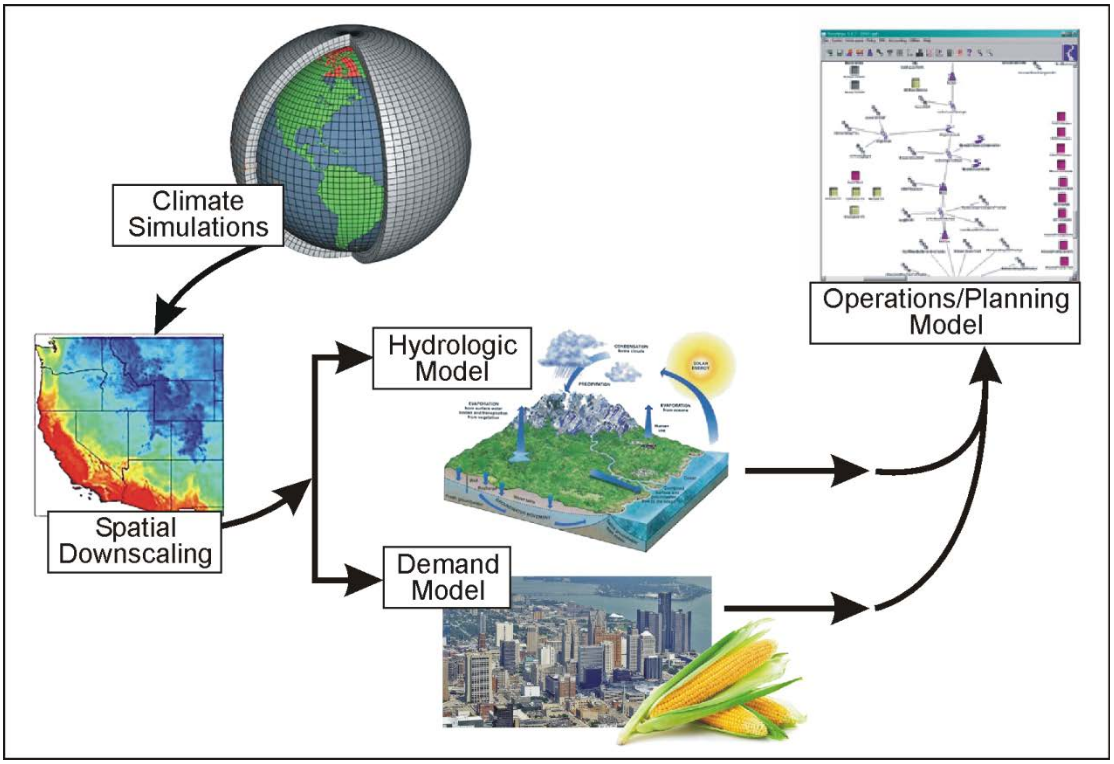
Appendix D: Development of Hydrologic Projections



U.S. Department of the Interior
Bureau of Reclamation
Upper Colorado Region
Albuquerque Area Office

December 2013

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

The U.S. Army Corps of Engineers Mission is to deliver vital public and military engineering services; partnering in peace and war to strengthen our Nation's security, energize the economy and reduce risks from disasters.

Sandia Laboratory Climate Security program works to understand and prepare the nation for the national security implications of climate change.

Acronyms and Abbreviations

ABCWUA	Albuquerque Bernalillo County Water Utility Authority
BCSD	Bias Correction and Spatial Disaggregation
CDF	cumulative distribution functions
cfs	cubic feet per second
CMIP3	Coupled Model Intercomparison Project Phase 3
dd	decimal degree
GCM	General Circulation Models
IPCC	Intergovernmental Panel on Climate Change
MRGCD	Middle Rio Grande Conservancy District
RCM	Regional Climate Models
URGSiM	Upper Rio Grande Simulation Model
URGWOM	Upper Rio Grande Operations Model
VIC	Variable Infiltration Capacity (hydrologic model)
WCRP	World Climate Research Programme

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I. Document Purpose and Organization

In this Appendix, we describe the methods used to generate the hydrologic projections presented in the Upper Rio Grande Impact Assessment (URGIA) from global climate models. Specific activities performed as part of this project include:

Development of projections of hydrologic impacts of climate change through 2100, according to the procedure shown in Figure 1:

- Downscaling of temperature and precipitation projections from global climate models to a spatial scale relevant for regional planning.
- Performance of hydrologic modeling to develop specific projections of streamflow within this basin.
- Use of these streamflow projections to simulate future operations of Reclamation projects and related Federal and non-Federal activities and infrastructure in the basin with the available water supplies and anticipated demands to develop a picture of future changes in water supply and demand that can be expected as a result of climate change alone.

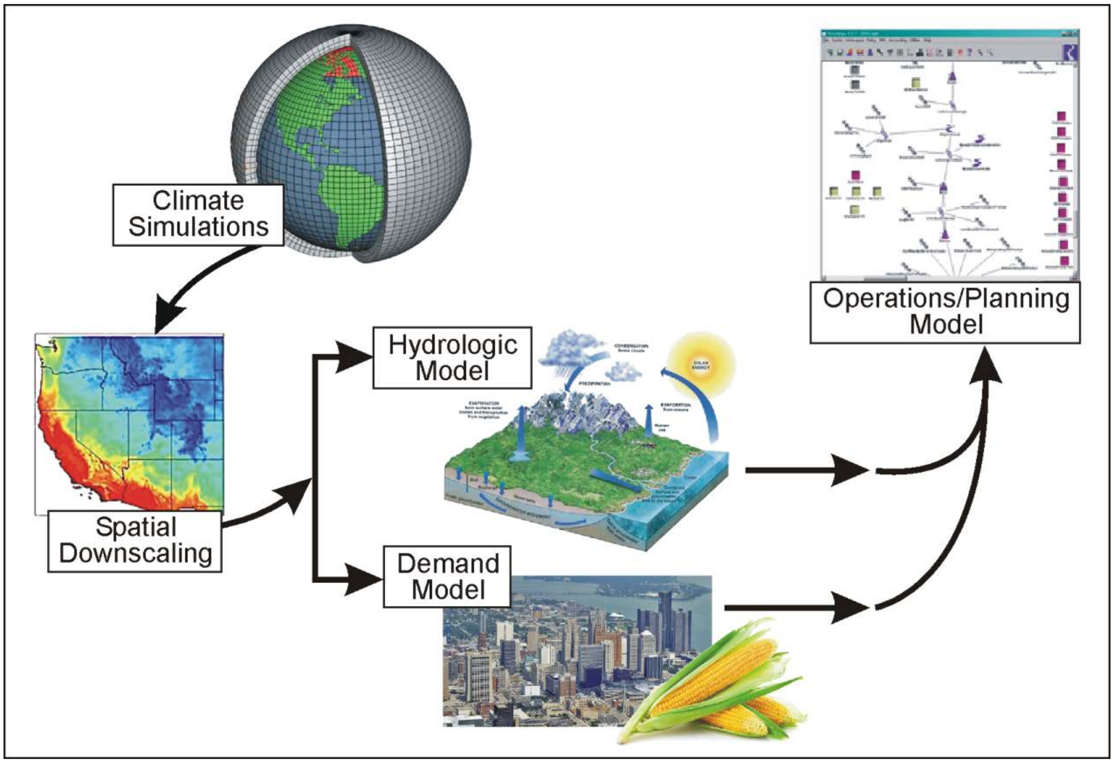

Figure 1.—Modeling and analytical steps involved in developing local hydrologic projections.

Details describing the methods employed in each of these steps, along with uncertainties associated with the methods, are provided in this Appendix.

The Upper Rio Grande Impact Assessment is purposefully conducted in a manner that assesses the potential impacts of climate change alone, and does not attempt to project what future development or management actions may be, including how population may change , how power generation may evolve, or how land use, including the amount and type of irrigated agriculture, may change. While factors such as these will undoubtedly be affected by climate change, they are also changing due to societal factors that are independent of climate change.

II. General Description of Climate Change Projections

The state of practice for evaluation of the long-term availability of water supply is to incorporate a range of approaches to characterize past and projected climate. The approaches may include use of paleo-conditioned climate data and use of projections from General Circulation Models (GCMs). Paleo-conditioned climate and hydrology data include data developed from studies of tree rings, pollen, ice cores, ocean and lake sediments, stable and radioisotopes, and other long-term climatic records to capture the natural climate variability over thousands of years, which may exceed the range of variability found in the instrumental record. This information is evaluated statistically to characterize the uncertainties in climatic conditions. Projections of future climate changes through the use of GCMs have been steadily increasing in sophistication and complexity over the past several decades, and this is approach taken in the URGIA.

The World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al. 2007) produced multiple 20th through 21st century climate projections for the Intergovernmental Panel on Climate Change (IPCC) Forth Assessment Report (IPCC 2007). These climate projections are based on an assemblage of GCM simulations of coupled atmospheric and ocean conditions, with a variety of initial conditions of global ocean-atmosphere system, and four distinct “storylines” about how future demographics, technology and socioeconomic conditions might affect the emissions of greenhouse gases. The four families of emissions scenarios (A1, A2, B1 and B2) are described in the IPCC *Special Report on Emissions Scenarios* (IPCC 2000), which states that the scenarios are potential futures based on assumptions of global economic activity and growth. Corresponding carbon dioxide (CO_2) emissions and atmospheric concentrations for some of the emissions scenarios are shown in Figure 2 below.

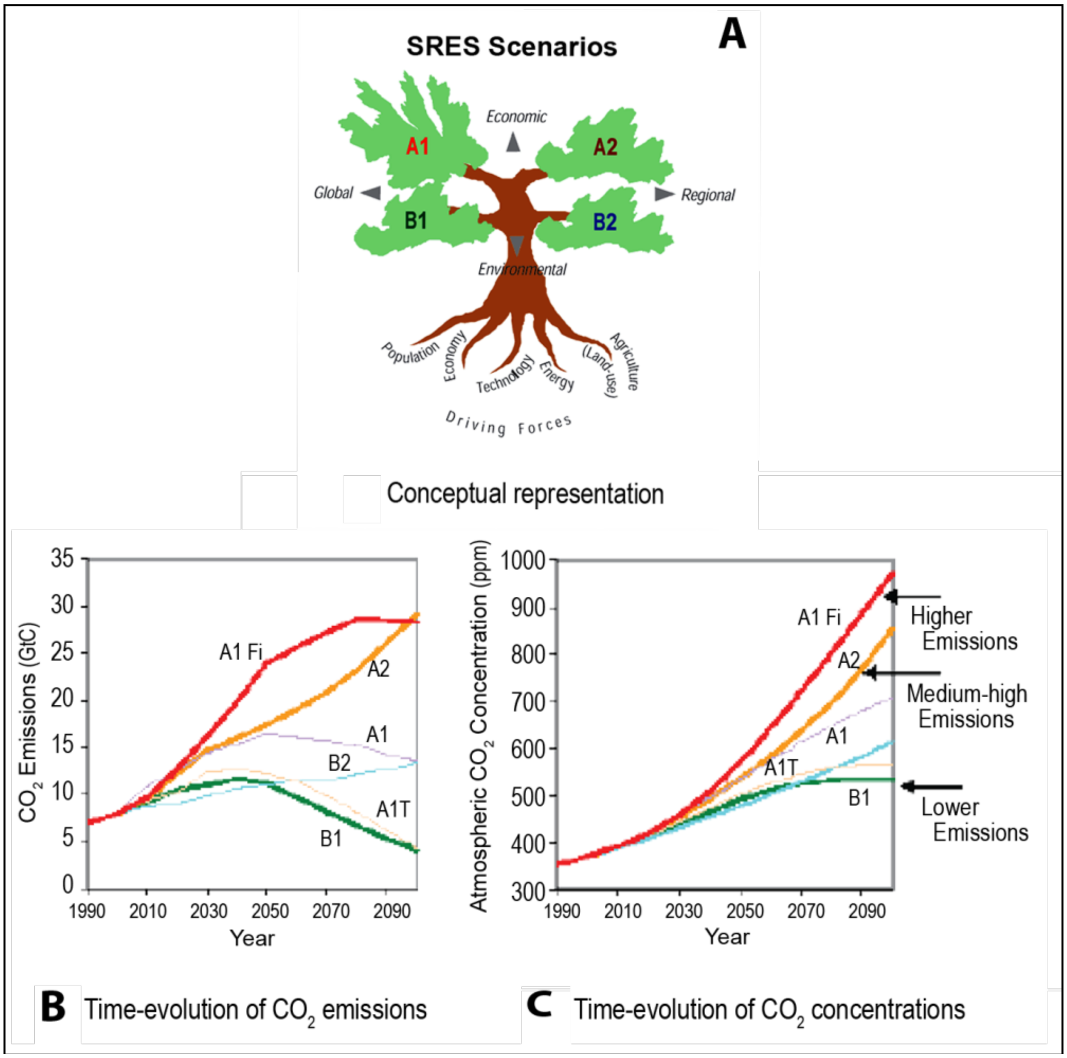

Figure 2.—Carbon dioxide emissions and atmospheric concentrations for some emission scenarios.

The development of climate projections by the World Climate Research Programme and an associated assessment report by the IPCC is a recurring 7-year process. The next generation of climate projections under the Coupled Model Intercomparison Project Phase 5 (CMIP5) has been developed at the time of completion of the URGIA, and the development of the next assessment report (Fifth Assessment Report, or AR5) is underway. Although the most recent suite of climate projections based on the CMIP5 models use a different approach for representing future greenhouse gas emissions, and in many cases the GCMs have improved representations of the physical atmospheric ocean system, projections based on CMIP Phase 3 are still widely used in impact assessments and remain a valid approach for evaluating climate change impacts.

The spatial resolution of the GCM climate projections is typically on the order of 1-2 degrees of latitude/longitude, which is too coarse for use in regional and project-scale planning because finer scale geographic features, which may significantly influence local climate, are not represented. Also, GCM output is generally archived on a monthly timescale, adding to the limitations of its use for water resources planning studies. Therefore, projections of finer scale regional conditions require a method of downscaling GCM projections in both space and time. Typical downscaling methods include: dynamical, which uses Regional Climate Models (RCM) that are based on boundary conditions defined by GCMs; and statistical, which uses statistical techniques to relate finer-scale regional climate characteristics to larger scale GCM projections. Although dynamical downscaling is increasingly used as a methodology for producing climate projections, it is computationally intensive, which makes it prohibitive for many long-term planning studies. Therefore, the URGIA relies on the statistical downscaling approach for developing future local climate projections.

Statistical methods have been widely applied to produce spatially-continuous fields of temperature and precipitation at fine scales (< 10 miles) covering the entire United States. Reclamation, in cooperation with Lawrence Livermore National Laboratory, Santa Clara University, Climate Central, and the Institute for Climate Change and its Societal Impacts, has developed an archive of 112 monthly and daily statistically downscaled projections of temperature and precipitation based on CMIP Phase 3, using the Bias Correction and Spatial Disaggregation (BCSD) technique of Wood et al (2002). These projections cover the entire United States at 1/8 degree spatial resolution (12 kilometers) for the period from 1950 through 2099. These projections were produced from results of 16 different CMIP3 GCMs, simulating 3 different emissions scenarios (A2 [high emissions], A1B [moderate emissions], B1 [low emissions]) along with various assumptions about initial ocean – atmosphere conditions. A detailed description of the BCSD method is contained in Reclamation’s West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections (Reclamation 2011c).

Streamflow simulations based on projections of future climate using the BCSD approach described above were performed using the Variable Infiltration Capacity (VIC) Model. The VIC model (Liang et al. 1994, Liang et al. 1996, and Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. It has been widely used in large scale hydrologic studies across the globe to explore the implications of climate change on water and related resources.

To produce future projections of streamflow consistent with the above described statistically downscaled climate projections, the VIC model is applied once for each set of temperature and precipitation projections associated with a GCM and emissions scenario combination. The described routing model generates simulated natural streamflow over the period 1950 through 2099, consistent with the time period for transient (or BCSD) climate projections.

It should be noted that transient streamflow projections such as those developed here are most useful if analyzed at a monthly timestep, as was done in this study. Daily time-step realizations from BCSD downscaling have been found to frequently contain unrealistic daily precipitation estimates, especially at smaller spatial scales of interest in water resources planning.

Similar to the concept and process previously described for removing systematic biases in GCM simulations, a bias correction procedure was applied to remove systematic biases in natural streamflow simulated by the VIC model. Bias-correction techniques may be applied at locations where reconstructed observed natural streamflows exist. These techniques produce flows that very closely match the long-term statistics and time series behavior of a natural or modified flow dataset for a particular site. The bias corrected monthly values are then used to rescale the simulated daily flow sequences produced by the hydrologic model to produce bias corrected daily streamflows.

These bias-corrected streamflow projections from the VIC model were used as input to the Upper Rio Grande Simulations Model (URGSiM) to simulate the effects of local water operations on the projected available water. URGSiM uses hydrologic and climatic inputs to simulate the movement of surface water and ground water through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico, including:

- Rio Chama and Jemez River tributary systems
- Española, Albuquerque, and Socorro regional groundwater basins.

URGSiM simulates operations in nine surface reservoirs, interbasin transfers from the Colorado River Basin to the Rio Grande Basin (via Reclamation’s San Juan-Chama Project), and agricultural diversions and depletions in the Chama, Española, and Middle Rio Grande valleys (most of which occur via irrigation infrastructure originally built by Reclamation as part of the Middle Rio Grande Project). Table 1 lists key information associated with the reservoirs included in URGSiM.

Table 1.—Reservoirs Simulated in URGSiM

Reservoir	River System	Modeled Capacity (acre-feet)	Primary Manager	Primary Purposes
Heron	Willow Creek, (Rio Chama)	401,300	Reclamation	Storage
El Vado	Rio Chama	195,440	Reclamation	Storage
Abiquiu	Rio Chama	1,198,500	USACE	Flood Control and Storage
Nichols and McClure	Santa Fe River	3,940	City of Santa Fe	Storage
Cochiti	Rio Grande	589,159	USACE	Flood Control
Jemez	Jemez River	262,473	USACE	Flood and Sediment Control
Elephant Butte	Rio Grande	2,023,400	Reclamation	Storage
Caballo	Rio Grande	326,670	Reclamation	Reregulation

The Upper Rio Grande Simulation Model (URGSiM) uses monthly flow, precipitation, and temperature (minimum and maximum) to simulate evapotranspiration and crop water requirements. These variables are generated from the historical VIC simulation (using the Maurer et al. 2002 dataset) and future VIC projections.

III. Processing of Climate Projections from General Circulation Models

III.A. Description of BCSD Approach

The BCSD approach involves statistical bias correction of GCM simulations of temperature and precipitation at the GCM spatial scale and monthly time step and spatial downscaling from the GCM spatial scale to the regional scale of interest. An additional step to disaggregate monthly timestep data to daily may be applied but is not part of the analysis for the URGIA. The approach is described in further detail below.

Statistical bias correction is carried out by first aggregating gridded the temperature and precipitation observations (in this case the using the dataset developed by Maurer et al 2002) to the GCM spatial scale and then using quantile mapping techniques to remove the systematic bias in the GCM simulations (Wood et al. 2002). Quantile mapping techniques work by creating a one-to-one mapping between two cumulative distribution functions (CDF): one based on the GCM simulations and the second based on the aggregated observations. Through this procedure, the GCM simulations inherit the same CDF as the aggregated observations over the historical period used for quantile mapping. The output of this process is a bias corrected version of the large scale GCM monthly time series for temperature and precipitation for the entire GCM monthly time series (from 1950 through 2099 in this study). This process assumes that GCMs have a consistent bias over their historical simulation period and future simulation period.

After large-scale bias correction of monthly temperature and precipitation at GCM spatial scale over the chosen historical period, values at the GCM grid scale are interpolated to the fine scale grid (1/8th degree scale in this study). These values are then scaled to produce the fine-scale spatial variability of the gridded observations.

After spatial disaggregation of bias-corrected monthly climate projections, the monthly projection time series at each grid cell are temporally disaggregated to the daily time scale by a random sampling of observed daily variability represented by a carefully screened set of relatively wet months. The choice of relatively wet conditions as the basis of the temporal downscaling step is intended to minimize the occurrence of a relatively wet month being paired to a relatively dry daily time series at the grid scale, which can create unrealistically large daily precipitation values. In the most recent version of the code that is used here, an arbitrary ceiling of 150 percent of the observed maximum precipitation value for each cell is also imposed by “spreading out” very large daily precipitation values into one or more adjacent days. The value of precipitation for the month is preserved, however.

The result of the statistical downscaling process is a suite of monthly and daily climate projections that can inform a long-term planning study. In the URGIA, the daily climate projections are used as input into a hydrology model to generate similar projections of water balance variables and natural streamflow at select locations in the basin.

III.B. Development of Runoff and Streamflow Projections

III.B.1. The Variable Infiltration Capacity (VIC) Model

Streamflow simulations based on projections of future climate using the BCSD approach (described above) were performed using the VIC Model. The VIC model (Liang et al. 1994, Liang et al. 1996, and Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. It has been widely used in large scale hydrologic studies across the globe and to explore the implications of climate change on water. The model configuration used here is consistent with that used in the Reclamation's West-wide Climate Risk Assessment (Reclamation 2011c). Namely, we apply VIC model version 4.0.7 to simulate surface runoff and baseflow per model grid cell.

The model is driven by daily weather forcings of precipitation, maximum and minimum air temperature, and wind speed. Additional model forcings that drive the water balance, such as solar (short-wave) and long-wave radiation, relative humidity, vapor pressure, and vapor pressure deficit, are calculated within the model. The VIC model contains a subgri scale parameterization of the infiltration process and also represents subgri scale vegetation variability using multiple vegetation types and properties per grid cell. Potential evapotranspiration is calculated using a Penman Monteith approach (e.g., Maidment 1993). VIC also contains a subdaily (1-hour time step) snow model (Cherkauer and Lettenmaier 2003, Wigmosta et al. 1994, and Andreadis et al. 2009).

The streamflow routing model developed by Lohman et al. (1996) is implemented to translate grid scale runoff and baseflow produced by the VIC model to natural streamflow at select locations in a river channel network. Natural flows are defined as streamflows that would exist in the absence of diversions and return flows resulting from human activities.

The VIC model has been successfully applied over snowmelt dominated watersheds. Simulated snowpack (e.g., Andreadis et al. 2009) and simulated routed natural flow (e.g., Payne et al. 2004) have been shown to reproduce observations in mountainous regions across the Western U.S. Simulations over larger river basins, as opposed to small subwatersheds, tend to perform better due to the integration of biases that may exist in smaller subwatersheds (e.g. misrepresentative climate inputs). Due to the applied VIC model spatial resolution, the model may not appropriately represent physically processes that occur at finer spatial scales.

The VIC model has a 3 layer presentation of the soil column, and the bottom-most layer is representative of shallow baseflow. The model does not have the capability to simulate detailed surface water/groundwater dynamics that may be significant in some regions. As such, the VIC model is limited in its ability to successfully simulate natural streamflow in river basins with significant groundwater influence.

III.B.2. Streamflow Projections for the Upper Rio Grande Basin

To produce future projections of streamflow consistent with the above described statistically downscaled climate projections, the VIC model is applied once for each set of temperature and precipitation projections associated with a GCM and emissions scenario combination. The described routing model generates simulated natural streamflow over the period 1950 through 2099, consistent with the time period for transient (or BCSD) climate projections. The following section describes how developed streamflow projections from the VIC model are used as input to the Upper Rio Grande Operations Model (URGWOM).

It should be noted that transient streamflow projections such as those developed here are most useful if analyzed at a monthly time step. Daily time step realizations from BCSD downscaling have been found to frequently contain unrealistic daily precipitation estimates, especially at smaller spatial scales of interest in water resources planning. These artifacts of the downscaling approach can occur, for example, when a relatively wet future condition is paired at specific grid locations with a relatively dry month used for daily disaggregation. In effect, a few isolated storms in the dry month are made much larger to reflect the relatively wet month from the GCM simulation. Although the version of the BCSD code used in this study places some quantitative (but essentially arbitrary) limits on increases in daily precipitation during the temporal disaggregation step, the effects on daily precipitation must be interpreted with caution.

III.C. Development of Crop Water Demand Projections (URGSiM)

URGSiM uses monthly flow, precipitation, and temperature (minimum and maximum) to simulate evapotranspiration and crop water requirements. These variables are generated from the downscaled GCMs and VIC simulations. URGSiM uses a Hargreaves-based Reference Evapotranspiration (ET_o) equation, in combination with crop coefficients for five vegetation types from the Food and Agriculture Organization of the United Nations Irrigation and drainage paper 56 (FAO-56; Allen et al. 1998). For further information on development of crop requirements in URGSiM, see Appendix E.

Historical climate as well as climate projections (temperature and precipitation), used by URGSiM, were generated for each station listed in Table 2. Historical climate covers a time period from 1950 through 1999. The climate projections using the BCSD approach cover a time period from 1950 through 2000.

Table 3 summarizes URGSiM nodes which require monthly streamflow inputs. Historical simulated as well as projected natural streamflows generated by the VIC model (and subsequent routing model) are bias corrected using the approach described in the previous section. Bias corrected monthly flows are then used as inputs to URGSiM.

Table 2.—Meteorological Stations Used in the URGSiM Analysis

ID	Name
NM9999	Heron Reservoir
NM2837	El Vado Dam
NM0041	Abiquiu Dam
NM1630	Cerro
NM0245	Alcalde
NM3031	Española
NM1982	Cochiti Dam
NM6693	Pena Blanca
NM4366	Jemez Reservoir
NM9999	Angostura
NM0231	Albuquerque Bosque
NM0234	Albuquerque Airport
NM5147	Los Lunas
NM9999	Jarales
NM0915	Bernardo
NM0640	Socorro
NM9999	Bosque del Apache (BDA) North
NM1138	Bosque del Apache
NM2848	Elephant Butte Dam
NM1286	Caballo Dam
NM0131	New Mexico State University

Table 3.—VIC Nodes Used in the URGSiM Analysis

VIC Node	Description
LOBAT	Rio Grande near Lobatos, CO
CERRO	Rio Grande near Cerro NM
QUEST	Red River below Fish Hatchery near Questa, NM
RPUEB	Rio Pueblo de Taos below Los Cordovas, NM
EMBCK	Embudo Creek at Dixon, NM
RBLNC	Rio Blanco below Blanco, CO
LNAVA	Little Navajo River below Little Oso Dam, CO
NAVAJ	Navajo River below Oso CO
GALIS	Galisteo Creek below Galisteo Dam, NM
JEMEZ	Jemez River near Jemez, NM
NFCAL	North Floodway Channel near Alameda, NM
TIJER	Tijeras Arroyo near Albuquerque, NM
SDIVC	South Div. Channel above Tijeras Arroyo near Albuquerque, NM
PUERC	Rio Puerco near Bernardo, NM
CCNGC	Costilla Creek near Garcia, CO
RCNLP	Rio Chama near La Puente, CO
ROCLM	Rio Ojo Caliente at La Madera, NM
RNNFD	Rio Nambe below Nambe Falls Dam near Nambe, NM
SFRCL	Santa Fe River above Cochiti Lake, NM
CORNM	Conejos River near Mogote, CO
LPRNO	Los Pinos River near Ortiz, CO
SARAO	San Antonio River at Ortiz, CO
RGNDN	Rio Grande near Del Norte, CO

III.D. Bias Correction of Routed Streamflow Projections

Similar to the concept previously described for removing systematic biases in GCM simulations, a bias correction procedure using quantile mapping techniques was applied to remove systematic biases in natural streamflow simulated by the VIC model. One example of a systematic bias in the VIC model relates to its inability to accurately simulate groundwater-surface water interactions in those watersheds which are heavily influenced by groundwater. The Upper Rio Grande watershed is an excellent example of this type of river basin.

Bias-correction techniques may be applied at locations where reconstructed observed natural streamflows exist. These techniques produce flows that very closely match the long-term statistics and time series behavior of a natural or modified flow dataset for a particular site. The bias corrected monthly values are then used to rescale the simulated daily flow sequences produced by the hydrologic model to produce bias corrected daily streamflows. This technique introduces sometimes an undesirable discontinuity in the bias corrected daily values from the end of the month to the beginning of the next month. To minimize this artifact between months, boundaries between months are smoothed while keeping sum of daily streamflow equal to monthly value. Although the time series behavior of these simulated daily flows are not always identical to the observed naturalized or modified data, the daily flow duration curves are faithfully reproduced overall for each month. These bias corrected values are often very useful in water planning studies such as the URGIA, especially for providing inputs to operations models.

For this study, bias correction was performed using historic flows in the URGSiM database (see Appendix E). Bias corrections were not applied to historic flows in the North Floodway Channel because no VIC flows are available for this node. Three Santa Fe basin flow traces were bias corrected. Historic flows for the gage “Santa Fe near Santa Fe” were used so that the gain (local inflow) between that location and the outflow of the Santa Fe River to Cochiti Reservoir could be computed. McClure Reservoir inflows were bias corrected to represent the naturalized flow for “Santa Fe near Santa Fe.” Bias corrections were done to the nodes listed in Figures 3 through 6 illustrate the effects of bias correction on VIC simulated natural streamflow. Figure 3 and Figure 4 illustrate an example of a site having a relatively small bias in flow compared with observed natural flow. Figure 5 and Figure 6 illustrate an example of a site with a relatively large bias in flow compared with observed natural flow.

Figure 7 shows the simulated and bias-corrected flows for the May data for the sixth run at the Lobatos station. In the simulated data, there are 21 instances after the year 2000 (out of 100 May flow values) in which the simulated flows exceed the historical maximum simulated flow (about 10,000 cfs). In the bias-corrected projections, these are the only instances where the bias-corrected flows exceed the historical simulated maximum.

The entire dataset shows that in the time period before 2000 (1950 through 1999), all runs for all stations result in flows that are at or below historic levels. However, post-2000 (2000 through 2099) simulated flows that are greater than the historical simulated flows can result in flows that are greater than the historical observed maximum (or less than the historical observed minimum). This is expected and is done in an effort to maintain the increased variance and extreme values that are simulated with the climate projections.

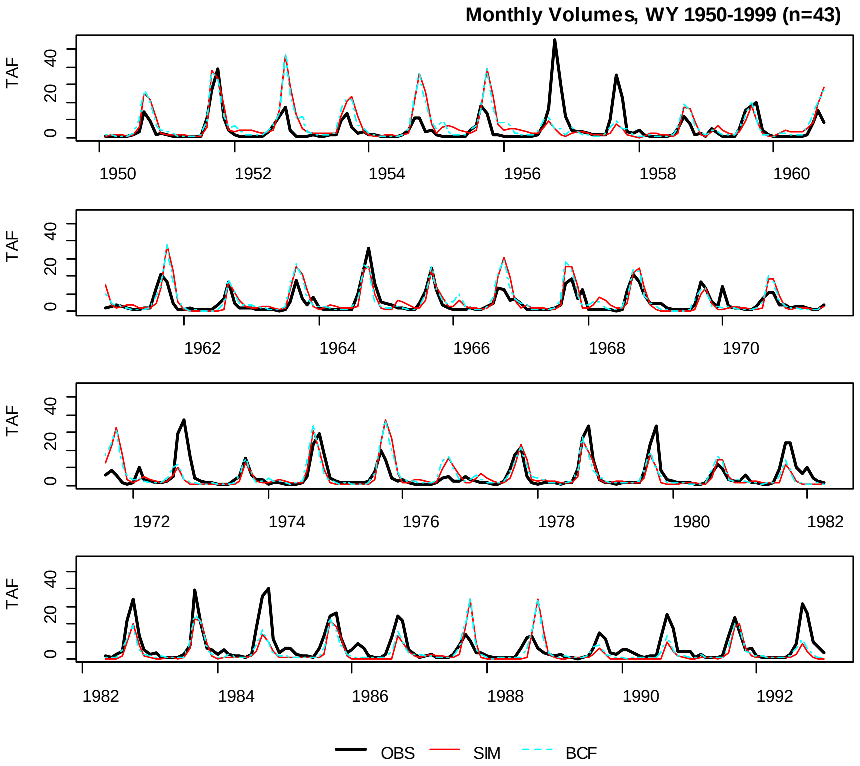

Figure 3.—Historical simulated runoff, small-bias example: monthly time series before and after correction.

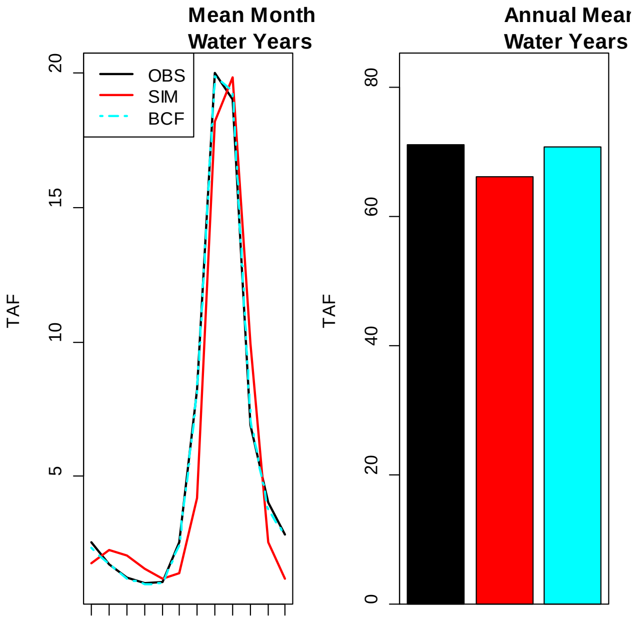

Figure 4.—Historical simulated runoff, small-bias example: monthly and annual means.

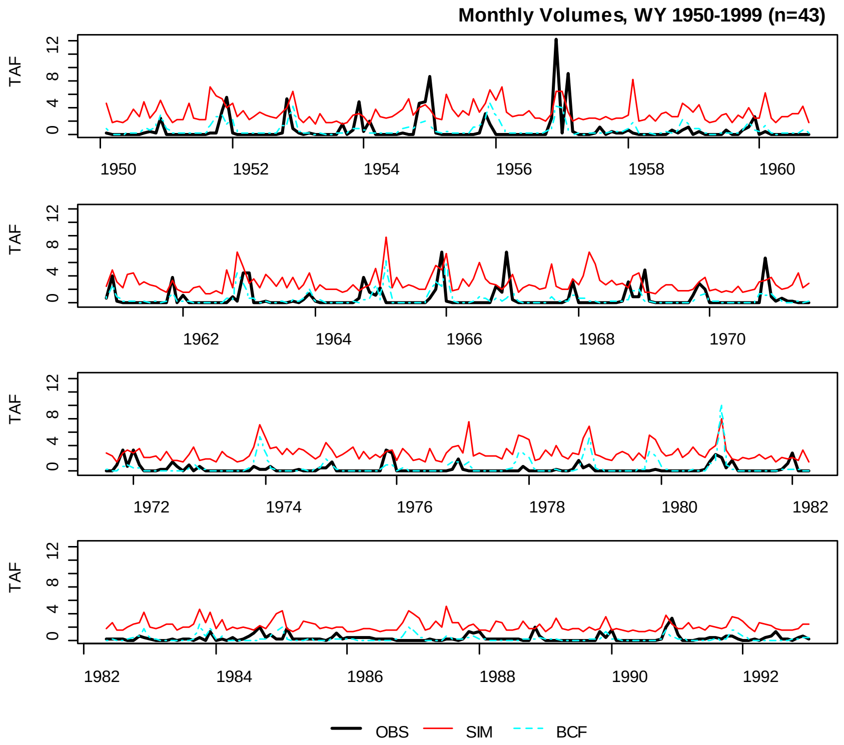

Figure 5.—Historical simulated runoff, larg bias example: monthly time series before and after correction.

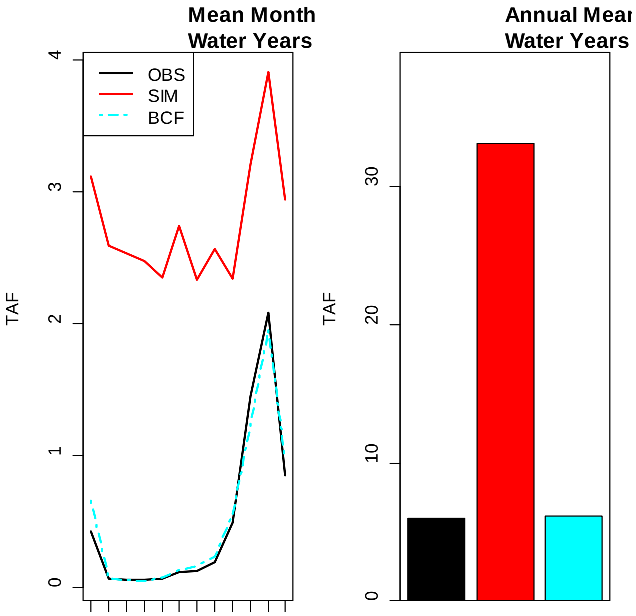

Figure 6.—Historical simulated runoff, larg bias example: monthly and annual means before and after bias correction.

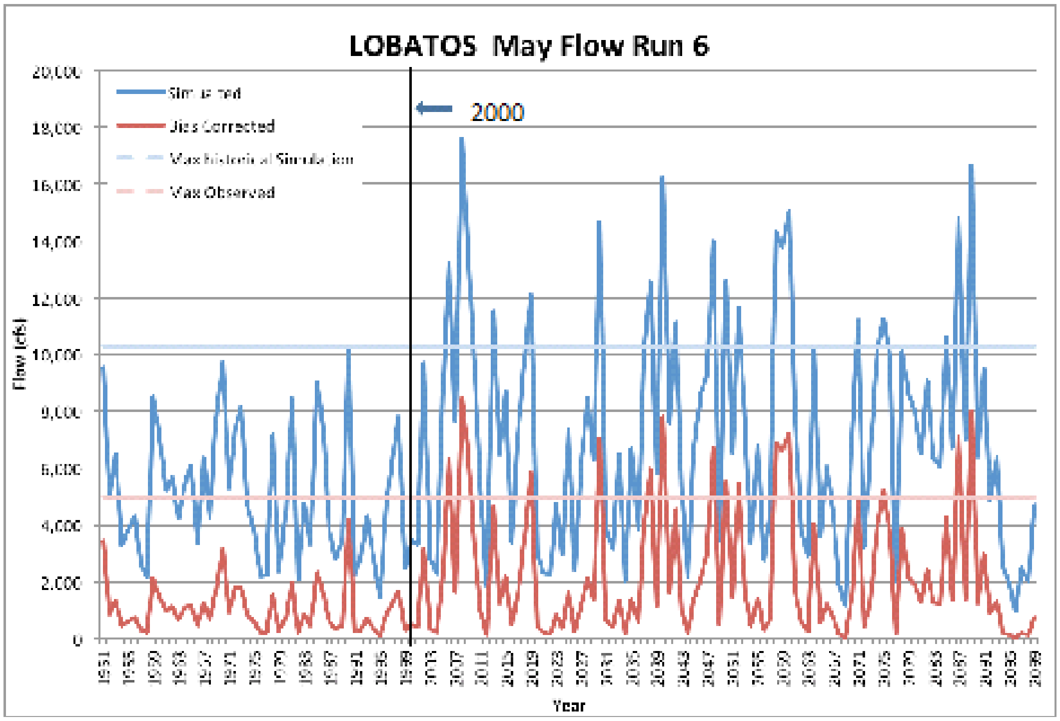

Figure 7.—Comparison of various projections showing May flows at the Lobatos gage.

IV. Performance of Hydrologic Simulations

IV.A. Monthly Tim Step Transient Simulations

This section explains the performance and analysis of monthly-resolution transient simulations of system operations.

IV.A.1. URGSiM Overview

URGSiM uses hydrologic and climatic inputs to simulate the movement of surface water and groundwater through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico (including the Rio Chama and Jemez River tributary systems) and the Española, Albuquerque, and Socorro regional groundwater basins. URGSiM simulates operations in nine surface reservoirs, interbasin transfers from the Colorado River Basin to the Rio Grande Basin (via Reclamation’s San Juan-Chama Project), and agricultural diversions and depletions in the Chama, Española, and Middle Rio Grande Valleys (most of which occur via irrigation infrastructure originally built by Reclamation as part of the Middle Rio Grande Project). Table 1 lists key information associated with the reservoirs included in URGSiM.

URGSiM tracks several different water ownership accounts in order to simulate the complex reservoir operations that occur in the Upper Rio Grande. San Juan-Chama Project water (see Appendix E) is grouped into seven types. Five of the San Juan-Chama Project water types correspond to Contractors for this water, and are shown along with their annual Contract amount in Table 4: These five groupings are for the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the Middle Rio Grande Conservancy District (MRGCD), Cochiti Recreation Pool, City and County of Santa Fe, and a Combined account which includes all other contractors. Another San Juan-Chama Project classification exists for the Federal Pool in Heron Lake, which is water that has been diverted from the Colorado Basin, but hasn't been allocated to a San Juan-Chama Project Contractor, or was allocated but not called for in a specific period of time and so reverted. Finally there is a classification for water leased from a San Juan-Chama Project Contractor by Reclamation for use in maintaining environmental flows during periods of low flows.

Table 4.—San Juan-Chama Project Contractor Groupings Used in URGSiM and Annual Contract Amount

Contractor	Contracted Volume [acre-feet per year]
Albuquerque Bernalillo County Water Utility Authority	48,200
Middle Rio Grande Conservancy District	20,900
City and County of Santa Fe	5,605
Cochiti Recreation Pool	5,000
Combined	15,495
Total	**95,200**

This overview is meant to provide only a summary description of URGSiM to facilitate an understanding of URGIA simulations and results. For a more detailed and complete description of URGSiM, see Appendix E.

IV.A.2. URGIA Specific Model Setup

URGSiM requires hydrologic inflows at 21 locations corresponding to stream gaging stations with long-term historic records, as well as temperature and precipitation information at 21 different locations corresponding to climate measurement stations with long term historic records. The stream gage locations are shown in Table 5, and the climate station locations are shown in Table 6. For the URGIA transient analysis, the hydrologic inflows at the needed locations were generated by bias correction of output from the VIC model driven by the CMIP3 BCSD temperature and precipitation data as discussed previously, while the

Table 5.—URGSiM Hydrologic Input Locations

Gage Name	USGS Gage ID	CODWR Gage	Datum Elevation (ft amsl)	Latitude (dd)	Longitude (dd)
Rio Grande near Del Norte		RIODELCO	7980	37.68944	106.46056
Conejos River near Mogote		CONMOGCO	8269	37.05389	106.18694
Los Pinos River near Ortiz		LOSORTCO	8042	36.98222	106.07361
San Antonio River at Ortiz		SANORTCO	7970	36.99306	106.03806
Costilla Creek near Garcia	8261000		7821	36.98917	105.53167
Red River below Fish Hatchery	8266820		7105	36.68278	105.65389
Rio Pueblo de Taos below Los Cordovas	8276300		6650	36.37917	105.66667
Embudo Creek at Dixon	8279000		5859	36.21083	105.91306
Rio Chama near La Puente	8284100		7083	36.6625	106.6325
Blanco Diversion near Pagosa Springs		BLADIVCO		37.20361	106.80972
Rio Blanco below Blanco Diversion		RIOBLACO	7858	37.20361	106.81167
Little Oso Diversion near Chromo		LOSODVCO		37.07556	106.81056
Little Navajo River below Little Oso Diversion		LITOSOCO		37.07717	106.81147
Oso Diversion near Chromo		OSODIVCO		37.03028	106.73722
Navajo River below Oso Diversion		NAVOSOCO	7665	37.03028	106.73722
Rio Ojo Caliente at La Madera	8289000		6359	36.34972	106.04361
Rio Nambe below Nambe Falls Dam	8294210		6840	35.84611	105.90972
Santa Fe River above McClure	8315480		7920	35.68869	105.82408
Santa Fe River above Cochiti	8317200		5505	35.54722	106.22889
Galisteo Creek Below Galisteo Dam	8317950		5450	35.46389	106.21306
Jemez River near Jemez	8324000		5622	35.66194	106.74278
North Floodway Channel near Alameda	8329900		5015	35.19806	106.59972
S. Diversion Channel above Tijeras Arroyo	8330775		4930	35.00278	106.65722
Tijeras Arroyo near Albuquerque	8330600		4999	35.00278	106.64806
Rio Puerco near Bernardo	8353000		4722	34.41028	106.85444

Each location corresponds to a USGS or Colorado Department of Water Resources stream gage with a long period of record.

Table 6.—URGSiM Climatic Data Input Locations

Station Name	NWS Cooperative Network Number	Lat [dd]	Long [dd]
Heron Reservoir	NA	36.853	-106.671
El Vado Dam	292837	36.600	-106.733
Abiquiu Dam	290041-2	36.233	-106.433
Cerro	291630	36.750	-105.600
Alcalde	290245	36.100	-106.067
Espanola	293031	36.000	-106.083
Cochiti Dam	291982	35.633	-106.317
Pena Blanca	296693	35.581	-106.334
Jemez Reservoir	294366	35.390	-106.534
Angostura	NA	35.375	-106.503
Albuquerque Bosque	NA	35.261	-106.596
Albuquerque Airport	290234	35.050	-106.617
Los Lunas	295150	34.767	-106.761
Jarales	NA	34.612	-106.755
Bernardo	290915	34.417	-106.833
Socorro	298387	34.083	-106.883
Bosque del Apache - North	NA	33.870	-106.862
Bosque del Apache	291138	33.767	-106.900
Elephant Butte Dam	292848	33.150	-107.183
Caballo Dam	291286	32.900	-107.300
NMSU	298535	32.282	-106.760

Each location corresponds to a temperature and precipitation station with a historic record back to at least 1950
Dd = decimal degree

temperature and precipitation inputs come directly from the CMIP3 BCSD data. The URGIA transient analysis is 112 different runs, one for each CMIP3 GCM simulation. Each run starts in October of 1950 and ends in September of 2099 (149 years).

IV.A.3. Model Assumptions

In addition to climate change specific hydrologic and climate inputs, specific assumptions related to initial conditions and operations-related model parameters were necessary for the URGIA analysis. Initial conditions used for URGIA, including reservoir storage by water type, San Juan-Chama Project diversions for the previous 9 years, human population, and irrigated and riparian area by reach and crop, are summarized in Appendix E. Other model assumptions specific to URGIA are listed below.

The URGIA runs are from 1950 through 2099 in terms of climate and hydrologic inputs from the GCM models only, and are fixed to present values for human related factors.

Human population is fixed at approximate 2010 levels throughout the URGIA analysis (U.S. Census Bureau 2010). This assumption, while not representative of population during the historic period, and unlikely to represent the future, allows the modeled impacts to be attributed exclusively to climate change. Human population values used can be found in Appendix E.

Similarly, reservoirs, irrigation infrastructure and operations rules currently in place in the system are assumed to be in place throughout the URGIA runs. Thus, though the San Juan-Chama Project was not completed until 1972, that infrastructure is included in the entirety of every URGIA transient simulation.

Similarly, in the Base Case Scenario, irrigated area and crop mix in the model are held static for the entire model run (1950 through 2099). The irrigated areas used by URGSiM are:

- 4,867 acres along the Rio Chama (based on adjudicated rights)
- 188 acres along the Rio Grande between Taos Junction Bridge and Embudo
- 4,700 acres served by the Rio Grande between Embudo and Otowi
- 5,371 acres served by the Jemez River within the model extent.
- 57,346 acres in the Middle Rio Grande of New Mexico (based on values interpreted by the New Mexico Interstate Stream Commission from year 2000 IKONOS imagery; unpublished).

In addition to this agricultural area, URGSiM includes:

- 2,305 acres of irrigated area in Bosque del Apache National Wildlife Refuge (see Appendix A).
- Riparian area based on New Mexico Interstate Stream Commission interpretation of 2000 IKONOS imagery (unpublished):
  - 667 acres above Cochiti
  - 711 acres along the Jemez River
  - 45,360 acres along the Rio Grande between Cochiti and San Marcial

- 7,635 acres of riparian area between San Marcial and Elephant Butte from Reclamation's ET Toolbox (Brower 2008).

Groundwater levels, which are influenced by pumping history, start each simulation with approximately 2010 conditions, which are from URGSiM at the end of a Base Case Scenario 1975 through 2010 simulation.

If the New Mexico's Compact (Colorado et al. 1938) credit goes above 100,000 acre-feet, a start-of-calendar-year relinquishment occurs, taking the credit from whatever level it has reached down to 70,000 acre-feet, and creating relinquishment credits that can be used by reservoir operators for storage of native water during Article VII conditions.

It is assumed that 10,000 acre-feet per year of San Juan-Chama Project water will be available for lease by Reclamation from the Combined Contractor account for use in maintaining environmental flows in the Upper Rio Grande.

"Letter water" is the term for San Juan-Chama Project water used by any of the Contractors to offset some external impact on the river system, usually related to groundwater pumping impacts on river flows. This impact is calculated by the New Mexico Office of the State Engineer which then requests releases from Heron be made to offset the impacts. That request is via a letter from the New Mexico Office of the State Engineer to Reclamation, thus the term "letter" water. Letter Water is calculated within URGSiM for ABCWUA and the City and County of Santa Fe. It turns out that URGSiM calculations of ABCWUA and County of Santa Fe pumping impacts on the river are very slow because of the spatially aggregated groundwater representation in URGSiM. That, coupled with no population growth, leads to no letter water requirements for either entity in the URGIA runs. Other letter water requirements are not included because the impact that they are offsetting is not an impact explicitly modeled in URGSiM.

All other things being equal, increased temperature leads to increased evaporative demand and, therefore, to increased agricultural demand. Current and future agricultural operations in the Middle Rio Grande as modeled by URGSiM are based on a monthly target for agricultural flows into Cochiti Reservoir and a demand schedule for monthly diversions at four diversion points along the river: below Cochiti, Angostura, Isleta, and San Acacia. These static demand schedules are based on communications with MRGCD and are not explicitly related to agricultural demand. However, these static demand schedules might be r evaluated as demands rise. For URGIA runs, the decision was made to operate throughout the simulations according to current rules, practices, and cropping patterns to evaluate what would happen under current operations with varying supplies and demands and not try to simulate how the system would adapt to try to keep up with increasing demands. The flow targets at Cochiti reservoir (which determines storage releases from El Vado) as well as the diversion schedules at each diversion point are shown in Table 7.

Table 7.—Total MRGCD Demand Schedule in Cubic Feet per Second (cfs) at Cochiti and MRGCD Diversion Demands at the Four Diversion Locations Used by URGSiM for URGIA

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Total Demand at Cochiti	400	700	900	925	925	900	700	550
MRGCD Diversion:								
Cochiti	100	110	130	150	150	130	110	100
Angostura	90	140	170	200	200	200	170	120
Isleta	195	390	430	500	500	450	410	290
San Acacia	100	180	200	220	200	180	160	120

All winter values (November through February) are zero.

Using the GCM based hydrologic and climatic data along with the specified initial conditions and operations related assumptions listed here, URGSiM was run 112 times to create the suite of runs that encompass the Base Case Scenario. Each run covered the 149 year model period.

An additional set of 112 simulations was generated for a Compact Compliance Scenario, in which it was assumed that the State of New Mexico would take management actions, such as reducing riparian or agricultural area, to assure compliance under the Rio Grande Compact. Output from the simulations performed to support this scenario does not specify what these management actions might be.

IV.B. Initial Model Conditions for Upper Rio Grande Climate Change Impact Assessment

Table 8 provides the initial conditions for the URGIA modeling analyses using URGSiM.

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Initial Native Storage	Heron	AF	361
Initial Native Storage	El Vado	AF	#N/A
Initial Native Storage	Abiquiu	AF	1
Initial Native Storage	Cochiti	AF	0
Initial Native Storage	Jemez	AF	0
Initial Native Storage	Elephant Butte	AF	236,966
Initial Native Storage	Caballo	AF	2,026
Initial El Vado Native Storage	MRGCD	AF	137,090
Initial El Vado Native Storage	PP	AF	0
Initial El Vado Native Storage	USBR	AF	2,752
Initial SJC Storage	Heron, Alb	AF	0
Initial SJC Storage	Heron, MRGCD	AF	12,923
Initial SJC Storage	Heron, City & County SF	AF	4,519
Initial SJC Storage	Heron, CochitiRec	AF	5
Initial SJC Storage	Heron, Combined	AF	12,434
Initial SJC Storage	Heron, USBR	AF	0
Initial SJC Storage	El Vado, Alb	AF	0
Initial SJC Storage	El Vado, MRGCD	AF	20,626
Initial SJC Storage	El Vado, City & County SF	AF	0
Initial SJC Storage	El Vado, CochitiRec	AF	0
Initial SJC Storage	El Vado, Combined	AF	2,010
Initial SJC Storage	El Vado, USBR	AF	0
Initial SJC Storage	Abiquiu, Alb	AF	128,672
Initial SJC Storage	Abiquiu, MRGCD	AF	2,000
Initial SJC Storage	Abiquiu, City & CountySF	AF	3,407
Initial SJC Storage	Abiquiu, CochitiRec	AF	0
Initial SJC Storage	Abiquiu, Combined	AF	9,373
Initial SJC Storage	Abiquiu, USBR	AF	4,984
Initial SJC Storage	Cochiti, Alb	AF	0
Initial SJC Storage	Cochiti, MRGCD	AF	0
Initial SJC Storage	Cochiti, City & County SF	AF	0
Initial SJC Storage	Cochiti, CochitiRec	AF	47,619
Initial SJC Storage	Cochiti, Combined	AF	0
Initial SJC Storage	Cochiti, USBR	AF	0
Initial SJC Storage	Jemez, Alb	AF	#N/A

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Initial SJC Storage	Jemez, MRGCD	AF	#N/A
Initial SJC Storage	Jemez, City & County SF	AF	#N/A
Initial SJC Storage	Jemez, CochitiRec	AF	#N/A
Initial SJC Storage	Jemez, Combined	AF	#N/A
Initial SJC Storage	Jemez, USBR	AF	#N/A
Initial SJC Storage	Elephant Butte, Alb	AF	20,936
Initial SJC Storage	Elephant Butte, MRGCD	AF	0
Initial SJC Storage	Elephant Butte, City & County SF	AF	0
Initial SJC Storage	Elephant Butte, CochitiRec	AF	0
Initial SJC Storage	Elephant Butte, Combined	AF	0
Initial SJC Storage	Elephant Butte, USBR	AF	0
Initial SJC Storage	Caballo, Alb	AF	#N/A
Initial SJC Storage	Caballo, MRGCD	AF	#N/A
Initial SJC Storage	Caballo, City & County SF	AF	#N/A
Initial SJC Storage	Caballo, CochitiRec	AF	#N/A
Initial SJC Storage	Caballo, Combined	AF	#N/A
Initial SJC Storage	Caballo, USBR	AF	#N/A
Initial Heron Fed Pool		AF	258,167
Initial Compact Balance		AF	9,1246
Esp Basin Initial GW Heads	1	ft	5,947.6
Esp Basin Initial GW Heads	2	ft	5,693.5
Esp Basin Initial GW Heads	3	ft	6,000.7
Esp Basin Initial GW Heads	4	ft	5,895.8
Esp Basin Initial GW Heads	5	ft	5,684.8
Esp Basin Initial GW Heads	6	ft	5,849.9
Esp Basin Initial GW Heads	7	ft	6,209.8
Esp Basin Initial GW Heads	8	ft	5,484.1
Esp Basin Initial GW Heads	9	ft	6,004.3
Esp Basin Initial GW Heads	10	ft	6,546.6
Esp Basin Initial GW Heads	11	ft	5,742.6
Esp Basin Initial GW Heads	12	ft	6,159.6
Esp Basin Initial GW Heads	13	ft	6,524.6
Esp Basin Initial GW Heads	14	ft	5,589.5
Esp Basin Initial GW Heads	15	ft	5,384.9

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Esp Basin Initial GW Heads	16	ft	5,678.9
Alb Basin Initial GW Heads	1	ft	5,321.2
Alb Basin Initial GW Heads	2	ft	5,214.7
Alb Basin Initial GW Heads	3	ft	5,158.4
Alb Basin Initial GW Heads	4	ft	5,293.4
Alb Basin Initial GW Heads	5	ft	5,229.5
Alb Basin Initial GW Heads	6	ft	5,162.6
Alb Basin Initial GW Heads	7	ft	5,237.6
Alb Basin Initial GW Heads	8	ft	5,176.3
Alb Basin Initial GW Heads	9	ft	5,274.8
Alb Basin Initial GW Heads	10	ft	5,203.8
Alb Basin Initial GW Heads	11	ft	5,427.6
Alb Basin Initial GW Heads	12	ft	5,169.6
Alb Basin Initial GW Heads	13	ft	5,368.7
Alb Basin Initial GW Heads	14	ft	5,134.4
Alb Basin Initial GW Heads	15	ft	5,067.4
Alb Basin Initial GW Heads	16	ft	4,990.4
Alb Basin Initial GW Heads	17	ft	4,915.8
Alb Basin Initial GW Heads	18	ft	5,070.5
Alb Basin Initial GW Heads	19	ft	4,983.2
Alb Basin Initial GW Heads	20	ft	4,915.1
Alb Basin Initial GW Heads	21	ft	5,161.5
Alb Basin Initial GW Heads	22	ft	4,995.5
Alb Basin Initial GW Heads	23	ft	5,030.5
Alb Basin Initial GW Heads	24	ft	4,917.1
Alb Basin Initial GW Heads	25	ft	4,958.6
Alb Basin Initial GW Heads	26	ft	5,225.5
Alb Basin Initial GW Heads	27	ft	4,919.9
Alb Basin Initial GW Heads	28	ft	4,817.2
Alb Basin Initial GW Heads	29	ft	4,959.6
Alb Basin Initial GW Heads	30	ft	4,913.3
Alb Basin Initial GW Heads	31	ft	4,872.4
Alb Basin Initial GW Heads	32	ft	4,819.5
Alb Basin Initial GW Heads	33	ft	4,755.3
Alb Basin Initial GW Heads	34	ft	4,899.3

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Alb Basin Initial GW Heads	35	ft	4,871.9
Alb Basin Initial GW Heads	36	ft	4,820
Alb Basin Initial GW Heads	37	ft	4,758.9
Alb Basin Initial GW Heads	38	ft	4,900.4
Alb Basin Initial GW Heads	39	ft	4,912.5
Alb Basin Initial GW Heads	40	ft	4,871.8
Alb Basin Initial GW Heads	41	ft	4,875.1
Alb Basin Initial GW Heads	42	ft	4,823.1
Alb Basin Initial GW Heads	43	ft	4,776.3
Alb Basin Initial GW Heads	44	ft	4,869.2
Alb Basin Initial GW Heads	45	ft	4,881.9
Alb Basin Initial GW Heads	46	ft	4,835.3
Alb Basin Initial GW Heads	47	ft	4,791.2
Alb Basin Initial GW Heads	48	ft	4,704
Alb Basin Initial GW Heads	49	ft	4,710
Alb Basin Initial GW Heads	50	ft	4,774
Alb Basin Initial GW Heads	51	ft	4,727
Soc Basin Initial GW Heads	1	ft	4,579.4
Soc Basin Initial GW Heads	2	ft	4,498.8
Soc Basin Initial GW Heads	3	ft	4,427.6
Soc Basin Initial GW Heads	4	ft	4,640.7
Soc Basin Initial GW Heads	5	ft	4,589.2
Soc Basin Initial GW Heads	6	ft	4,599.8
Soc Basin Initial GW Heads	7	ft	4,559.5
Soc Basin Initial GW Heads	8	ft	4,508.6
Soc Basin Initial GW Heads	9	ft	4,519.9
Soc Basin Initial GW Heads	10	ft	4,849.9
Soc Basin Initial GW Heads	11	ft	4,437.9
Soc Basin Initial GW Heads	12	ft	4,439.8
Irrigated Ag Acreage to start Scenario		acre	66,000
Initial North Well User Populations	City of Espanola	people	11,489
Initial North Well User Populations	County of Los Alamos	people	18,783
Initial North Well User Populations	City of Santa Fe	people	69,063
Initial North Well User Populations	Domestic well users north of Otowi	people	3,785

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Initial North Well User Populations	Domestic well users south of Otowi	people	16,999
Initial Middle City Populations	City of Bernalillo	people	7,322
Initial Middle City Populations	Rio Rancho	people	84,061
Initial Middle City Populations	City of Albuquerque	people	523,649
Initial Middle City Populations	Los Lunas	people	17,139
Initial Middle City Populations	Belen	people	7,267
Initial Middle City Populations	Socorro	people	9,669
Initial Middle City Populations	T or C	people	8,560
Initial Non-City Reach Population	WC2HRN	people	183
Initial Non-City Reach Population	HRN2ELVDO	people	2,427
Initial Non-City Reach Population	ELVDO2ABQ	people	4,835
Initial Non-City Reach Population	ABQ2CTA	people	28,174
Initial Non-City Reach Population	LBO2CRO	people	12,677
Initial Non-City Reach Population	CRO2TJB	people	23,192
Initial Non-City Reach Population	TJB2EMB	people	12,390
Initial Non-City Reach Population	EMB2OTW	people	26,370
Initial Non-City Reach Population	OTW2CTI	people	89,718
Initial Non-City Reach Population	CTI2SFP	people	10,968
Initial Non-City Reach Population	JMZ2JCD	people	664
Initial Non-City Reach Population	SFP2ALB	people	157,463
Initial Non-City Reach Population	ALB2BDO	people	100,519
Initial Non-City Reach Population	BDO2SA	people	5,689
Initial Non-City Reach Population	SA2SM	people	1,405
Initial Non-City Reach Population	SM2EBT	people	11,224
Initial Non-City Reach Population	EBT2CBO	people	2,618
Initial Non-City Reach Population	CBO2LSB	people	16,259
Initial Non-City Reach Population	LSB2MSLA	people	66,750
Initial Non-City Reach Population	MSLA2EP	people	19,860
Previous Azotea Tunnel Diversions	1 year prior to start year	AF	105,024
Previous Azotea Tunnel Diversions	2 years prior to start year	AF	139,910
Previous Azotea Tunnel Diversions	3 years prior to start year	AF	104,971
Previous Azotea Tunnel Diversions	4 years prior to start year	AF	78,803
Previous Azotea Tunnel Diversions	5 years prior to start year	AF	155,238
Previous Azotea Tunnel Diversions	6 years prior to start year	AF	84,908

Table 8.—Initial Model Conditions for the Upper Rio Grande Climate Changes Impact Assessment

Variable	Element	Unit	Value
Previous Azotea Tunnel Diversions	7 years prior to start year	AF	6,2704
Previous Azotea Tunnel Diversions	8 years prior to start year	AF	63,02
Previous Azotea Tunnel Diversions	9 years prior to start year	AF	110,577

AF = acre-feet.

IV.C. Calibration Parameters for URGIA Runs

Much of the documentation and analysis of calibration discussed in this document is associated with an older calibration of URGSiM. The following tables are designed to allow future modelers to see the calibration that was used for URGIA.

V. Sources of Uncertainty

This analysis is built upon a series of model runs, starting with GCM runs at a global scale, followed by land surface modeling (rainfall-runoff) at a basin scale, and finally operations modeling at the river network level. Each of these models represents a conceptual simplification of a complex physical system that is imperfectly understood. Moreover, statistical methods are also used to connect these model types. GCM output is statistically downscaled for use in the land surface model and operations model, and statistical methods are used to condition the uncalibrated land surface model output for use in the operations model. Output from each model carries with it uncertainties associated with simplification and lack of understanding of the modeled system, and each statistical transformation of the output increases these uncertainties. By definition, these uncertainties are difficult to quantify, but the uncertainties associated with each step in this process are explored in the following sections.

V.A. Uncertainties Associated with Impact Assessment Approach

This section summarizes uncertainties associated with the use of GCM climate projections as well as downscaling approaches applied in the URGIA. The information presented is gathered from Reclamation (2011a) as well as other peer-reviewed literature and reflects the use of best available datasets and data development methodologies.

Table 9.—Groundwater-Related Values

Values Exported from URGSiM-WWCRA.Hde.5.16.2013							
	Shallow Aquifer Zone	Ground Surface Elevation (ft above msl)	River Channel Elevation (ft)	River Channel Conductivity (ft/day)	River to Drain Distance (miles)	Drain Base Elevation (ft above msl)	Drain Conductivity (ft/day)
Albuquerque Groundwater Basin	Cochiti1	5400	5339	0.2	NA	NA	5
	Cochiti2	5233	5218	0.5	0.42	5213	5
	Cochiti3	5169	5159	0.5	0.53	5154	5
	Jemez1	5442.5	5430.5	0.25	NA	NA	5
	Jemez2	5194	5185	0.25	NA	NA	5
	SanFelipe1	5078.7	5068	0.5	0.0005	5063	5
	SanFelipe2	4998.5	4988	0.5	0.16	4983	5
	SanFelipe3	4946	4937	0.11	0.01	4932	5
	AbqBer1	4928	4918	0.5	0.08	4913	5
	AbqBer2	4884.5	4873	0.5	0.24	4868	5
	AbqBer3	4830	4818.5	0.5	0.17	4813.5	5
	AbqBer4	4770	4754.5	0.5	0.6	4749.5	5
	SanAcacia1	4724.5	4705.5	0.5	1.7	4700.5	5
Socorro Groundwater Basin	SA2BDA	4586	4583	0.5	3	4570.5	25
	BDA2SM	4507	4500	0.5	3	4491	25
	SM2EBGW	4470.7	4458	0.5	3	4456	25

Table 10.—Canal Leakage Related Values

Values Exported from URGSiM-WWCRA.Hde.5.16.2013	
Reach	Parallel Canal Calibration Factor
Cochiti to San Felipe	3
Jemez to Jemez Canyon Dam	2
San Felipe to Albuquerque	5
Albuquerque to Bernardo	4
Bernardo to San Acacia	16
San Acacia to San Marcial	8

Table 11.—Reservoir-Related Values

Values Exported from URGSiM-WWCRA.Hde.5.16.2013		
Reservoir	**Parameter**	**Value**
Heron	Heron native inflows factor	6.80%
El Vado	La Puente reduction threshold (cfs)	2000
	La Puente reduction factor	35%
Abiquiu	Abiquiu local inflows correlation to Jemez near Jemez Pueblo gage	54%
Cochiti	Lake bottom (river bed in 1st shallow aquifer zone) conductivity (ft/day)	0.2
Jemez	Jemez local inflow correlation to Jemez near Jemez Pueblo gage	52%
	Jemez local inflow cutoff (cfs)	200
Elephant Butte	Shallow aquifer surface elevation San Marcial to Elephant Butte (ft)	4471
Caballo	EB to Caballo ungaged effective area (acre)	26,000

Table 12.—Reach-Related Values

Values Exported from URGSiM-WWCRA.Hde.5.16.2013		
Reach	**Parameter**	**Value**
El Vado to Abiquiu	Ungaged correlation to Ojo Caliente @ La Madera	35%
Abiquiu to Chamita	Ungaged correlation to Ojo Caliente @ La Madera	3.5%
	Riparian area (acres)	80
Lobatos to Cerro	None	
Cerro to Taos Junction Bridge	Ungaged correlation to Rio Pueblo de Taos near Rio Grande	37%
Taos Junction Bridge to Embudo	Embudo Creek high flow threshold (cfs)	200
	Embudo Creek high flow reduction	23%
Embudo to Otowi	Ungaged correlation to Rio Nambe below dam	120%
Otowi to Cochiti	Calibrated with Cochiti Reservoir	
Cochiti to San Felipe	Ungaged correlation to Galisteo Creek	156%
	Carriage water	15%
San Felipe to Albuquerque	Ungaged correlation to North Floodway Channel	92%
	Carriage water	15%
Albuquerque to Bernardo	Carriage water	0%
Bernardo to San Acacia	Rio Puerco reduction factor	36%
	Carriage water	15%
San Acacia to San Marcial	Carriage water	14%
San Marcial to Elephant Butte	Calibrated with Elephant Butte Reservoir	
Elephant Butte to Caballo	Calibrated with Caballo Reservoir	

V.A.1. Global Climate Forcing

Although this report considers climate projections representing a range of future greenhouse emission pathways (Reclamation 2011a), the uncertainties associated with estimating these pathways are not explored in this analysis. Such uncertainties include those introduced by assumptions about:

- Technological and economic developments, globally and regionally
- How those assumptions translate into global energy use involving greenhouse gas emissions
- Biogeochemical analysis to determine the fate of greenhouse gas emissions in the oceans, land, and atmosphere

  Also, not all of the uncertainties associated with climate forcing are associated with greenhouse gas assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., figure SPM-2 in IPCC 2007). Note that this report uses an ensemble of downscaled climate and hydrologic projections (Reclamation 2011a) that stem from GCMs collectively reflecting three scenarios of greenhouse gas emissions (IPCC 2000): B1 (low emissions), A1B (moderate emissions), and A2 (high emissions). For the purposes of this report, results from these projections are pooled based on the assumption that these scenarios are equally plausible and the lack of information to suggest otherwise. As shown in IPCC 2007, for early to middle 21st century, the projections ensembles (temperature and precipitation) are similar for each scenario, suggesting that choice of emissions scenario does not significantly influence projection uncertainty in this timeframe. However, by the end of the 21st century, the scenario-specific ensembles of temperature projections do start to diverge, with the A2 (high emissions) scenario leading to substantially larger warming than the B1 (low emissions) scenario.

V.A.2. Global Climate Simulation

This report considers climate projections produced by stat of-the-art coupled ocean-atmosphere climate models. Even though these models have shown an ability to simulate the influence of increasing greenhouse gas emissions on global climate (IPCC 2007), there are still uncertainties about the scientific community's understanding of physical processes that affect climate, including how to simulate such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycle, vegetative and other biological changes). Uncertainties in simulating regional atmospheric circulation response to changes in global climate forcing are relevant in projecting effects on regional to local weather patterns (e.g., effects on storm track positions approaching the West Coast, effects on North American Monsoon over the Colorado and Rio Grande basins, or effects on interplay between Pacific, Arctic, and Gulf of Mexico air masses affecting precipitation conditions over the Great Plains).

In addition, the process of specifying initial climate system conditions at the beginning of 20th and 21st century simulations (e.g., heat distribution throughout the oceans) permits projections to stem from different "distributed initial conditions," which also contributes to projection uncertainties at the regional scale (Hawkins and Sutton 2009), particularly for precipitation (Hawkins and Sutton 2010). Finally, it is noted that this report does consider these uncertainties by surveying projection information from a multimodel ensemble, similar to the approach used in the IPCC Fourth Assessment (IPCC 2007). However, as noted in the Fourth Assessment, even this "ensemble of opportunity" may not cover the entire range of uncertainty associated with global climate simulation.

V.A.3. Climate Projection Bias Correction

Analyses (Reclamation 2011c) presented within this document assume that GCM biases toward being too wet, too dry, too warm, or too cool should be identified and accounted for prior to use in implications studies like sensitivity analyses. However, the procedure to remove biases in climate projections relative to a historical baseline can affect the apparent "climate change," from a historical period to a future period, expressed by the projections (biased versus bias-corrected). This has been shown within Reclamation (2011b), where the method for bias correcting the climate projections appears to have altered projected precipitation changes to be slightly wetter over much of the Western U.S.[1] This, in turn, leads to less adverse future hydrologic changes than if hydrologic change projections had been based on changes from the non-bias-corrected climate projections.

V.A.4. Climate Projection Spatial Downscaling

The analyses presented within this report use climate projections that have been downscaled using BCSD, a non-dynamical and relatively simple spatial disaggregation technique (Wood et al. 2002). Although this technique has been

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[1] When 25th, 50th, and 75th percentile precipitation changes were identified within the ensemble of projections over the Western U.S., it was found that percentage changes from bias-corrected projections were generally zero to a few percent greater than percentage changes from the non-bias-corrected projections (Figure 9 of Reclamation 2011b).

used to support numerous water resources impacts studies, uncertainties remain about the limitations of empirical downscaling methodologies relative to more sophisticated dynamical methods that rely on coupling outputs from global climate models to the inputs of finer resolution regional climate models. Nevertheless, the spatial disaggregation technique was used due to the ease in applying it to a large collection of climate projections over the Western U.S. for the 21st century and, thus, to better sample the uncertainty due to global model simulations compared to what feasibly could be done using dynamical methods.

V.A.5. Watershed Vegetation Changes Under Climate Change

In Reclamation (2011b) and related literature sources cited by that study, the chosen approach for assessing hydrologic effects under projected climate changes is to use a “surface-water hydrologic” model that computes hydrologic conditions given changes in weather while holding other watershed features constant. Vegetation features might be expected to change as climate changes. These vegetation changes, in turn, would affect runoff through changes to evapotranspiration and infiltration processes. However, such changes are difficult to forecast and are not accounted for in this approach.

V.A.6. Quality of Hydrologic Model Used to Assess Hydrologic Effects

In Reclamation (2011b) and most of the cited literature sources, the chosen approach for assessing hydrologic effects typically has involved using “surface water hydrologic” models, which account for the shallow surface layers of the watershed, but do not consider the full range of watershed groundwater processes and interactions of groundwater with surface water. Further, these surface water hydrologic models generally are not designed to represent the water balance processes of large water bodies (e.g., Elephant Butte Reservoir). Thus, while the direction of projected hydrologic changes is expected to be a robust result from these hydrologic models, the magnitude of change is less certain and possibly affected by the omission of key hydrologic processes related to groundwater and/or large water bodies. Potentially due to these factors, the model results presented in Reclamation (2011b) were shown to imperfectly reproduce historical runoff conditions in the Upper Rio Grande Basin.

Some of these imperfections could be reduced through refined redevelopment, or “calibration,” of the models. To support such model refinement, preliminary activities might be spent on updating naturalized flow datasets, where observed flows have been adjusted for the effects of upstream reservoir operations, water diversions, return flows, and other impairments. Updates ideally would focus on extending periods of record, expanding the list of locations, and ensuring the uniformity of methods used to construct such datasets. As it is, available natural flow datasets across the eight reporting basins are specified for inconsistent periods and for a limited list of locations. Completing such updates also would set up the ability to consistently report on historical streamflow trends in the eight major reporting basins, where trends are based on historical natural flow estimates. The analyses presented in the URGIA do not include such updates and, instead, focus on changes information from runoff simulations, as described above.

V.A.7. Reporting Centrally Projected Effects Rather than Range of Possibility

This report evaluates future hydrology associated with a large collection of current climate projections. In this respect, the report represents projection uncertainties associated with climate forcing (i.e., greenhouse gas emissions) and global climate simulation (given that the collection of projections represents a collection of atmospheric ocean general circulation models). However, subsequent uncertainties are not quantified in this report, namely those associated with bias correction and spatial downscaling (BCSD) of global climate projections and assessment of the hydrologic response of this processing of the projections. Further, from the collection of hydrologic projections developed, the URGIA is framed to draw attention to central projection estimates (or median conditions within the “cone” of projection information) rather than the range of possibility implied by the complete cone of information. However, it is acknowledged that the collection of projections underlying these results also suggests a broad range of uncertainty about future regional climate and hydrologic conditions, varying from period to period during the 21st century. Uncertainties also exist beyond the median change statistics presented within this report for temperature, precipitation, and April 1st snowpack. The presentation in the URGIA that emphasizes median change was selected for clarity in communication. For characterization of how these changes could vary across the climate projections considered, please refer to Reclamation (2011a).

V.A.8. Climate Projections from the Coupled Model Intercomparison Project Phase 3 and Phase 5

The development of climate projections by the World Climate Research Programme and an associated assessment report by the IPCC is a recurring 7-year process. The next generation of climate projections, Coupled Model Intercomparison Project Phase 5 (CMIP5), was not available at the time that the analyses were performed for the URGIA. However, these projections have recently been developed and are providing the basis for the next IPCC assessment report (Fifth Assessment Report, or AR5), which is currently being prepared. Although the most recent suite of climate projections based on the CMIP5 models use a different approach for representing future greenhouse gas emissions, and many of the GCMs have improved representations of the physical atmosphere-ocean system, overall, this new suite of simulations are consistent with CMIP3 in most respects and provide support for analyses performed using CMIP3. Projections based on CMIP3 are still widely used in Impact Assessments and remain a valid approach for evaluating climate change impacts.

The above discussions of uncertainty related to climate forcings and downscaling techniques are based on analysis of projections from the CMIP3 suite of simulations. The models and scenarios of emissions used in CMIP5 differ in several ways from those used in CMIP Phase 3:

- CMIP5 simulations account for increasing greenhouse gas concentrations not by emission scenario but instead by applying four Representative Concentration Pathways (RCPs), each of which is representative of a particular amount of radiative forcing (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively) occurring by the year 2100.

- Model resolution has generally increased by a factor of 2 (i.e., CMIP 5 models have on average twice the number of grid cells representing the atmosphere than CMIP3 models).

- Although many of the models used in CMIP5 are similar in structure to those used in CMIP3, many incorporate updated physics and add or improve individual process representation. Some of the models used in CMIP5 reflect a fundamental advancement in model structure by incorporating biogeochemical cycling: this new class of models is referred to as Earth System Models.

It is important to recognize that while CMIP5 offers new information, more work is required to better understand CMIP5 and its differences from CMIP3. In some regions, model resolution is likely the leading factor resulting in differences. In the North American Monsoon region, for example, the higher resolution of CMIP5 models allows these models to better capture the landward moisture transport and overland convection that results in monsoon precipitation events.

The CMIP Phase 5 projections represent a new opportunity to improve our understanding of climate science, which is evolving at a rapid pace. While CMIP 5 projections may inform future analyses, many completed and ongoing studies remain informed by CMIP Phase 3 projections that were selected as best information available at the time of study. Even though CMIP Phase 5 provides the latest available suite of climate projections, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP 3 projections. Current state of practice relies on one or both suites of climate projections for use in impacts studies.

V.B. Operations Models Uncertainty

URGSiM reflects physical processes that occur in the Upper Rio Grande as water:

- Moves through the river
- Is stored in reservoirs
- Evaporates into the atmosphere
- Seeps into the groundwater
- Is distributed to farms and cities through engineered structures
- Is transpired through plants and trees among other processes

Modeling of each of these processes is based on some combination of physical laws (predominantly conservation of mass in the case of URGSiM), operations rules, and observation based empirical relationships. Model behavior is calibrated to historic observations by manipulating model parameters associated with poorly quantified physical properties of the system (e.g., hydraulic conductivity), or poorly understood physical processes (e.g., the amount of ungaged inflow to a reach as a function of precipitation or nearby gaged streams). URGSiM was calibrated based on 1975 through 1999 historic observations of river flows, reservoir levels, and groundwater levels. URGSiM was “validated” by using 2000 through 2005 hydrologic and climatic inputs to drive the model, and comparing model outputs—especially simulated river flows and reservoir levels to observed values. In both calibration and validation, there is a distribution of “residuals” associated with comparing a given model output to actual observations where available. For a quantitative description of these residuals, see Appendix E.
A qualitative list of the most significant model uncertainties in URGSiM follows.

- **Surface water flows. –** Uncertainties come from gage inaccuracies, which are more significant as one moves downstream through the Rio Grande system and gages are located in areas with sandy bottoms and thus variable cross sectional areas. For some discussion on gage uncertainties in the URGSiM model extent, see Appendix E. This gage uncertainty will directly impact bias correction of VIC hydrographs which are inputs to URGSiM for this study. Uncertainties also come from a lack of gaged information. In fact, the most important calibration parameter in URGSiM reaches upstream of Cochiti Reservoir is ungaged surface water inflow, which is modeled as a function of a nearby stream gage.

- **Actual agricultural ET. –** Potential evapotranspiration can be calculated with a reasonable degree of certainty with good meteorological data; however, those data are spatially and temporally limited in the URGSiM modeled area. Actual evapotranspiration depends on the crop planted, the crop area, and the amount of water actually applied to the field. Crop and area data are temporally limited in the URGSiM extent. Though water in the agricultural conveyance system is gaged at strategic locations along large ditches and drains, it is essentially unknown how much water is actually applied to the fields.

- **Riparian evapotranspiration. –** In URGSiM, riparian evapotranspiration is calculated from potential evapotranspiration (discussed above) and groundwater depth, calibrated to values represented in the regional groundwater models (see Groundwater discharge/recharge bullet below).

- **Reservoir evaporation rates. –** Reservoir evaporation rates are based on pan evaporation times an empirically derived factor designed to account for the mostly thermal based differences between pan and reservoir evaporation. URGSiM uses a factor of 0.7 for all reservoirs in the Upper Rio Grande.

- **Surface water/groundwater interactions**. – Due to large spatial groundwater zones, URGSiM has trouble resolving the impacts of a single well field on river leakage. Thus, groundwater pumping impacts on the river are muted.

- **Groundwater discharge/recharge. –** Groundwater discharge to the river is a temporally invariant term in URGSiM based on gage analysis upstream of the Rio Grande near Embudo Station and the Rio Chama near Chamita gages. Downstream of these gages groundwater recharge is temporally invariant based on average recharge estimates used in regional groundwater models for the Española Groundwater Basin (Frenzel 1995), Albuquerque Groundwater Basin (McAda and Barroll 2002), and Socorro Groundwater Basin (Shafike 2007). No change to groundwater discharge in the upper reaches, or recharge in the groundwater basins as a result of climate change is considered here.

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