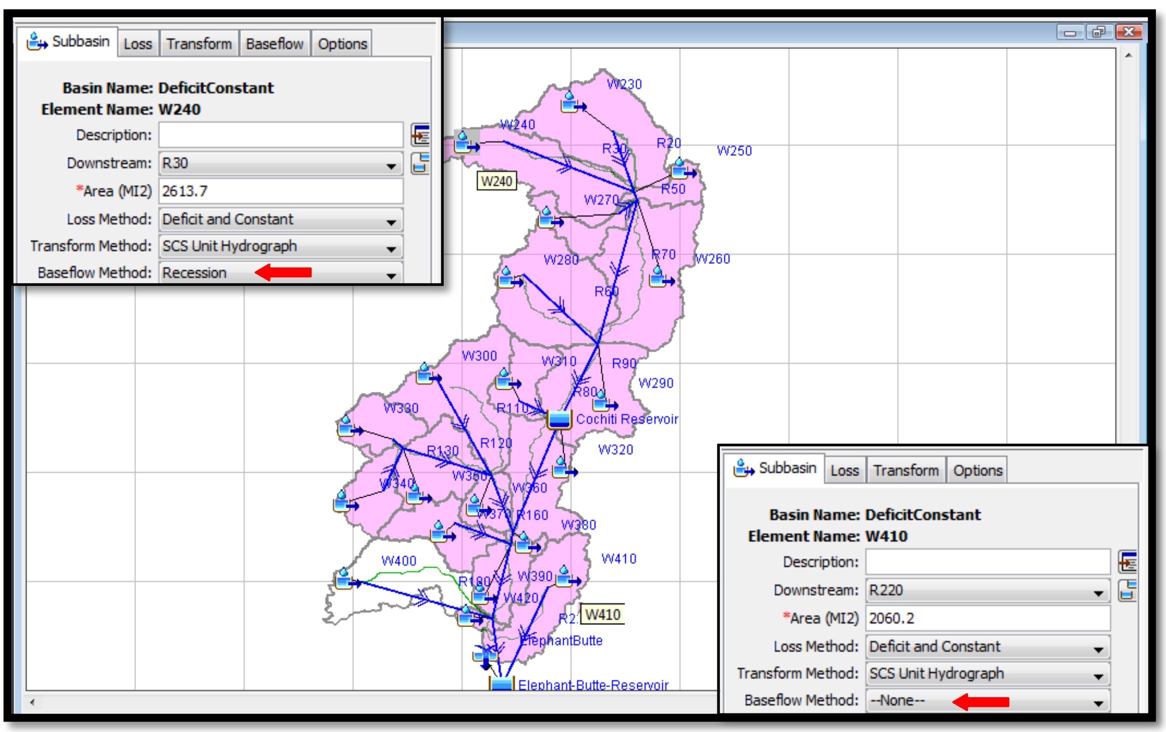


Figure 20: Selection of Sub-basin Parameters

Figure 20 illustrates two distinct stream characteristics of two types of sub-basins in the watershed: the year-round flow and the emphemeral streams. The sub-basins with year round flow have a defined baseflow method. The areas of all sub-basins were computed in HEC-GeoHMS based on the spatial data from the DEM.

Loss Method

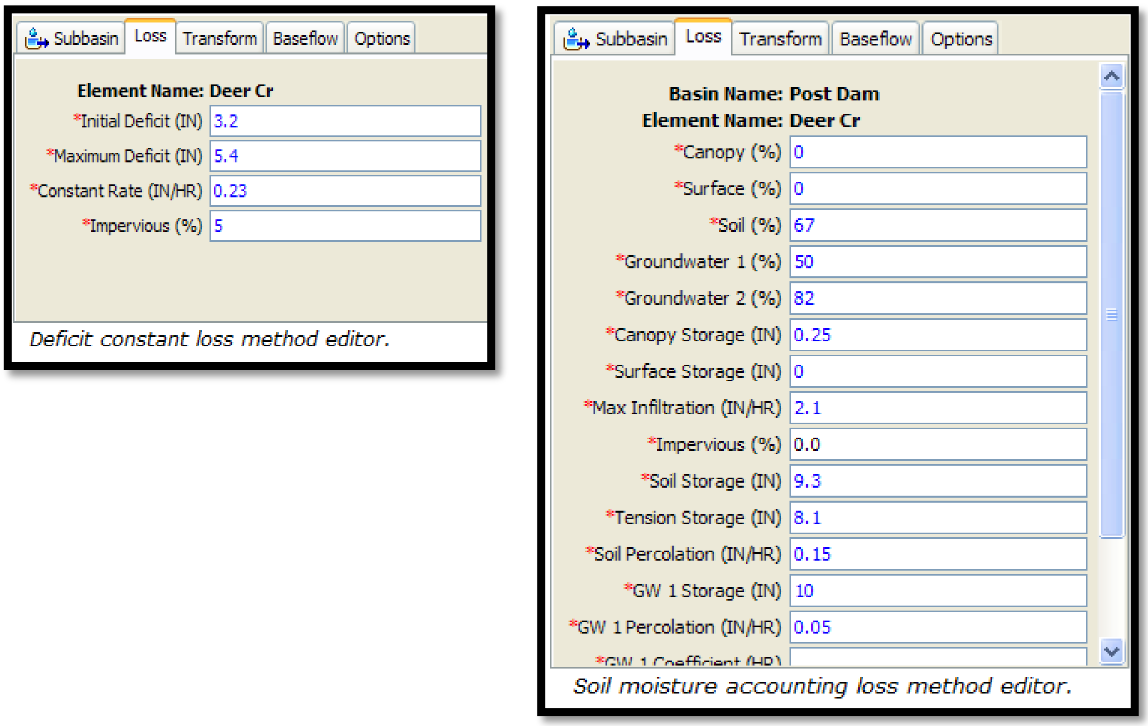


Figure 21: Parameters for Loss Methods (HEC-HMS 3.4 User's Manual)

The intention when the curve number grid (Figure 13) was initially created was to provide the inputs for the SCS grdded loss method to compute infiltration. However, this method was designed to simulate only storm events. Among the ten loss methods, only the "Deficit and Constant" and "Soil Moisture Accounting" can be used with the meteorologic method that computes evapotranspiration. The "Deficit and Constant" method requires four inputs while the "Soil Moisture Accounting" requires eighteen different inputs as seen in Figure 21. "Deficit and Constant" was selected to simplify one of the many steps of the modeling process. The parameters for the "Deficit and Constant" loss were estimated based on the soil type of the sub-basins from the soil map generated in the process to build the curve number grid.

Transform Method

The transform method generates the unit hydrograph for a storm event. Unit hydrographs are the plots of flow rate versus time to represent how a sub-basin reponds to one unit of precipitation depth. The overall response of the sub-basin to any precipitation depth is achieved by multiplying the unit hydrograph with the appropriate ratio between the precipitation amount and the unit of precipitation depth.

From HEC-HMS 3.4 User's Manual, the transform method is very important for event-based simulation to capture when the peak flow occurs. The observed streamflows at three control locations as illustrated in Figure 15 were monthly averages which did not show event peaks. Therefore, thre was no obligation in the selection of a specific transform method to replicate event peaks. Initially, the curve number grid was generated for the SCS gridded curve number loss method. To be consistent in methodology, SCS unit hydrograph was selected as the transform method for the above loss method. When the loss method was changed to Deficit and Constant to accommodate the continuous simulation, the SCS unit hydrograph was kept for the model. The input parameter of the SCS unit hydrgraph was the time lag which was computed for each sub-basins with HEC-GeoHMS based on the spatial data of the DEM. Other loss methods are more complicated because in addition to the parameters that can be computed in HEC-

GeoHMS, there are coefficients and constants that can only be acquired through calibration.

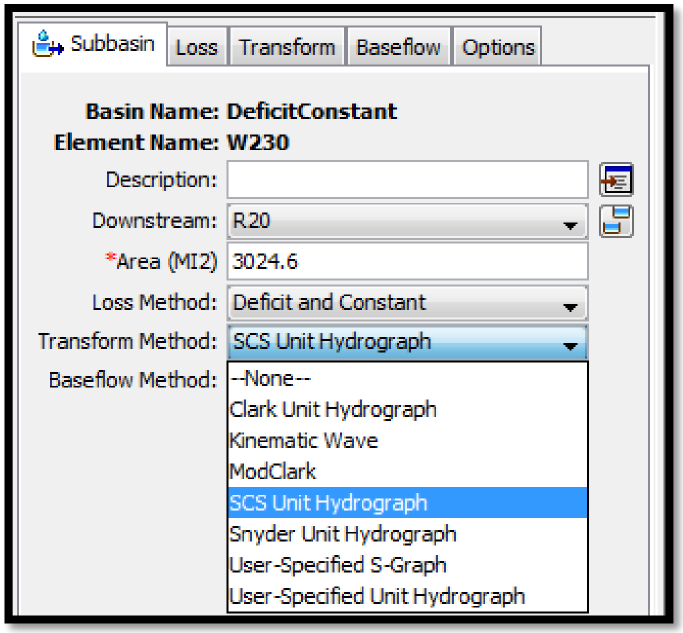
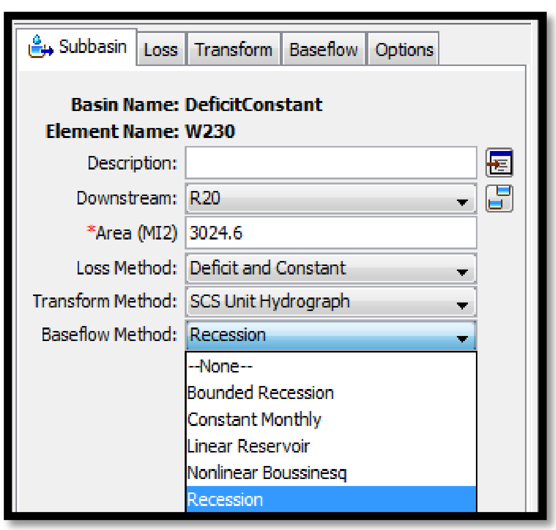


Figure 22: Selection of Transform Method

Baseflow Method



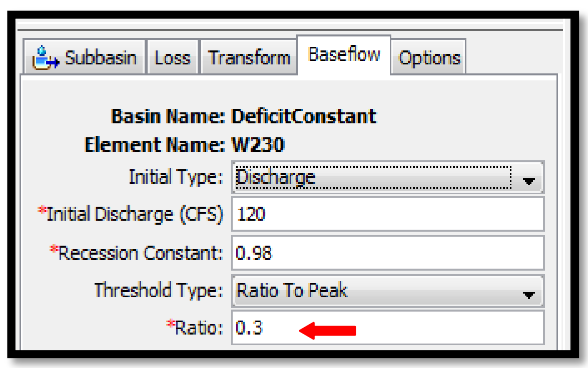
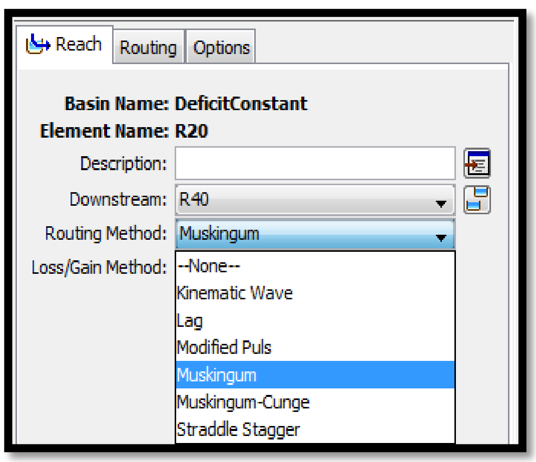


Figure 23: Selection of Baseflow Method

The baseflow method processes the calculation of the sub-surface interaction. There are five different baseflow methods. Some methods are more appropriate for event-based simulations while other were designed for continuous simulations. Only the Bounded Recession and Recession methods are appropriate for long term run. The Bounded Recession method irrelistically imposes constant limits for monthly baseflows for long run simulations while the Recession method resets the baseflow after each events. Therefore, it was more reasonable to use the Recession method. The initial discharge was the initial observed streamflow of the sub-basin. If a sub-basin does not have a gauged station, an approximation of the initial discharge does not affect the overall result of the 30-year long simulation because the model adjusts itself after the first year. The recession constant was achieved through the calibration process. The "ratio to peak" is the mechanism to reset the baseflow as the flow rate on the falling limb decreases to the ratio percentage of the peak flow. The ratio of 0.3 was the result of the calibration process.

Reaches

Reaches represent stream segments of the river system in the area of study. There are six different routing methods. If "None" is selected, the wave will translate instantaneously without attenuation. The Kinematic Wave method is more appropriate for homogenous channels where side slopes and channel cross section shapes are required. The Lag routing does not incorporate the attenuation effect. The Modified Puls method required the Storage-Discharge function which is not realistic for the river system in the area of study. The Muskingum Cunge method requires parameters with high uncertainty such as Manning's n values for the banks and the cross section of the long stretch of the Rio Grande in the area of study. The Straddle Stagger method is not clear about if the attenuation is included in the computation or not, which left the Muskingum method as the selection. This method requires the Muskingum K which is the travel time through the reach. By knowing the reach length, the travel time could be estimated. The Muskingum X is the indicator of attenuation which varies between 0.0 (maxium attenuation) to 0.5 (no attenuation). The value of 0.3 for Muskingum X was achieved through the calibration process.



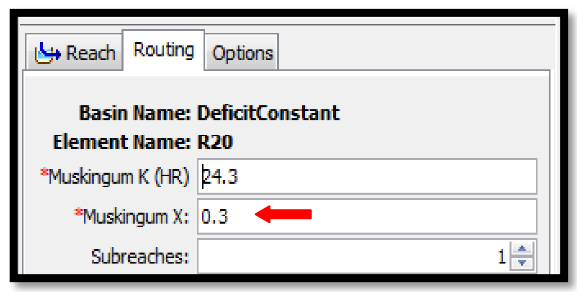


Figure 24: Reach Routing Methods

APPENDIX G: CALIBRATION AND VERIFICATION OF MODEL

Calibration

There is an option in HEC-HMS to optimize the modeled streamflow by selecting certain parameters to be changed. However, due to the abundant parameters and sub-basins that need to be optimized for a 30-year period, HEC-HMS kept crashing. According to Cunderlik and Simonovic (2004), they encountered similar crashing problems for the 9-year continuous model for the UTRb. Therefore, manual calibration of parameters by varying one and keeping all others constant was applied.

Calibration was applied to the first year of the period to replicate the spring snowmelt peak. The calibrated parameters were the snowmelt threshold for the meteorologic model, the recession constants and the ratios to peak of the baseflow method, and the Muskingum X of the routing method which could not be estimated from the preprocessing of the watershed GIS data with HEC-GeoHMS.

The parameters of the initial calibration were used to expand the model to simulate ten years of streamflows. The second round of calibration adjusted the parameters to best represent the 10-year trend. According the Yapo et al. (1996), a continuous model for eight years or more was a good representation of the trend regardless of the time period of simulation. Therefore, the calibrated model for the first ten years would be used to verify the ability of the model to simulate data in the next two decades with reasonable outcome.

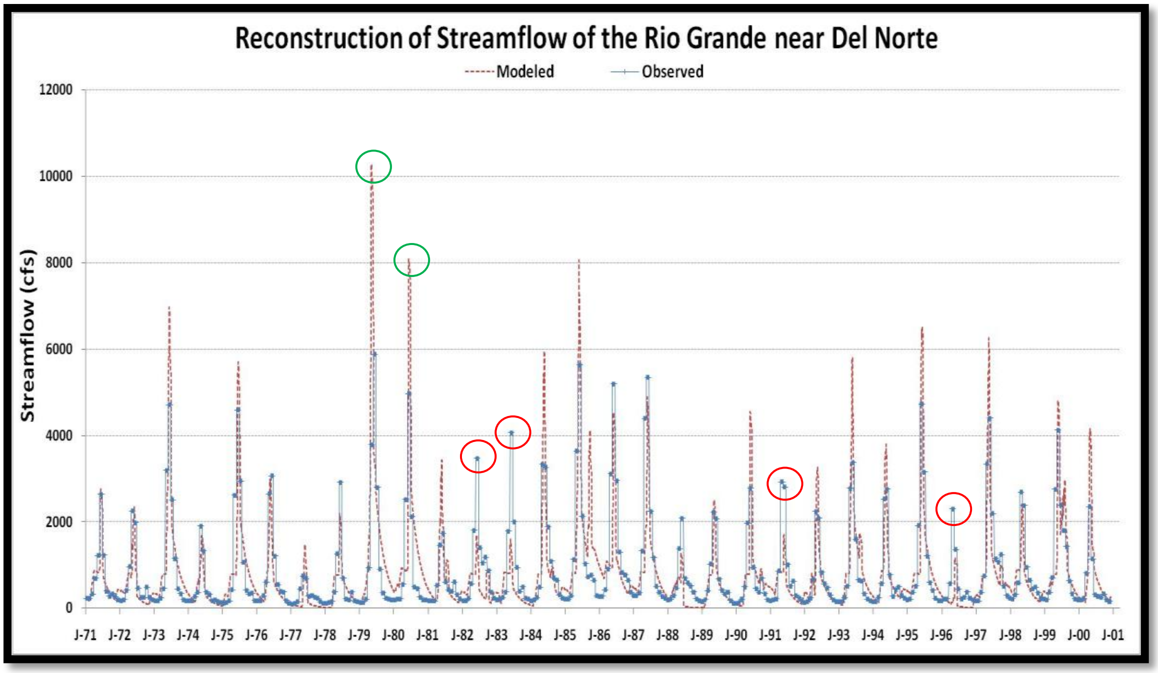


Figure 25: Reconstructed Streamflow of the Rio Grande near Del Norte

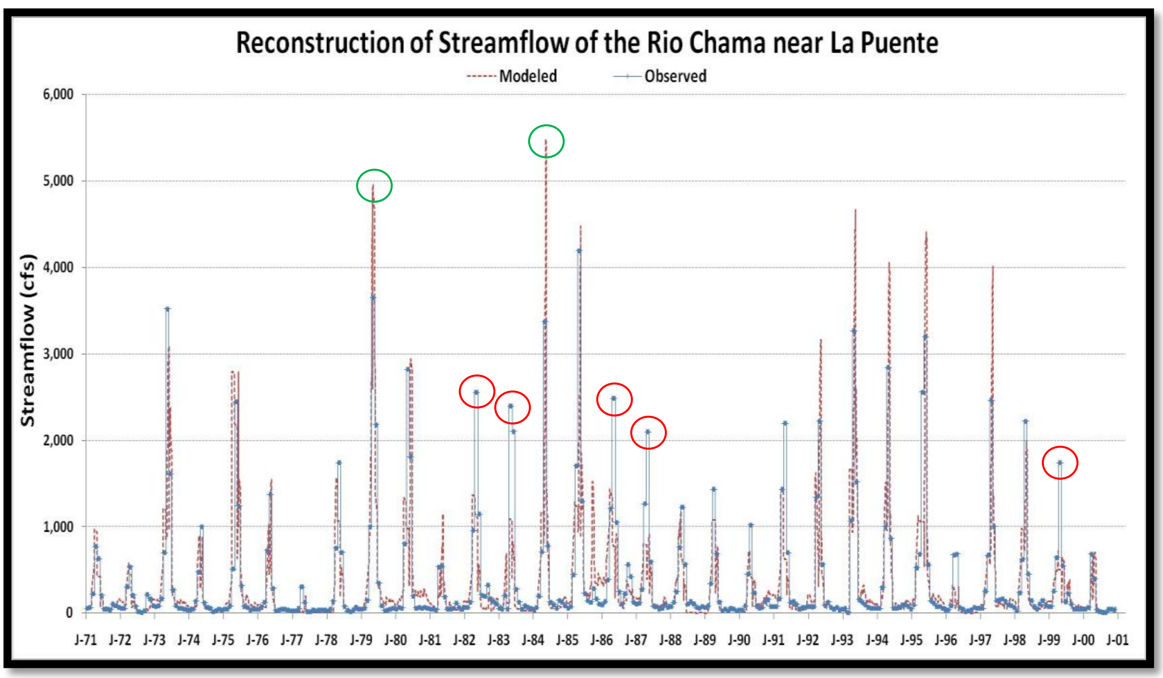


Figure 26: Reconstructed Streamflow of the Rio Chama near La Puente

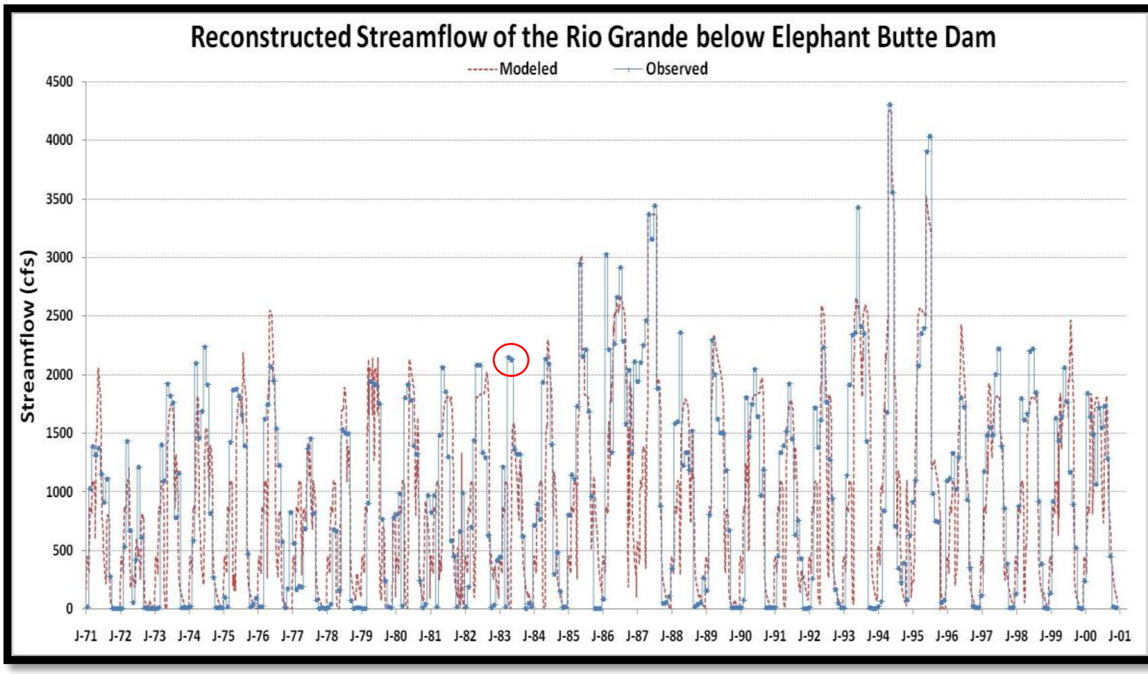


Figure 27: The Reconstructed Streamflow at Elephant Butte Outlet

After the verification process, the 10-year model underwent the third round of calibration to expand the model to the 30-year span. Only minor adjustments were made, for instance the recession constants and the ratios to peak of some sub-basins. The reconstructed streamflows at three control gauges are illustrated in Figues 25, 26, and 27.

The model significantly overestimated the peak streamflows at Del Norte for 1979 (4,000 cfs) and 1980 (3,000 cfs), and underestimated the peaks for 1982 (2,000 cfs), 1983 (2,500 cfs), 1991 (1,500 cfs), and 1996 (1,500 cfs). For the same years at Elephant Butte outlet, only the peak for 1983 (700 cfs) was underestimated. For the La Puente sub-basin, the model did not capture the peaks for 1982 (1,200 cfs), 1983 (1,500 cfs), 1986 (1,000 cfs), 1987 (1,200 cfs), and 1999 (1,000 cfs) while significatnly overestimated the peaks for 1979 (1,000 cfs) and 1984 (2,000 cfs). Details of the statistical error analyses will be discussed in the next section.

When the spring runoff peaks were overestimated, it could be the results from using spatially averaged precipitation for the sub-basins. When higher elevation locations were assigned more precipitation than they actually received, more accumulated snow resulted in overestimated spring snowmelt runoff. Also by using the spatially averaged temperature, it was assumed that the entire sub-basin was at the same temperature. When lower elevation locations were assigned colder temperatures than reality, precipitation was considered snowfall at lower elevation and, therefore, was accumulated, which overestimated spring snowmelt runoff.

Similary, the underestimated peaks elsewhere could be explained by using the spatially averaged time-series data. Overall, the model averaged out the errors from sub-basins and performs fairly well at the Elephant Butte outlet. Statistical error analyses will be presented in the next section to evaluate the performance of the model.

Statistical Error Analysis for Calibration of 30-year Model

To better visualize the modeled streamflows, the results at Elephant Butte were reduced from 22,000 data points to 360 data points for 30 years with MATLAB codes. The monthly average streamflows were computed, and the final results were reported as monthly averages as seen in Figure 28.

This HEC-HMS model is strictly the simulation of precipitation-runoff. It does not account for water withdrawal for irrigation, inputs from artificial tributary sources such as water treatment plants, and groundwater pumping. Groundwater wells that feed the Rio Grande in Colorado should make the observed streamflows higher than the modeled ones. Some characteristics of the artificial discharge at Elephant Butte are illustrated in Figure 27. The modeled volume represented by the blue line is lower than the observed volume which is influenced by the wastewater discharge and groundwater pumping for Albuquerque municipal use and Colorado feeding wells. On the falling limb from July to November, increased water withdrawal for summer irrigation lowers the observed discharge at Elephant Butte represented by the red line. The transition from November to December of the observed discharge shows an increase in streamflow after irrigation stops in November.

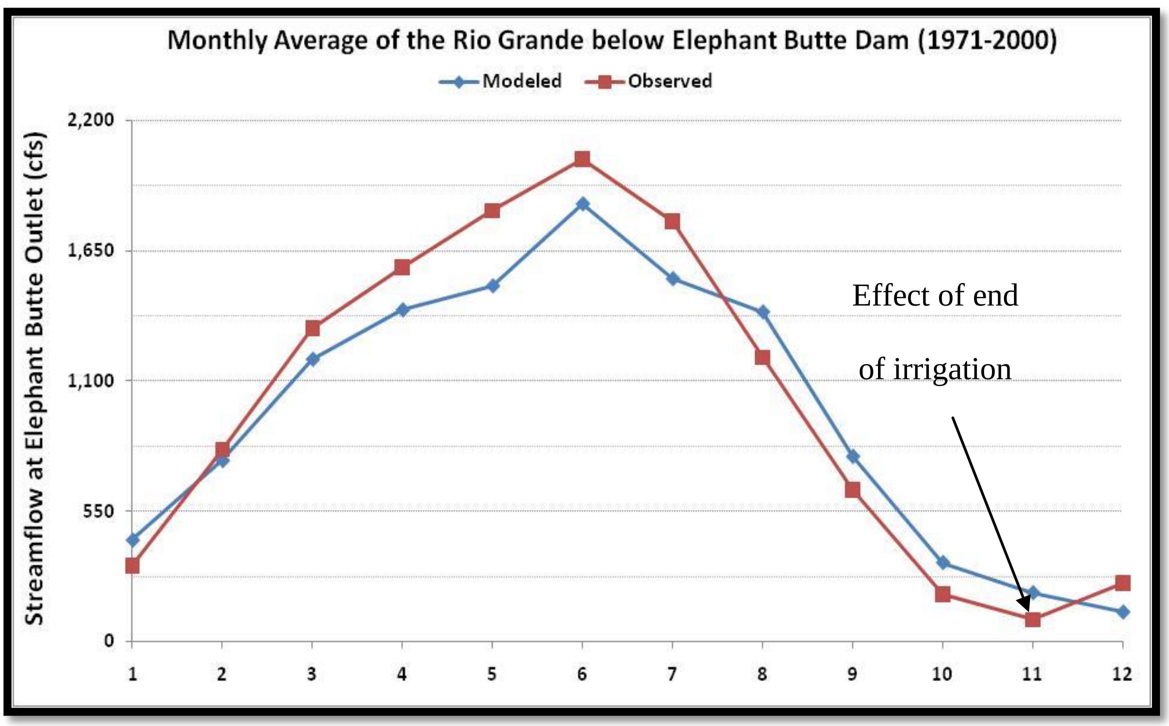


Figure 28: Modeled versus Observed Streamflows at Elephant Butte Outlet

Statistical error analyses were performed on the modeled verusus the observed streamflow at the verification gauges. As referenced to Cunderlik and Simonovic (2004), the following objective functions were selected for analyses:

- Peak-weighted root mean square error (PWRMSE): giving greater weight to simulated errors near peak streamflows.

$$PWRMSE = \sqrt{\frac{\sum_{t=1}^{n}(\frac{Qo\,(t) - Qm\,(t)}{Qo\,(t)})^2\,(\frac{\mathrm{Qo}\,(\mathrm{t}) + \mathrm{Qa}}{2*\mathrm{Qa}})}{n}}\;; \quad \mathrm{Qa} = \frac{1}{n}\sum_{t=1}^{n}\mathrm{Qo(t)} \qquad (2)$$

  Q_O = observed streamflow; Qm = modeled streamflow; Qa = average of observed streamflow

- Sum of squared residuals (SSR): giving more weight to large errors and less weight to smaller errors.

$$SSR = \sqrt{\frac{\sum_{t=1}^{n}(\frac{Qo\,(t) - Qm\,(t)}{Qo\,(t)})^2}{n}} \qquad (3)$$

- Sum of absolute residuals (SAR): giving equal weights to all errors.

$$SAR = \sum_{t=1}^{n}\left|\frac{\mathrm{Qo}\,(\mathrm{t}) - \mathrm{Qm}\,(\mathrm{t})}{\mathrm{Qo}\,(\mathrm{t})}\right| \qquad (4)$$

Monthly modeled versus observed averages at Del Norte and La Puente are illustrated in Figure 29 and Figure 30. The data to plot Figures 28, 29, and 30 were used in the statistical error analysis and are summarized in Table 5 to show how the model performs elsewhere other than at the outlet gauge of which observed streamflows were used in the calibration process.

Table 5: Statistical Error Analyses

TABLE 5	PWRMSE	SSR	SAR
Del Norte	7.6%	8.6%	2.5%
La Puente	7.2%	8.2%	2.4%
Elephant Butte	7.8%	9.1%	2.6%

At three locations, the unweighted errors (SAR) are smallest. It is intuitive that SAR averages out the large and small errors since they are equally weighted. The Peak-weighted errors are slightly smaller than the weighted errors, which indicates there are more large errors elsewhere than in the vicinity of the peak flows.

The model performed slightly better at La Puente than at Del Norte. One of the limitations of HEC-HMS is that there is no option to use more than one meteorologic model for one basin model unless twenty-one hydrologic models were created for twenty-one sub-basins. The meteorologic model replicates the climate conditions representing by precipitation, evapotranspiration, and snowmelt. For large watersheds with high elevation differences, it is not realistic to apply the same snowmelt parameters such as the melt rate or the snowmelt threshold for all locations due to radiation effects, wind conditions, etc. The water capacity of the snowpack should not be constant based on the spatial variabilities of the watershed. The overall performance of the model is slighly lower at the Elephant Butte outlet than at the two upstream control gauges because the streamflow of the Rio Grande downstream from Cochiti is influenced by release rules based on the flood control policy and the minimum discharge requirement for the silvery minnow.

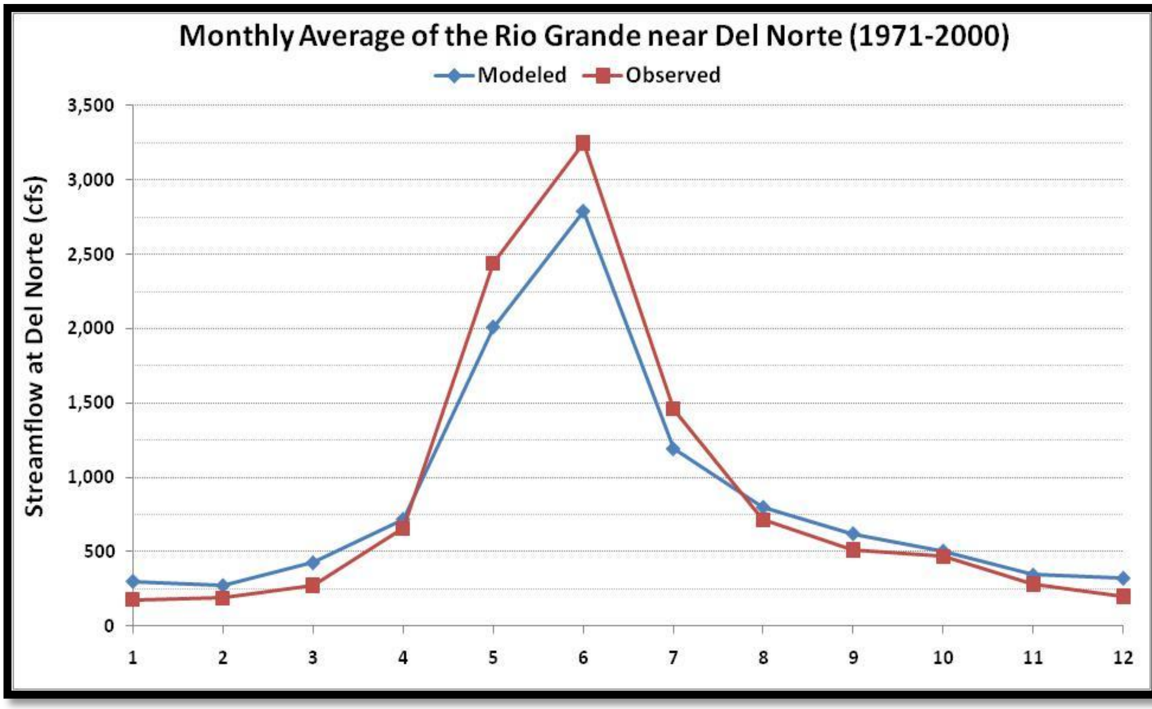


Figure 29: Modeled versus Observed Streamflows at Del Norte

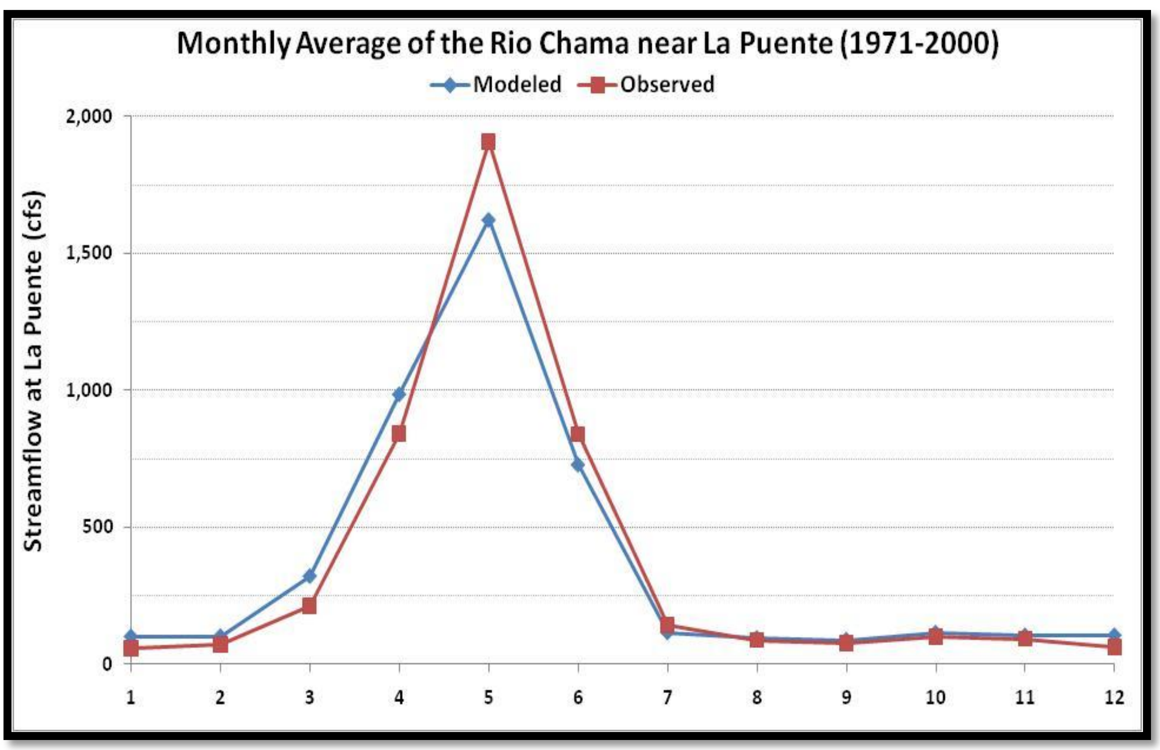


Figure 30: Modeled versus Observed Streamflows at La Puente

Validation

Validation is the process to assess the ability of the calibrated model to reconstruct measurements from input datasets other than those used for the calibration. In the validation process, all calibrated parameters should not be adjusted. The reconstructed streamflows were compared with the observed streamflows to determine the performance of the model. Yapo et al. (1996) indicated that any continuous model spanning above eight years would be a statistically reasonable representation of the trend regardless of the time period. Cunderlik and Simonovic (2004) used a 9-year model from 1987 to 1996 to check against the following nine years of the observed data. Before the HEC-HMS rainfall-runoff model for the Rio Grande was finalized for the 30-year run, it had been calibrated for the first year of the first decade to replicate the spring snowmelt runoff peak to approximate the parameters for the snowmelt threhold. The one-year preliminary calibration was then developed into the 10-year model for the period from 1971 to 1980 as seen in Figure 31 . It was then used with the precipitation and temperature from the following two decades to reconstruct streamflows for the 1981-1990 and 1991-2000 periods. Figures 32, 33, 34, and 35 show the validation results of the monthly average results at Del Norte and La Puente.

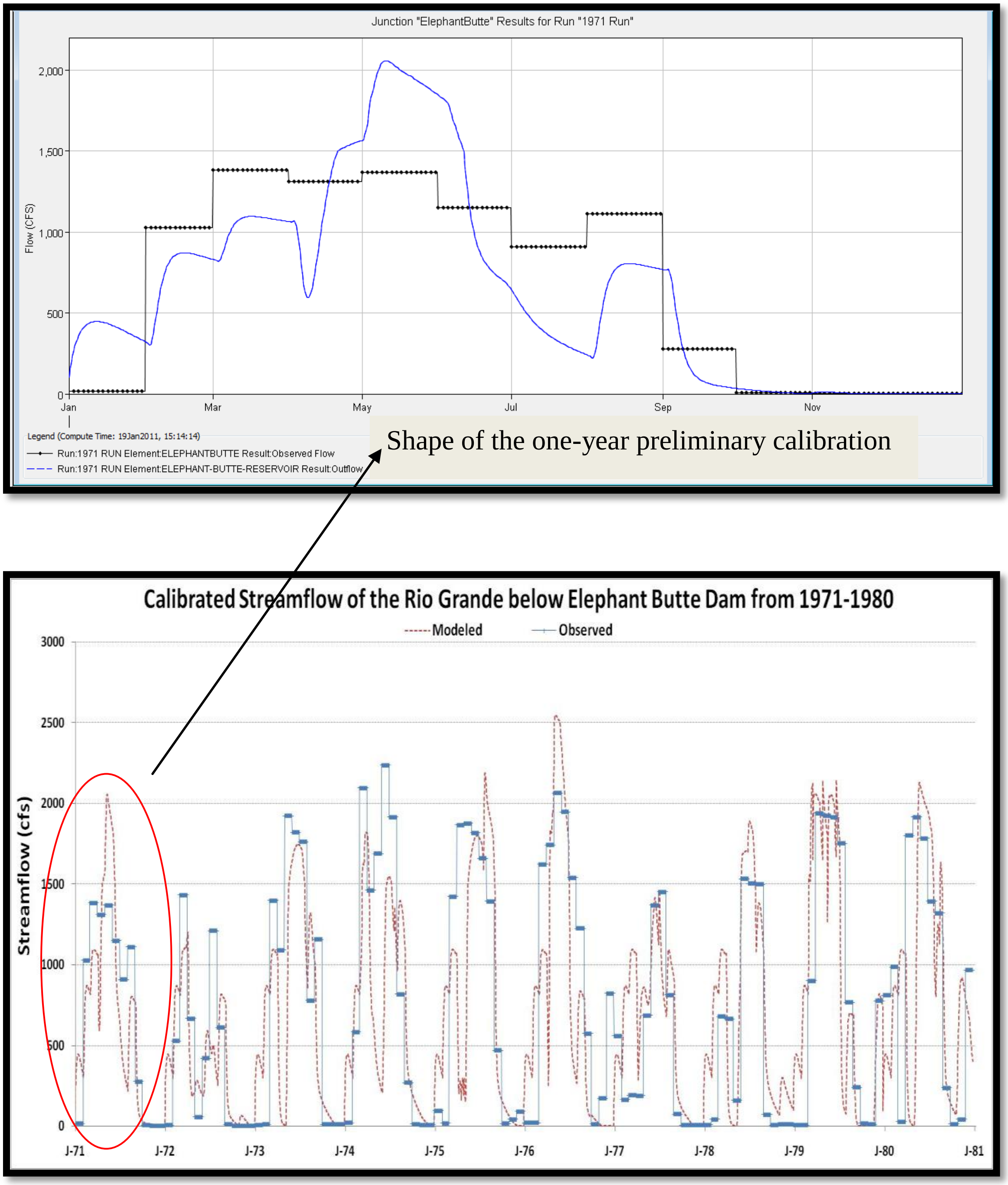


Figure 31: Ten-year Calibration at Elephant Butte Outlet

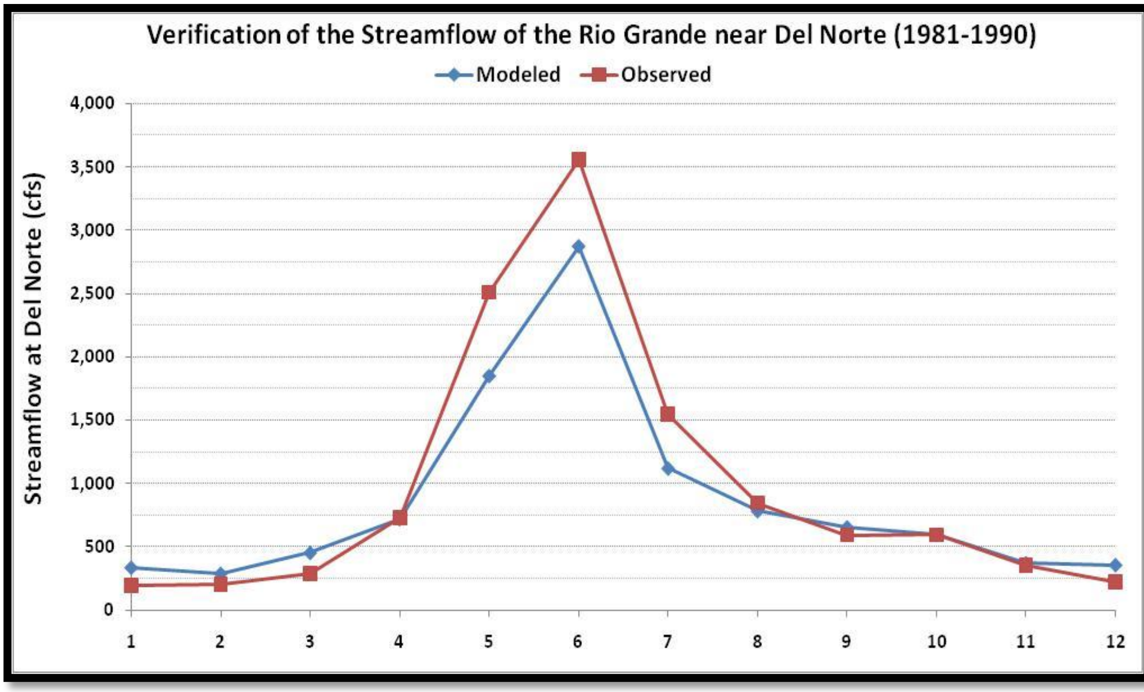


Figure 32: Validation for 1981-1990 Period for Del Norte

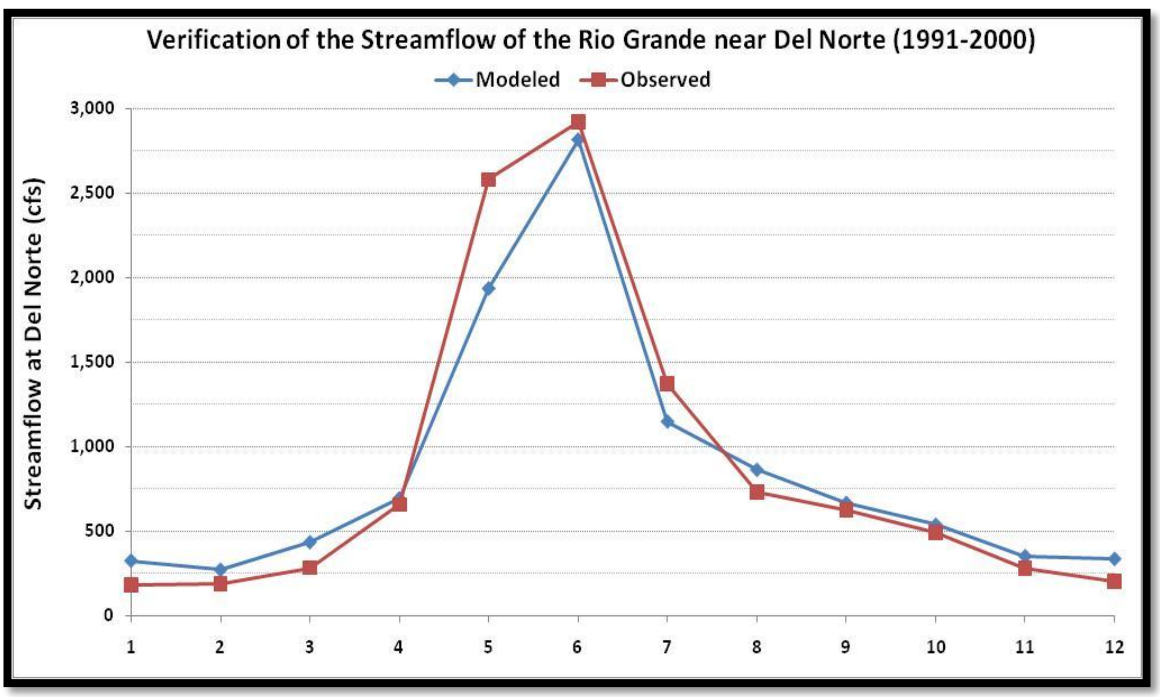


Figure 33: Validation for 1991-2000 Period for Del Norte

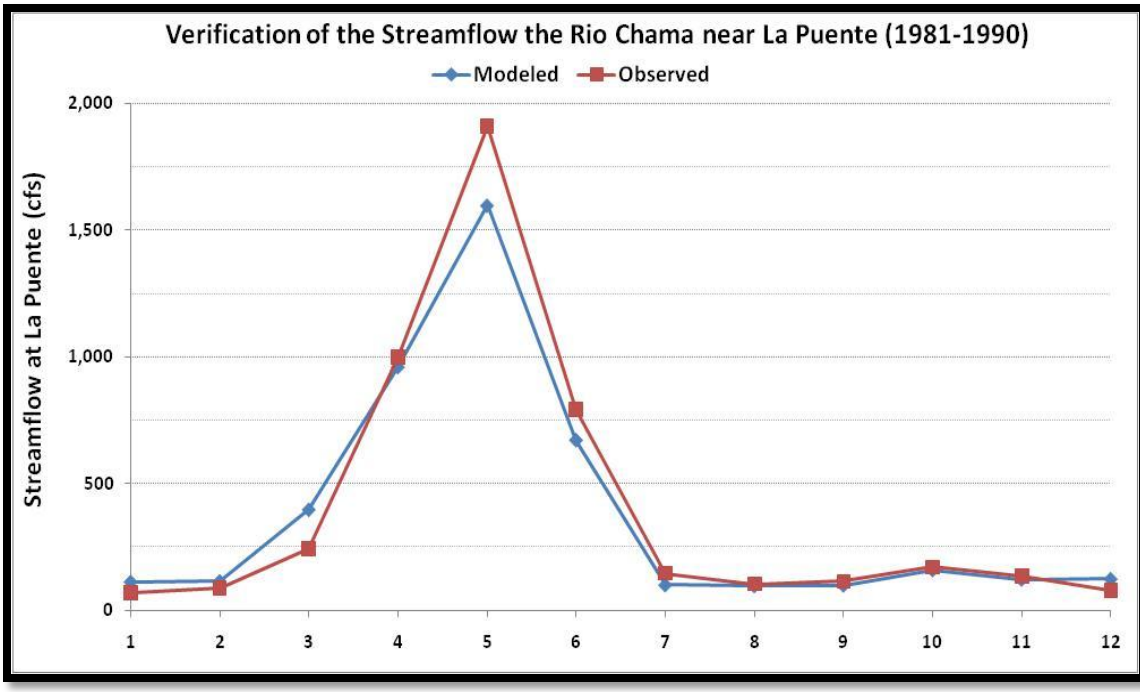


Figure 34: Validation for 1981-1990 Period for La Puente

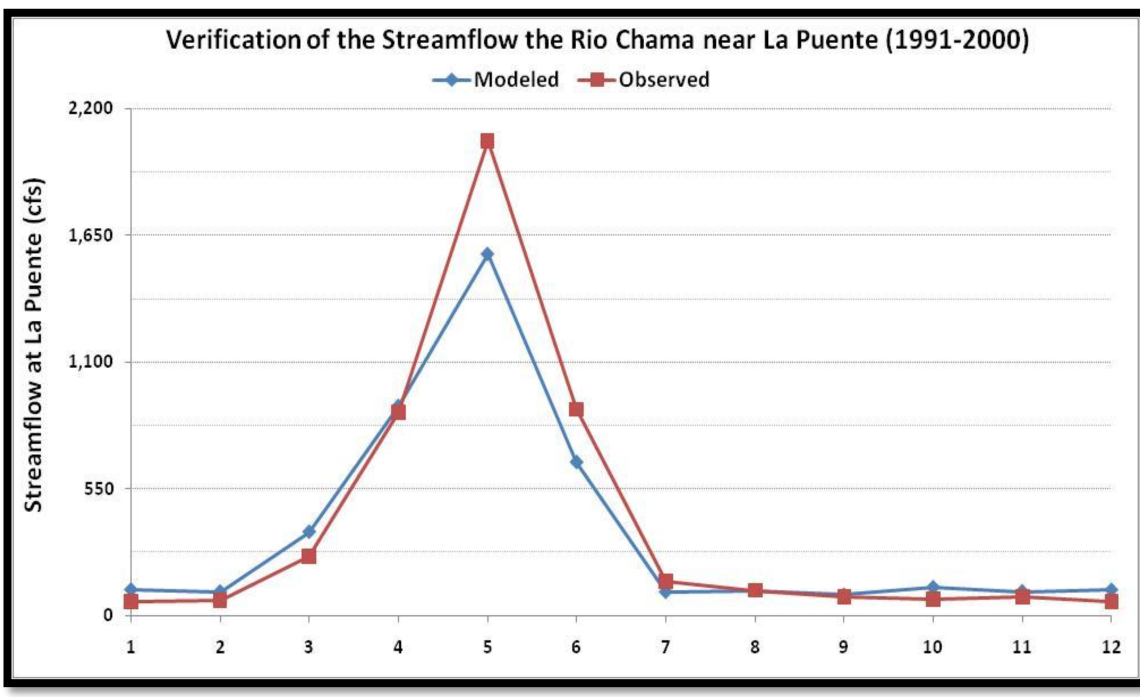


Figure 35: Validation for 1991-2000 Period for La Puente

Statistical Error Analysis for Validation of 10-year Model

Similar statistical error analyses were conducted for the validation process by applying equations 2, 3, and 4 to the reconstructed streamflows and the observed discharges. The results are summarized in Table 6.

Table 6: Statistical Error Analyses of the Validation Results

TABLE 6	PWRMSE			SSR			SAR		
	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000	1971-1980	1981-1990	1991-2000
	Calibration	Validation		Calibration	Validation		Calibration	Validation	
Del Norte	7.6%	7.1%	7.5%	8.6%	7.8%	8.6%	2.5%	2.3%	2.5%
La Puente	7.2%	6.7%	9.6%	8.2%	7.6%	11.1%	2.4%	2.2%	3.2%

Errors of 10% and below indicate reasonable performance of models (Cunderlik and Simonovic, 2004). The results from the last decade are not as strong as the previous one, especially for La Puente sub-basin. La Puente average streamflow is about half of Del Norte average streamflow. Therefore, the same magnitude of discrepancies in streamflow reconstruction will amplify the errors. Overall, the results of the statistical error analysis prove that the 10-year calibration period is long enough to represent the trend regardless of the selection of the decade.

With reasonable reconstructed results, the 10-year model was expanded to the 30-year model since the ultimate objective of this research was to project 30-year streamflows of the Rio Grande for the near future and long-term future climate change scenarios. There were minor fine-tuning changes between the 10-year and the 30-year models to adjust the streamflow meeting points between three decades.

Sensitivity Analysis

Sensitivity analysis is the process to determine how sensitively the model reacts to the changes of its input parameters. There are two types of sensitivity analyses which are the local and global methods (Cunderlik and Simonovic, 2004). For the local sensitivity analysis, one parameter is varied while others are kept constant. In the global sensitivity analysis, all parameters are varied over their ranges. The results of both methods are reported as a set of sensitivity functions for each parameter.

For this research, the timing of snowmelt runoff and the total volume are the two primary concerns for long term water availability assessment. Sensitivity analyses were performed to determine how sensible peak discharges and total annual volume were when they were subject to changes of some parameters of the meteorologic model in Figure 36.

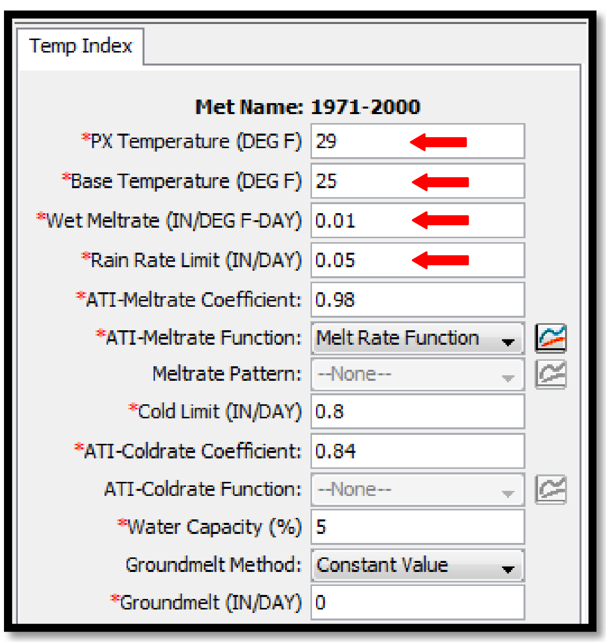


Figure 36: Parameters of the Meteorologic Model for Sensitivity Analyses

The first four parameters of the meteorologic model were selected for the local sensitivity analysis. These four parameters were chosen in this analysis because PX Temperature and Base Temperature were the calibrated values, and the Wet Meltrate and Rain Rate Limit were adopted from similar works. Other parameters of the meteorologic model were recommended values from HEC-HMS User's Manual based on USACE's experiences in large varieties of applications of the software. Therefore, those parameters should not be varied. The 10% change increment was applied to each parameter while others were kept constant for the local sensitivity analysis. Referenced to HEC-HMS 3.4 User's Manual, the parameters used in the sensitivity analysis are described as following:

- PX Temperature is used to distinguish between precipitation as rainfall or snowfall. This value was obtained through the calibration process.
- Base Temperature determines the temperature index which was used to calculate snowmelt. This value was obtained through the calibration process.
- Wet meltrate is the melting rate when precipitation rate is greater than rain rate limit. This value was adopted from Colombie's Master's Thesis (2007) which was referenced to D. Mosnier, EDF, "Ingenierie de amenagements hydrauliques", 2006.
- Rain rate limit sets the upper bound of rain rate over which there will be snow on rain effect. This value was adopted from Colombie's Master's Thesis (2007).

Table 7 summarizes the analysis results of the PX and Base Temperatures.

Table 7: Sensitivity Analyses for PX and Base Temperatures

% Change of Parameters	PX Temperature			Base Temperature		
	% Volume Change	% Peak Change	PEAK SHIFT (months)	% Volume Change	% Peak Change	PEAK SHIFT (months)
10%	-2.98%	0.00%	0	-13.29%	-25.36%	0
20%	-2.74%	2.74%	0	-24.11%	-65.84%	+1
30%	-3.50%	0.81%	0	-31.67%	-76.96%	+2
-10%	-2.98%	0.20%	0	16.49%	-5.05%	-1
-20%	-2.98%	0.30%	0	25.07%	-17.14%	-1
-30%	-2.98%	0.30%	0	31.05%	-26.29%	-1

Table 8 summarizes the analysis results of the Wet Melt Rate and Rain Rate Limit.

Table 8: Sensitivity Analyses for Wet Melt Rate and Rain Rate Limit

% Change of Parameters	Wet Melt Rate			Rain Rate Limit		
	% Volume Change	% Peak Change	PEAK SHIFT (months)	% Volume Change	% Peak Change	PEAK SHIFT (months)
10%	-2.97%	0.00%	0	-2.93%	-0.02%	0
20%	-2.96%	0.00%	0	-2.93%	-0.02%	0
30%	-2.95%	0.00%	0	-2.93%	-0.02%	0
-10%	-2.99%	0.00%	0	-2.99%	0.01%	0
-20%	-3.00%	0.00%	0	-2.97%	0.05%	0
-30%	-3.01%	0.00%	0	-3.00%	0.03%	0

Referenced to HEC-HMS 3.4 User's Manual, the PX temperature ranges from 1 ^{o}C to 2 ^{o}C above the Base Temperature. By increasing the PX temperature, more precipitation was considered snowfall, which resulted in more snow accumulation. Consequently, the snowmelt-induced peak increased as reported in Table 7. Another effect of increasing snow accumulation was the slight decrease of the annual volume because the timing of snow accumulation occurred earlier at the end of the year, which increased evaporation.

Decreasing the PX temperature resulted in more precipitation coming as rainfall. Decreasing the PX temperatures by 10%, 20% and 30% in the sensitivity analyses was equivalent to subtracting 2.9 ^{o}F, 5.8^{o}F, and 8.7 ^{o}F respectively from the initial PX value which was 4 ^{o}F above the base temperature. The difference between the air temperature and the base temperature determines how much snow melts. By dropping the PX temperatures below the base temperature, the precipitation coming as rainfall would not be available for immediate runoff, which increased snow-induced peak as reported in Table 7. The effects on peak discharges and total annual volumes did not change once the PX temperatures were below the base temperature, because all precipitation was not available for immediate runoff.

The Base Temperature had complicated impacts on the model. When the air temperature is above the base temperature, there is a temperature gradient for snowmelt. The higher the base temperature was, the less gradient there was to drive snowmelt in the early months of spring, which significantly reduced the peak discharges. It took longer to melt the accumulated snow, which saturated the soil surface for a longer time and increased infiltration and evaporation. Consequently, the total annual volume decreased as reported in Table 7. In the worst case when the base temperature was increased by 30%, the peak discharge occurred two months later because June did not have the greatest temperature gradient for snowmelt.

Lowering the base temperature increased the temperature gradient for snowmelt during the winter months, which reduced spring snowmelt runoff. The peak shifted one month earlier because the temperature in May was significant enough to drive a lot of snowmelt. Monthly streamflows from October through May increased significantly because the temperature gradients were higher, which increased the total annual volume.

The Wet Melt Rate and the Rain Rate Limit did not affect the model as reported in Table 8. This indicates that the amount of precipitation coming as rainfall in the winter months was not significant enough for the watershed to experience the rain-on-snow effect.

APPENDIX H: RESULTS AND ANALYSES

Projection Results and Analyses

Precipitation and temperature data for the 1971-2000 period were spatially averaged at the centroids of all sub-basins. Future temperature and precipitation inputs for the projection of streamflows were derived from the 1971-2000 time-series data and Table1 and Table 2. Table 1 projects future precipitation under six climate change scenarios as percentage changes with respect to PRISM precipitation for the 1971-2000 period. Table 2 calculates future temperatures under six climate change scenarios as changes in Fahrenheit degrees with respect to PRISM temperatures for the 1971-2000 period.

Early study of the diurnal variations of temperatures in soils by Wollney (1883) and Bouyoucos (1913) indicated that at the depth beyond 8 inches, the change of temperatures between day and night of a loam soil during the summer was at most 3.6 ^{o}F. The maximum increase of temperature for the worst case scenario from Table 2 is approximately 10 ^{o}F which is approximately one-third of the diurnal variation in temperatures of a summer day. Soil temperatures affect water temperatures in soils, which have an impact on the hydraulic conductivity. As the temperature increases 1.8 ^{o}F above room temperature, the hydraulic conductivity drops to 98% compared to the value reported at room temperature (Das, 2006). Therefore, it can be concluded that the magnitude of temperature changes under six climate impact scenarios do not affect the properties of sub-surface soils.

The 30-year calibrated model used the projected precipitation and temperature to project streamflows at Elephant Outlet. There were almost 22,000 data points for the projected streamflows under each climate change scenario. MATLAB codes were written to reduce each projected streamflow dataset into twelve monthly averages as seen in Figure 37.

The USGS gauge of the Rio Grande at Otowi Bridge is used to determine the amount of water New Mexico is entitled to and has to deliver to Texas under the requirements of the Rio Grande Compact. Besides the projected results at Elephant Butte, the simulated outflows at Otowi were plotted as seen in Figure 38 and summarized in Table 9 to quantify how well New Mexico would be able to meet its delivery obligation to the Rio Grande Compact.

Table 9: Projection of Total Annual Volume Changes at Indicator Gauges

TABLE 9	Indicator Gauge	2030			2080		
		Wet	Middle	Dry	Wet	Middle	Dry
% Volume Change	Elephant Butte	-8.5%	-13.3%	-26.3%	-38.3%	-47.7%	-54.5%
	Otowi	-10.8%	-14.0%	-25.4%	-17.0%	-32.2%	-35.8%

Table 9 shows the progression of volume decreases under six climate change scenarios for Elephant Butte oulet and Otowi gauge. The projected changes for the near future scenarios are very similar at two locations. Long-term projected changes at Elephant Butte outlet are more severe than at Otowi. This indicates that the watershed downstream from Otowi will be more sensitive to climate change impacts.

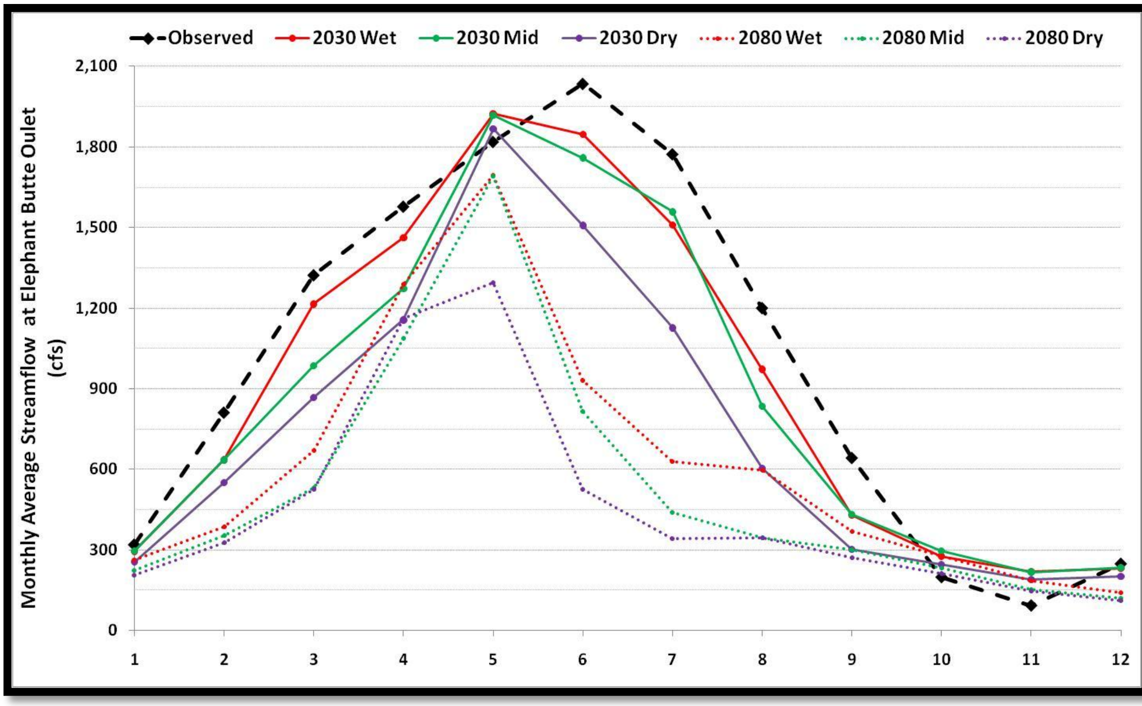


Figure 37: Projection of Streamflows at Elephant Butte Outlet

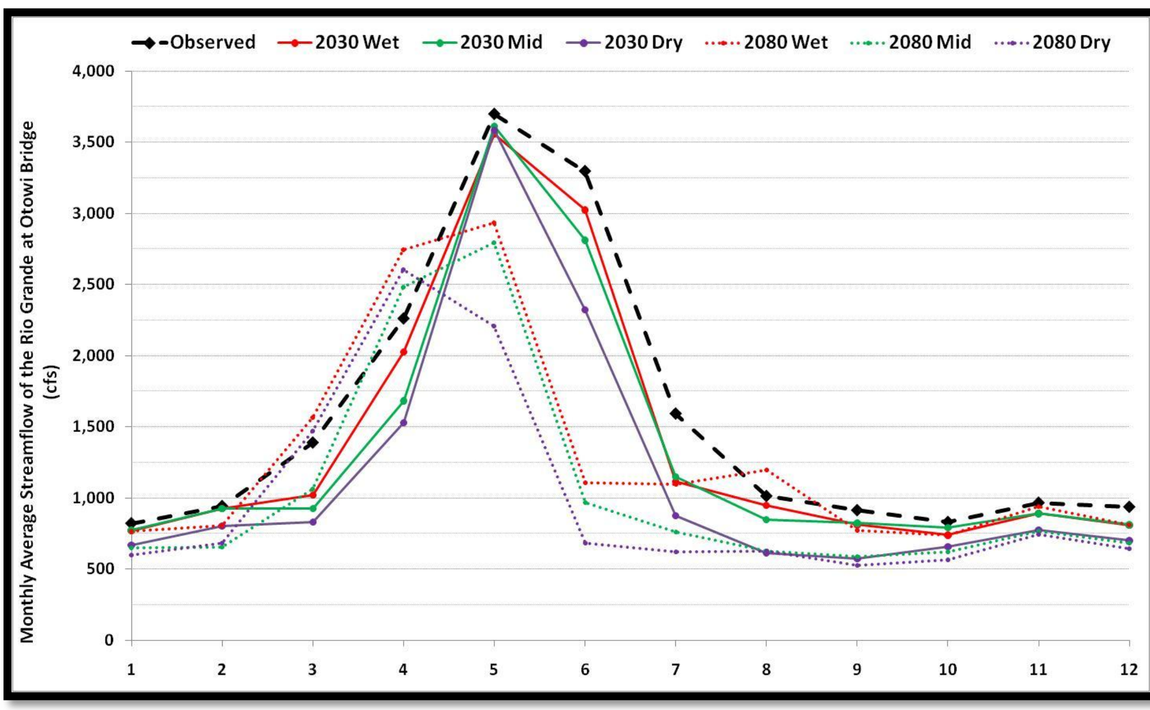


Figure 38: Projection of the Streamflow of the Rio Grande at Otowi Bridge

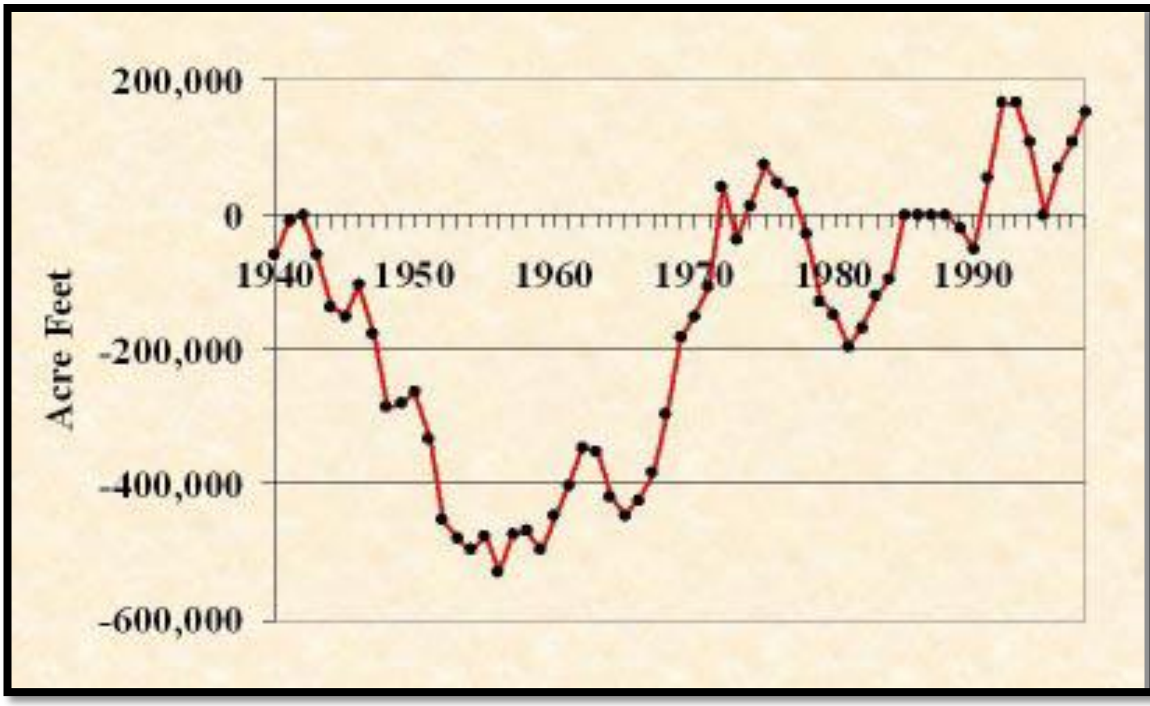


Figure 39: Historical Rio Grande Compact Deliveries from New Mexico

(1999 WRRI Conference Proceedings)

As seen in Figure 39, from 1971 to 2000, New Mexico had periods when it exceeded the delivery obligation as well as when it failed to meet the requirement of the Rio Grande Compact. For the near future projection when the streamflows of the indicator gauges decline at the similar rates as indicated in Table 9, it is likely that New Mexico will be entitled to less water apportions because New Mexico depletion entitlement is proportional to the incoming streamflow at the upstream indicator gauge. However, the long term projections at Elephant Butte outlet decline more dramatically than those at the upstream indicator gauge. At lower elevation areas such as the sub-basins downstream from Otowi, due to warmer temperature projection, there will be more snow-on-rain effects in the winter months, which increases winter runoff and decreases summer reservoir storage. Warmer temperatures also result in more evapotranspiration in the summer months, which worsens the situation. The delivery obligataion does not take into account more severe climate change impacts that the lower half of the watershed will encounter. Therefore, in order to maintain the water supply for its increasing water demand, New Mexico will face significant delivery debt to Texas. However, the cumulative debt cannot exceed 200,000 acre-feet which New Mexico has encountered during the 1971-2000 period (1999 WRRI Conference Proceedings), the “no-climate-change-impact” baseline. Being able to solve the future water budget problem will be a tough task for the water management authorities.

Another significant impact of the severely altered climate is the shift of peak streamflows as seen in Figure 37 and Figure 38. Therefore, peak evaporation will also shift to early spring due to decreased soil moisture in the summer months. This puts more stresses on native vegetation, which can affect their health and regeneration processes. Other aspects of New Mexico lifestyles will also be interrupted by the peak shift phenomena. Summer river rafting will be impossible; summer irrigation will be limited; declined summer reservoir storgage will have negative impacts on summer water activities. And there are many more hydrologic, economic, cultural, and ecological consequences that cannot be quantified due to limitations of human capacity.

APPENDIX I: SUMMARY AND CONCLUSION

This study explored the continuous modeling capability of HEC-HMS to calibrate a precipitation-runoff model for the Rio Grande watershed stretching from Del Norte, Colorado, to Elephant Butte, New Mexico. The model was then applied to project streamflows of the Rio Grande under different climate change scenarios. In order to prepare the input data for the model, multiple sources of data were utilized.

- DEM data were collected from USGS database. HEC-GeoHMS helped to delineate the watershed into 21 sub-basins and to calculate the hydraulic and hydrologic parameters of each sub-basin.
- PRISM provides continuous surfaces of precipitation and temperature time-series data which were spatially averaged at the centroid of each sub-basin.
- Observed streamflows to calibrate the model and to perform statistical analyses were extracted from USGS database for the Rio Grande below Otowi Bridge, the Rio Grande below Elephant Butte Dam, the Rio Grande near Del Norte, the Rio Chama near La Puente.
- Projected temperature and precipitation data were adopted from Smith and Wagner (2006) as well as Hurd and Coonrod (2008). Several model parameters were referenced to Colombie (2007), and USACE's HEC-HMS user's manual.

The structure of the model includes a basin created from HEC-GeoHMS, a meteorologic method to replicate the atmospheric conditions of the watershed and to perform water balance accounting, and a control specification to monitor the time period to run the simulation.

The model was first calibrated for the first year to replicate the spring snowmelt peak and to approximate the snowmelt threshold which was very sensitive to the performance of the model. The 10-year model (1971-1980) was developed from the initial one-year calibration. The performance of the 10-year model was tested on two sub-basins, Del Norte and La Puente, which have the two largest inflow contributions to the Upper Rio Grande. Since the model was only calibrated against the streamflow at Elephant Butte outlet, statistical analyses were conducted on the results at the two gauges at Del Norte and La Puente to see if the outputs were acceptable elsewhere besides at the Elephant Butte outlet.

Statistically, the calibration for any time period longer than eight years is a good representation of the trend regardless of the selected years (Yapo, 1996). With the input data from the two decades, 1981-1990 and 1991-2000, the 10-year calibration was used to verify the performance of the model on the decades of which data were not used for the calibration process. Statistical error analyses were performed on the reconstructed streamflows to verify the performance of the model with data inputs other than those used for the calibration period.

In the last round of calibration, the 30-year model was developed from the 10-year model with minor adjustments. With the reasonable assumption that the conductivity of soils would not be affected by climate change impacts and consequently that the watershed would behave similarly in the future as it did in the past, the 30-year calibrated model was used to project streamflows of the Rio Grande for the near and long-term futures. The projections for the worst case (2080 Dry) and the best case (2030 Wet) scenarios were plotted for Elephant Butte and Otowi as illustrated in Figure 40 and Figure 41. The changes in temperature in Fahrenheit degrees associated with these two extreme scenarios were plotted above the projected hydrographs to show the direct correlation of the temperature increases with the projected monthly averages. Not only does the annual volume decrease, but the snowmelt runoff peaks also occur sooner. Significant volume drops during the warmest months of the year when water is needed the most will negatively impact the scarce water supply for human consumptions, agricultural and industrial uses, and ecological sustainability in New Mexico.

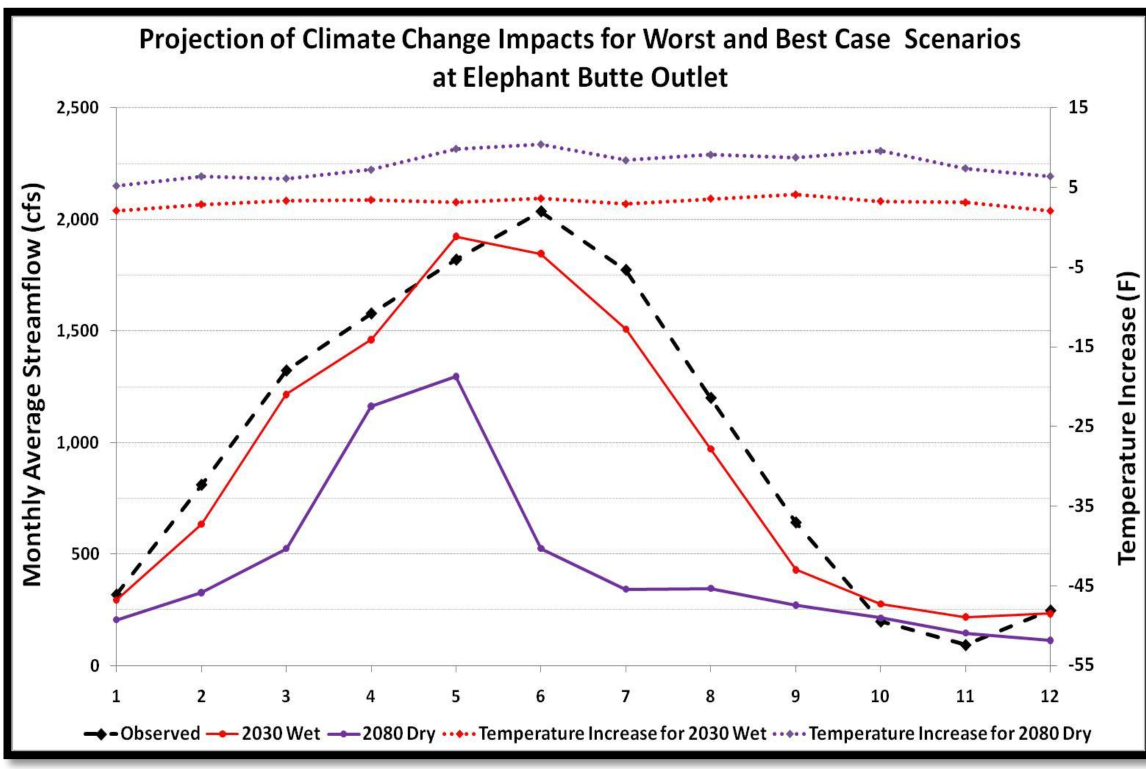


Figure 40: Streamflow Projection for Worst and Best Case Scenarios at Elephant Butte Outlet

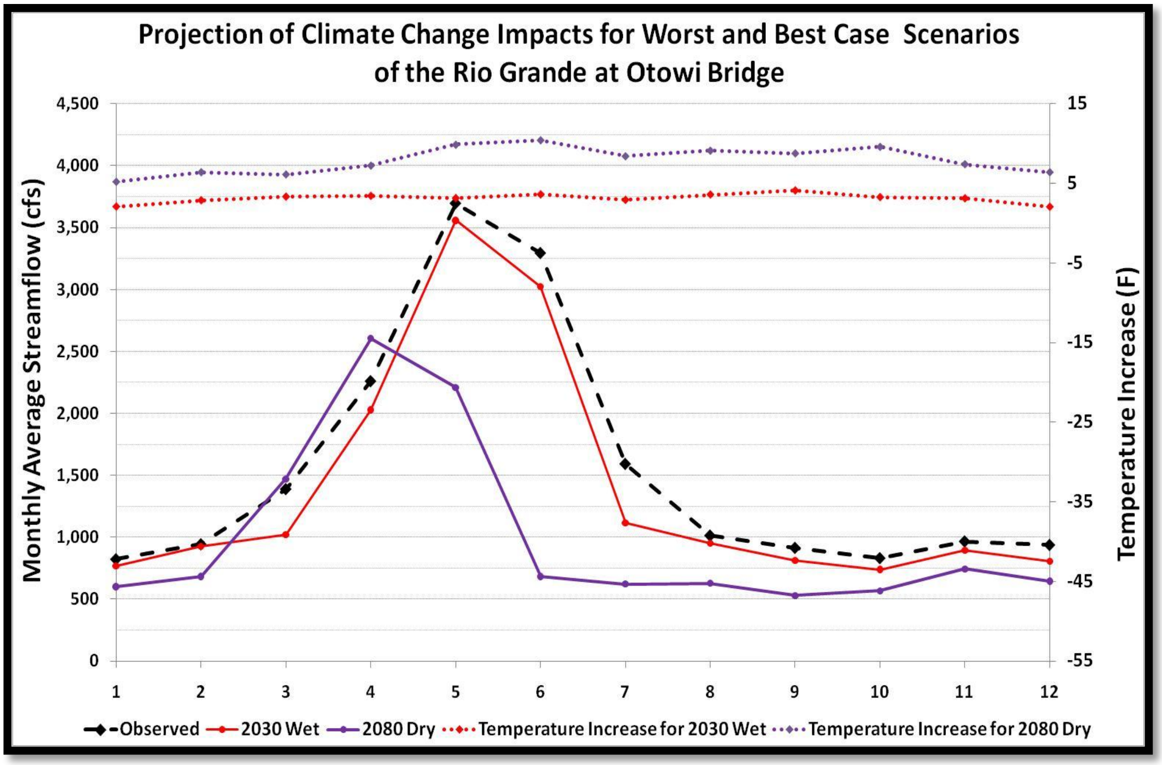


Figure 41: Streamflow Projection for Worst and Best Case Scenarios at Otowi

The results of the projected streamflows for the long-term future indicated that the sub-basins downstream from Otowi were more sensitive to climate change impacts. The delivery obligation does not take into account the fact that the lower half of the watershed will be more severely affected by long-term future climate change scenarios. In the period of calibration when it was considered the "no-climate-change-impact" baseline, New Mexico maxed out the water debt to Texas. As more severely altered climates projected by different climatic models occur, there is no doubt that New Mexico will not be able to fulfill its delivery obligation. The task to allocate water effectively to meet increasing water demands of New Mexico and to ensure the fulfillment of its delivery obligation in the future will be very challenging to the water management authorities.

APPENDIX J: TUTORIAL ON DATA PROCESSING IN HEC-GEOHMS

Terrain Processing with HEC-GeoHMS

Order of terrain processing:

- Fill sinks: to avoid unwanted sinks in DEM. In put file = raw DEM
- Flow direction: input file = filled DEM
- Flow accumulation: input file = flow direction file. This process takes very long if the area of the DEM is large (> 1,000 mi^2)
- Stream definition: input file = flow accumulation file. Users need to specify the stream threshold. Otherwise, the default value is 1/100 of the total number of DEM cells. Using 1/50 of the total number of DEM cells results in reasonable sizes of sub-basins created later.
- Stream segmentation: input file = stream grid defined from stream definition process
- Catchment grid delineation: input files = flow direction file and stream link file defined from the stream segmentation process
- Catchment polygon: input file = catchment grid
- Drainage line: input files = stream link defined and flow direction
- Adjoint Catchment: input files = drainage line and catchment polygon. The watershed with its drainage line is defined.

HMS Project Setup

Order of setting up a new HMS project:

- From HMS Project Setup dropdown menu, select Start new project. Users define project name, briefly describe project, and specify the location of Geodatabase created for the new project
- Use create project point icon to define the outlet of the basin
- From HMS Project Setup dropdown menu, select Generate project. Users need to verify all correct input files for the new project when the Generate Project window pops up. These input files are: Raw DEM, Hydro DEM (filled DEM), Flow Direction Gird, Flow Accumulation Grid, Stream Grid, Stream Link Grid, Catchment polygon, Adjoint Catchment, Project Area and Project Points.
- A new data frame for the HMS project is created. All information for the new data frame is extracted from the parent data frame which was created when the original DEMs were downloaded.
- Default layers calculated for the new data frame: Mainview DEM, RAW DEM, Filled DEM, Flow Direction, Stream Network, Stream Link, Catchment, River, Sub-basin

Computing of Basin Characteristics

Order of basin characteristics to be computed:

- River length: input layer: River
- River slope: input layers: RAW DEM and River
- Longest Flow Path: input layers: RAW DEM, Flow Direction Grid, Sub-basin
- Basin centroid: select Center of gravity method
- Centroid elevation: input layers: RAW DEM and Centroid

- Centroid flow path: input layers: Sub-basin, Centroid, Longest Flow Path

Develop Hydrologic Parameters

- Select HMS process: verify the input sub-basin and river layers and click OK. The Select HMS process window pop ups. Users need to select the appropriate loss method, transform method, and baseflow type for their watersheds
- River Auto Name: input layer: River
- Basin Auto Name: input layer: Sub-basin

HMS Export

Order to export the project into HMS:

- Map to HMS Units: input layers: RAW DEM, Sub-basin, Longest Flow Path, Centroidal Longest Flow Path, River, and Centroid. Users need to select the appropriate unit system (English or SI) for their projects.
- Check data: input layers: River, Sub-basin, Project Point, and Centroid. Copy down the location where the check file is saved.
- HMS Schematic: input layers: Project Point, Centroid, River, Sub-basin, HMS Link, HMS Node
- Toggle HMS legend: users can select between Regular Legend from ArcGIS or HMS legends
- Add coordinates: input layers: RAW DEM, HMS Link, and HMS Node
- Prepare data for export: input layers: Sub-basins and River
- Background map: select background shapefile; input for background shapefile:

Sub-basin and River. Copy down the location where the shapefile is saved.

- Basin file: the basin file model captures the hydrologic elements, their connectivity, and related geographic information in an ASCII text file that can be read by HEC-HMS. Copy down the location where the basin file is saved.

Creating HEC-HMS Project

- The basin file which includes all hydrologic elements created from can be imported into HEC-HMS from the File Menu → Import → Basin Model. Go to the location where the basin file was saved and select the basin file. Watershed parameters calculated from ArcGIS are stored with the basin file.
- The background map which includes the boundary of the watershed, the delineated sub-basin, the river, and the outlet can be imported into HEC-HMS from the View Menu → Background Map → Add. Select the background shapefile created in ArcGIS to import into HEC-HMS.

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