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Changing climatic conditions in the Colorado River Basin: Implications for water resources management in the Las Vegas Valley

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CHANGING CLIMATIC CONDITIONS IN THE COLORADO RIVER BASIN:

IMPLICATIONS FOR WATER RESOURCES MANAGEMENT IN THE

LAS VEGAS VALLEY

by

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ABSTRACT

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by

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Climate change affects the water available in a region. It also affects the water demand, because of the increase in temperature. A system dynamics model was developed for the Colorado River Basin (CRB), operating at a monthly time scale, to assess the potential impacts of climate change on streamflow in the Colorado River and its subsequent impact on the water resources management in the Las Vegas Valley (LVV). The effect of climate change on streamflow was evaluated using 16 global climate model outputs for 3 emission scenarios, also referenced in the Inter-Governmental Panel on Climate Change Fourth Assessment Report. Risk analysis of the water supply to the basin states dependent on the Colorado River was performed based on streamflow magnitude estimated using GCM outputs. Probabilities of Lake Mead levels to draw down below 327.7 meters (1075 feet) was investigated based on streamflow estimated using GCM outputs, and also on the future streamflow varying from 60 to 120 % of the historical average streamflow. The model was further developed to evaluate the impacts of climate change and population growth on the water resources in the LVV. Effect of climate change on water demand was also simulated using the same ensemble of 16 GCM outputs for the future temperature in the LVV. Demand management was

modeled as the long term solution to obtain the water sustainability in the LVV. Water demand and water supply were investigated for different scenarios of population growth rate and policies implemented for water conservation in the LVV. Policies refer to indoor-outdoor conservation and water pricing. The results showed that climate change has significant effect on streamflow in the CRB. The ensemble average of all the GCMs showed about 3% reductions in future streamflow by 2035. This created the possibility of curtailments to the water supply in the basin states. Approximately 14% probability of supply curtailment to the basin states was observed from the ensemble average of the GCMs. Similarly, averaged over the ensemble of all the GCMs, water supply reliability of about 0.86 was observed for the basin states. Population growth resulted in significant impact on water resources in the LVV. With the population growth as predicted and with no additional policies for water conservation, water demand was observed to exceed the supply in near future and the reliability of water supply to the LVV from the Colorado River was estimated to be 0.06. With no further population growth and no climate change, a reliability of 1 was observed. Reliability of water supply decreased with the changing climatic conditions. The ensemble average of all the GCMs predicted a 5% probability of Lake Mead levels to drop below 305 m (1000 ft) for the future simulation, if water supply to the basin states is continued below 305 m (1000 ft) water levels in Lake Mead. The results suggested a need of combined demand management policies and slower population growth to achieve the water sustainability in the LVV. This study has expanded the existing knowledge of the effect of climate change on streamflow in the CRB with the inclusion of the most plausible range of future climatic conditions. This study may help to facilitate the water managers by providing the broad choice of demand management policy options in developing sustainable water management practices to meet the increasing demand in the LVV.

Keywords: System dynamics, climate change, streamflow, Colorado River basin, Las Vegas Valley, Global Climate Models

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CHAPTER 1

INTRODUCTION

1.1. Background

Increase in global population, together with urbanization and industrialization, has resulted in increased water demand (WHO, 2009). Census data indicates that total population of the world has more than doubled in the last 60 years (2.6 billion in 1950 to 6.9 billion in 2010) (USCB, 2010). This has led the global water demand to triple between 1950 and 2003, with further projected to double by 2035 (Tidwell et al., 2004). Globally over 50% of all the renewable and available water has been already allocated for human use (Postel et al., 1996). As water demand increases for the growing population, meeting necessary environmental water requirements has become challenging around the world (Postel et al., 1996; Vorosomorty et al., 2000). At the same time, climate change impacts on the water resources further affects the available water and sustainable supply to the human and environmental needs.

Changing climatic conditions are related with the changes in the hydrologic cycle such as increasing temperatures, changing precipitation patterns, reduced snow cover, changing runoff (IPCC, 2008). As a result, annual average runoff is projected to increase at high latitudes and in some wet tropical areas, whereas it is projected to decrease over some of the dry regions at mid-latitude and in the dry tropical areas (IPCC, 2008). Change in climatic conditions increases the frequency of the extreme events like flood and droughts. Globally, drought areas have increased by more than 50% during the last century, with the further increases are projected by 1% to 30% by 2100 (Mata, 2008). Thus, the arid and semi-arid regions such as Western Australia, western and southwestern

United States, southern Canada, southern Africa, Mediterranean are particularly exposed to the impacts of climate change and are projected to experience the decrease in water resources due to climate change (IPCC, 2008; Mata, 2008).

At the same time, changing climatic conditions increase water demand due to the increase in temperature (Arnell, 1998). Increase in temperature increases outdoor water demand, particularly in the arid and semi-arid regions. Thus, the water resources system can be vulnerable due to the increase in water demand and decrease in supply, caused by the changing climatic conditions. Hence, future water management should include a broad range of possible responses including demand management to meet water shortages.

Demand management policies are necessary for future water management as a complement to the established approach of supply side management. Demand side management improves the customer's water use behavior with the available resources rather than seeking for the new sources of supply (Gleick, 2003). On the contrary, supply side management focuses on increasing the sources of supply using options such as reuse, desalination, transport of water from distant sources and some other. Supply side management, however, in the past, existed at a very expensive and irreversible ecological and environmental cost (Wang et al., 2011). Thus, a shift towards demand side management has been getting higher priorities in numerous regions around the world.

1.2. Research Motivation

The Colorado River is the vital river in southwestern United States. It supplies water to seven states within United States and to Mexico. The Colorado River Basin (CRB) is divided into Upper and Lower Basin, with Lees Ferry as the dividing point. The Upper basin serves Wyoming, Utah, Colorado and New Mexico and the Lower Basin serves Arizona, California and Nevada. Colorado River Compact of 1922 allocated 9.2 billion cubic meters per year (BCM/yr) to the Lower Basin states, 1.8 BCM/yr to Mexico and 9.2 BCM/yr to the Upper Basin states.

After the Compact of 1922 was signed, rarely the river has a 10 year average streamflow equal to the total share of 20.2 BCM/yr (Christensen et al., 2004). The two massive reservoirs namely Lake Powell and Lake Mead created by the Glen Canyon Dam and the Hoover Dam, respectively have been able to supply water to the basin states even in low flow years. However, the recent drought experienced in the CRB that started in October 1999 (USDOI, 2011) has affected the water availability in this region. Unregulated inflow to Lake Powell in water year 2002 was about 25% of its capacity, the lowest in the history (USDOI, 2011). Numerous studies have projected that the reservoir systems in the CRB will be experiencing decreased flow over next several decades, due to the changing climatic conditions (Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; Milly et al., 2005).

Several studies have projected that the Colorado River is likely to experience an increase in temperature in future (Gleick, 1987, 1985; Lettenmaier et al., 1992; McCabe and Wolock, 1999; Nash and Gleick, 1993). However, changes in magnitude and distribution of future precipitation pattern are still not consistent among these studies. Changing climatic conditions are projected to reduce runoff in the CRB, along with increasing rain to snow ratio and earlier snowmelt (Barnett and Pierce 2009; Christensen et al., 2004; Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; McCabe and Wolock, 2007; Milly et al., 2005; Rajagopalan et al., 2009). Since, runoff is the measure of sustainable availability of water (Milly et al., 2005), its reduction can have significant impacts upon the water supply to the basin states dependent on the Colorado River. Such an effect can also be experienced in the Las Vegas Valley in the state of Nevada, which is dependent on the Colorado River for meeting majority of its water demand.

The Las Vegas Valley (LVV) located in the Southern Nevada gets about 90% of its total supply from Lake Mead, which is replenished by the Colorado River. Approximately 370 million cubic meters/year (MCM/yr) of the Colorado River water is allocated to LVV (SNWA, 2011). Remaining 10% is met from the ground water pumped from deep ground water aquifers located in the LVV (SNWA, 2009). With the increase in population in this region by more than 2 times in 20 years between 1990 to 2010 (CBER, 2010), water demand has almost doubled (SNWA, 2009). With the population estimated to be nearly 3 million by 2035 (CBER, 2010), the water demand is further projected to increase (SNWA, 2009). On the contrary, the decreasing water levels in Lake Mead may create the possibility of supply curtailments to the actual allocation from the Colorado River, decreasing the water supply.

Under these conditions, keeping future supplies in line with future demand requires either increasing the supply or decreasing the demand. Although, Southern Nevada Water Authority (SNWA), the water management agency in the LVV, has been considering a wide range of options, increasing supply is both politically and economically expensive (Stave, 2003). With this realization, demand management practice is getting higher priority in this region. With demand management practices, per capita water consumption has been reduced from 1191 liters per day (lpd) in 2002 to 922 lpd in 2011, an overall reduction of around 25 % (SNWA, 2009). It is further expected to reduce this level to 752 lpd by 2035. However, the current per capita consumption of the LVV is still highest among other southwestern cities, which have similar climatic settings (Cabibi et al., 2006), hence leaving the space for further water conservation efforts.

With this motivation, the current research focused on the effect of climate change on streamflow in the Colorado River and implications for water resource management. Previous studies that focused on the water resource management such as Stave (2003), Tidwell et al. (2004), Ahmad and Prashar (2010), Qaiser et al. (2011), and Shrestha et al. (2011) considered water supply and demand; however, none of these studies have taken into account the effect of climate change on the water demand and supply. This study considered the integrated impacts of climate change on both the water supply and water demand, in addition to investigating the potential of various demand management policies to conserve water. The study used the most plausible range of future climatic conditions in the CRB with the inclusion of 16 global climate models and three emission scenarios, also referenced in the Inter-governmental Panel on Climate Change Fourth Assessment Report. Thus, the study provides the broadest range of the magnitude of future streamflow in the CRB. By providing the plausible future scenarios of climatic conditions, the changes required for obtaining the higher reliability of the future water management system can be considered.

1.3. Hypothesis and research objectives

The main objectives of research are:

1. To determine the effect of climate change on the magnitude of streamflow in the Colorado River Basin, and its implications on the water supply to the Lower Basin states.

   Hypothesis #1. The changing climatic conditions affect the magnitude of streamflow in the CRB. Decrease in precipitation and increase in temperature cause a reduction in the magnitude of streamflow in the CRB. The reduction in the magnitude of streamflow may decrease the water supply to the Lower Basin states.

2. To determine the impacts of climate change and increasing population growth on the water demand and water supply in the Las Vegas Valley.

   Hypothesis #2. Climate change increases the water demand in the LVV and may decrease the supply of water from the Colorado River. Increasing population growth increases the water demand in the LVV.

3. To determine the potential of different water management options in conserving water in the LVV. This involves investigating different demand management options for their potential in conserving water.

   Hypothesis #3. Demand management policies help to provide the sustainable water supply in the LVV for a longer duration of time.

To accomplish the research objectives, following tasks were performed:

Task 1: A hydrologic water balance model similar to Xu et al. (1996) was re-developed in system dynamics for the Upper Colorado River Basin, operating at a monthly time scale for the duration of 1970 to 2035. The model required as input the monthly temperature, monthly precipitation and monthly potential evapo-transpiration and generated streamflow as one of the major output. The hydrologic model was calibrated and validated for streamflow at Lees Ferry for the duration of 1970-1990 and 1991-1999, respectively. It was also validated for Lake Mead levels for the duration of 1970-1999.

Task 2: A dynamic simulation model was developed for the water demand and water supply assessment of the LVV under different scenarios of population growth, climate change, and water management options, for the duration of 1989 to 2035.The water balance model for LVV was validated for the water demand from 1989 to 2010.

Task 3: Future simulations were carried out for the duration of 2012 to 2035 for (i) the magnitude of streamflow at Lees Ferry, (ii) Lake Mead levels and probability of supply curtailments to the Lower Basin, (iii) risk evaluation of the water supply in the Lower Basin, (iv) potential of demand management options to conserve water, (v) water demand and water supply in LVV from the Colorado River, and (vi) risk analysis of water supply to the LVV from the Colorado River.

The following research questions were investigated in the study:

1. What changes in the magnitude of streamflow can be observed in the CRB till 2035 as a result of climate variability and change, and what can be the implications on the water supply to the Lower Basin states?
2. How long can the available water resources sustain the water demand of the LVV, given increasing population growth and changing climatic conditions?

3. What is the saving potential of different demand management policies adopted for water conservation?

1.4. Preview

The research follows the manuscript style. It starts with introducing the problem statement, research hypothesis and objectives, and research tasks as first chapter. It is followed by two manuscripts as second and third chapters. Second chapter describes the effect of climate change on streamflow in the Colorado River and its implications for the water resources management. Third chapter involves a comprehensive analysis of effect of climate change on water resources management in the Las Vegas Valley. Potential of different water conservation and pricing policies are tested for their effectiveness in conserving water under different conditions of climate change and population growth. The final or the fourth chapter concludes the manuscript with the conclusions and recommendations derived from the research.

CHAPTER 2

CHANGING CLIMATIC CONDITIONS IN THE COLORADO RIVER BASIN: IMPLICATIONS FOR WATER RESOURCES MANAGEMENT

2.1. Introduction

Increase in global population has affected the water demand (WHO, 2009). This has led the water demand to triple between 1950 and 2003 and is projected to double by 2035 (Tidwell et al., 2003). About two-thirds of the world population is expected to be affected by water scarcity over the next several decades (Alcamo et al., 1997; Seckler et al., 1998; Rijsberman, 2006). In addition, as population and associated water demand increases, meeting environmental needs is becoming challenging in numerous river basins around the world (Postel et al., 1996; Vorosmarty et al., 2000). Environmental water requirements may also impact the appraisal of water availability around the world (Smakhtin et al., 2004).

In addition, the effect of changing climatic conditions on the hydrologic regime is evident from different global climate model (GCM) outputs; however, the effect differs from region to region (IPCC, 2007). The majority of studies suggest that warmer climate is expected to shift the timing of snowmelt to earlier in the year (Regonda et al., 2005; IPCC, 2007; Christensen and Lettenmaier, 2007), causing water shortage in dry summer months. Such changes on the streamflow pattern increasingly contribute to the uncertainty in water resources management (Middelkoop et al., 2001). The preferred responses to the water challenges in such a condition include either increasing the water supply or decreasing the demand (Glecik, 2010; MacDonald, 2010).

Over 20th century, water managers have focused on increasing the supply to meet the water demand (Gleick, 2003; Peters et al., 2010). With this approach, the generation of hydropower and irrigation has expanded with the construction of about 45,000 large dams, which has moderated the risks of severe droughts and floods (Gleick, 2003; Molle and Turral, 2004). However, this approach has numerous environmental consequences along with high socio-economic costs (Wang et al., 2011). Thus, a shift towards demand management practices has been occurring recently. Rather than increasing the supply, demand management ensures that water use is reduced and makes the available water resources more sustainable (Brandes and Kriwoken, 2006). In response to both climatic and non-climatic changes, a shift to demand management has been practiced in some regions of southwestern United States, especially the Colorado River Basin.

The Colorado River Basin (CRB) is one of the most heavily regulated and over-allocated rivers in the world (Christensen and Lettenmaier, 2007). Temperature records across the CRB have shown warming over the past century, with the projections that this trend will continue (National Research Council, 2007). Peak spring snowpack melt is shifting earlier in time with the increasing temperature (Regonda et al., 2005; Mote et al., 2005; Stewart et al., 2005; National Research Council, 2007). The early snowmelt contributes to more winter runoff, while a reduction in summer inflows to the reservoirs causing dry summer months (USDOI, 2009).

Similarly, the magnitude and trend of the precipitation pattern is changing in the CRB (USDOI, 2009). McCabe and Wolock (1999) reported an increase in winter precipitation in the CRB. Similarly, Christensen and Lettenmaire (2007) reported that most of the GCMs show modest reductions in summer precipitation and increases in winter precipitation. There is little consensus regarding the change in precipitation patterns over the northern portions of the CRB (Dai, 2006).

Variability in precipitation patterns in CRB has caused significant uncertainty in the magnitude of streamflow, which differs considerably among studies. Hoerling and Eischeid (2007) used GCM outputs at a spatial scale of 150 kilometers (km) to drive a model using a statistical relationship of temperature and precipitation with streamflow. The study indicated a 45% reduction in streamflow in the Colorado River by 2050. Christensen and Lettenmaier (2007) forced 22 downscaled finer resolution GCM outputs at 12 km into high resolution Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Nijssen et al., 1997), and indicated the reduction to be approximately 5% over the next century. Milly et al. (2005), who used the raw GCM outputs at a spatial scale of 200 km, reported nearly 20% reduction in the streamflow of the Colorado River by 2050. Christensen et al. (2004) forced a single GCM output at 12 km spatial scale into the VIC model; this study concluded nearly an 18% reduction in the streamflow in the Colorado River. The changes in streamflow have been evident from the changes in the storage of two major reservoir storage systems, namely, Lake Powell and Lake Mead. The effect of climate change on the water volume in these reservoirs has been investigated by numerous studies (Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009; Rajagopalan et al., 2009), which have concluded that approximately 10-30% of the flow is expected to reduce in these reservoirs from 1985 to 2060. Thus, the numerous studies have suggested a decrease in the streamflow and in the storage of the reservoirs in the CRB. Since, runoff is the measure of sustainable water availability (Milly et al., 2005), its reduction could affect the water supply to states dependent on the Colorado River.

With this motivation, the present study focused on evaluating the impacts of climate change on the hydrologic regime and the water resources of the CRB. A system dynamics (SD) model, using 16 GCMs and 3 emission scenarios, was developed for the CRB for the duration of 1970 to 2035 to assess the changes in the streamflow and the water resources sustainability due to the changing climatic conditions. Previous efforts focused on evaluating the effect of climate change on the hydrologic regimes of the CRB using numerous GCM outputs and high resolution hydrologic models (Christensen et al., 2004; Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007). In addition to evaluating the effect of changing climatic conditions on the hydrologic regime with the use of GCM outputs, the current study also assessed the water sustainability in the basin states, based on risk analysis of the water supply system. With the inclusion of 16 GCMs for 3 emission scenarios, this is one of the broadest studies of the possible ranges of the future streamflow in the CRB.

The SD model runs on a monthly time scale, encompassing a period of 1970 to 2035. The period from 1970 to 1999 was used for calibrating and validating the model. The model performance was based on different measures that include root mean square error-observations standard deviation (RSR), percentage bias (PBIAS), Nash Sutcliff coefficient (NSE), correlation coefficient (R), mean absolute error, and average error between the actual and the simulated values. Datasets used in the current study include (i) Monthly precipitation, mean monthly temperature, monthly potential evapo-transpiration (PET); (ii) Water allocation of the basin states; (iii) Naturalized streamflow at different streamflow gages in Upper Colorado River Basin (UCRB); and (iv) operating rules for Colorado River reservoirs. The study is expected to help policy makers in incorporating the effects of climate change on the water resources management in the CRB.

2.2. Study area

The Colorado River extends to an area of 630,000 square kilometers in the United States (ACWA and CRWUA, 2005). The Colorado River heads in the Rocky Mountain in United States and ends at the Gulf of California. The annual average precipitation in the CRB is about 40 cm with a large temporal variability (Christensen and Lettenmaier, 2007). Snow pack in Rocky Mountain contributes about 70% of the total annual runoff in the CRB (Christensen et al., 2004); it is a snow melt driven basin that depends on the winter snow fall for its dry season supply (ACWA and CRWUA, 2005). Snow melt in about 15% of the total CRB area produces about 85% of the total annual runoff (ACWA and CRWUA, 2005). Colorado River supplies water to the parts of seven states within United States and to Mexico. The river basin is divided into Upper and Lower Basin, with Lees Ferry as the dividing point. The Upper Basin serves the states of Wyoming, Colorado, Utah, and New Mexico. The Lower Basin serves the states of Nevada, Arizona and California within United States as well as Mexico. Out of 90 different reservoirs in the CRB, Lake Mead and Lake Powell store about 85% of the total storage capacity of the basin (approximately 64 billion cubic meters (BCM)), which is about four times the annual average streamflow in the CRB (Christensen et al., 2004). Figure 2.1 shows the map of the study area along with the sub-basins and the stream flow gauge stations used in the study.

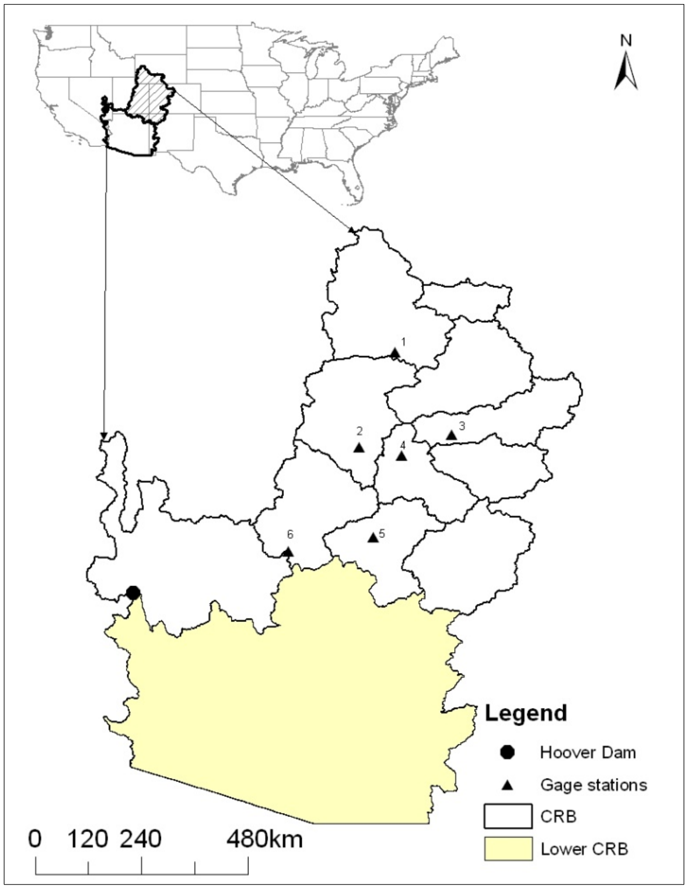

Figure 2.1. Map showing the study area in the Colorado River Basin with streamflow gauge stations in the Upper Basin used in the study. The study area includes the entire Upper Basin and a part of the Lower Basin upstream of the Hoover Dam

2.4. System Dynamics Modeling

System dynamics (SD) modeling was used to develop the simulation model for evaluating the impact of climate change on the streamflow and water resources in the CRB. SD was first found by Jay Forrester at Massachusetts Institute of Technology in 1961 (Ford, 1991). SD is the study of dynamic systems with the use of stocks and flows which influence each other through the feedback loops and time delays (Sterman, 2000). Feedback loops are created by the causal influence between the inputs and the outputs. SD is one of the best methods to learn about the complex systems that change with time, and provide feedback to each other generating dynamic behavior (Ford, 1991). A detailed description of SD modeling approach is available in Sterman (2000), Forrester (1996) and Ford (1999).

SD has a long history as a modeling paradigm (Ahmad and Simonovic, 2000). It has found its application in numerous water resources management problems (Winz et al., 2009). Winz et al. (2009) have provided a brief review of its application in water resources. Gober et al. (2010) have used SD to model the interaction between changing climatic condition and increasing population and their effect on future water supply in Phoenix, AZ. Other urban water management models developed using system dynamics are; community based water resources planning (Tidwell et al., 2004), to facilitate the public understanding of water conservation options (Stave, 2003), to evaluate the implication of municipal water conservation policies (Ahmad and Prashar, 2010), to evaluate the impact of water conservation on the outdoor water use (Qaiser et al., 2011), and to evaluate the complex water management in a river basin scale (Madani and Marino, 2008). Similarly, some of the other applications of SD in water resources management include reservoir operation (Ahmad and Simonovic, 2000), flood management (Li and Simonovic, 2002; Ahmad and Simonovic, 2004 and 2006), flood evacuation emergency planning (Simonovic and Ahmad, 2005), salinity load forecasting (Venkatesan et al., 2011a), water reuse (Venkatesan et al., 2011b), and evaluating water supply options in the Las Vegas Valley (Shrestha et al., 2011).

2.5. Data

The datasets used in the current study include GCM outputs, monthly potential evapo-transpiration, naturalized streamflow at different streamflow gauges in the UCRB, operating rules of Colorado River reservoir, and water allocation of the basin states.

2.5.1. Global climate model outputs

This study used bias-corrected climate model outputs for precipitation and temperature from 16 GCMs (Table 2.1) obtained from Coupled Model Inter-comparison Project phase 3 (CMIP3) of the World Climate Research Programme's (WCRP). Bias-correction is the process of removing the tendencies of a GCM to be too dry/wet/warm/cool when compared with the observed data for the past (CMIP3, 2007). Bias-correction of the datasets was originally done using quantile mapping technique. The original resolutions of the GCMs in Table 2.1 were obtained from Sharp (2010) and the references for the GCMs were obtained from CMIP3 (2007).

The CMIP3 datasets provide monthly precipitation and mean monthly surface air temperature from 1950 to 2099 for 16 GCMs. A total of 112 different projections of datasets are available at CMIP3 website. Spatial resolution of the data is 1/8° latitude – longitude (~12 km by 12 km); additional datasets are also available at 2° latitude – longitude (~200 km by 200 km). The datasets cover the contiguous United States, some portion of Southern Canada, and Northern Mexico, spanning 25.125° N to 52.875° N and -124.625° E to -67.000° E.

The current study used the GCM outputs at a spatial resolution of 2° latitude – longitude. For the duration of 1970 to 1999, the observed datasets for precipitation and temperature were used; for the duration of 2000 to 2035, bias-corrected GCM outputs were used. The bias-corrected GCM outputs differ for each GCM and emission scenario. For each GCM, three emission scenarios were used that include A1b, A2 and B1. The emission scenarios were differentiated on the basis of CO_2 emission concentration and technological advances by year 2100. A1b was categorized as the middle emission path, with a balance of the technological changes across all the fossil and non-fossil energy sources and CO_2 concentration reaching 720 ppm in 2100 (Seager et al., 2007) , whereas A2 was categorized as the higher emission path and leads to higher population growth with the global CO_2 concentration reaching 850 ppm by 2100. B1 was categorized as the lower emission path with global CO_2 concentration reaching 550 ppm by 2100 (Christensen and Lettenmaier, 2007). In B1 scenario, more economy is used towards service and information, with the use of sustainable technology (CMIP3, 2007). Driving forces for these emission scenarios are population, economic and social development, energy and technology, agriculture and land use emissions, other gaseous emission like Nitrous Oxide, Methane, and Sulfur Dioxide as shown in Figure 2.2.

Table 2.1. Description of the Global Climate Models, institution developing them, their resolution and original references (Source: Sharp, 2010; CMIP3, 2007)

	CMIP 3 models	Modeling group, Country	Atm Res (Degree)	Ocean Res (Degree)	References
1	BCC-CMI, 2005	Bjerknes Centre for Climate Research, China	1.9x1.9	1.9x1.9	Furevik et al., 2003
2	CGCM3.1(T47), 2005	Canadian Centre for Climate Modeling & Analysis, Canada	2.8x2.8	1.9x1.9	Flato and Boer, 2001
3	CNRM-CM3, 2004	Meteo-France / Centre National de Recherches Meteorologiques, France	1.9x1.9	0.5-2.0x2.0	Salas-Melia et al., 2005
4	CSIRO-Mk3.0	CSIRO Atmospheric Research, Australia	1.9x1.9	0.8x1.9	Gordon et al., 2002
5	GFDL-CM2.0, 2005	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	2.0x2.5	0.3-1.0x1.0	Delworth et al., 2006
6	GFDL-CM2.1, 2005	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	2.0x2.5	0.3-1.0x1.0	Delworth et al., 2006
7	GISS-ER, 2004	NASA/Goddard Institute for Space Studies (GISS, USA)	4.0x5.0	4.0x5.0	Russell et al., 2000
8	INM-CM3.0, 2004	Institute for Numerical Mathematics, Russia	4.0x5.0	2.0x2.5	Diansky and Volodin, 2002
9	IPSL-CM4, 2005	Institut Pierre Simon Laplace, France	2.5x3.75	2.0x2.0	IPSL, 2005
10	ECHO-G, 1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, Germany/ Korea	3.9x3.9	0.5-2.8x2.8	Legutke and Voss, 1999
11	ECHAM5/MPI-OM, 2005	Max Planck Institute for Meteorology, Germany	1.9x1.9	1.5x1.5	Jungclaus et al., 2006
12	MRI-CGCM2.3.2, 2003	Meteorological Research Institute, Japan	2.8x2.8	0.5-2.0x2.5	Yukimoto et al., 2001
13	CCSM3	National Center for Atmospheric Research, USA	1.4x1.4	0.3-1.0x1.0	Collins et al., 2006
14	MIROC3.2(medres), 2004	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	2.8x2.8	0.5-1.4x1.4	K-1 model developers, 2004
15	PCM, 1998	National Center for Atmospheric Research, USA	2.8x2.8	0.5-0.7x1.1	Washington et al., 2000
16	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research / Met Office, UK	2.5x3.75	1.25x1.25	Gordon et al., 2000

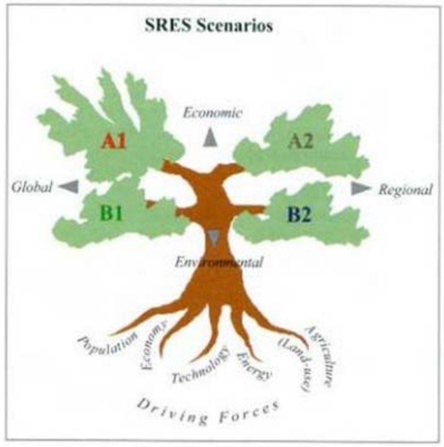

Figure 2.2. Description of the emission scenarios and driving forces (Source: CMIP3, 2007)

2.5.2. Potential evapotranspiration data

Monthly potential evapotranspiration (PET) data for UCRB were obtained from Vogel & Sankarasubramanian (2005) for duration of 1970 to 1990. A linear relationship was established between the historical (1970-1990) monthly PET and monthly temperature; the same relationship was used to compute PET beyond 1990.

2.5.3. Naturalized streamflow

Naturalized streamflow, with anthropogenic impacts removed, were obtained from USDOI (2010) for six different streamflow gages in the UCRB for the period of 1970 to 1999. This data was originally calculated by the Bureau of Reclamation by deducting the reservoir regulations, and consumptive uses (agriculture, municipal, industrial, and evaporation) from the historic observed flow (Prairie and Callejo, 2005). The streamflow gages included the Green River near Greendale, Utah; the Green River at Green River, Utah; the Colorado River near Cameo, Colorado; the San

Yuan near Bluff, Utah; the Colorado River near Cisco, Utah; and the Colorado River at Lees Ferry, Arizona.

2.5.4. Operating rules for Colorado River reservoirs

The operating rules for Colorado River reservoir operation included (i) Lake Mead elevation for the period of 1970 to 1999, obtained from USDOI (2011a) (ii) Lake Powell elevation for the period of 1970 to 1999, obtained from USDOI (2011d), (iii) Lake Powell evaporation for the period of 2000 to 2010, obtained from USDOI (2011d), (iv) The monthly evaporation coefficient for Lake Mead obtained from USDOI (2007, Appendix A) and (v) Fraction of monthly release obtained from USDOI (2007, Appendix A), where the fraction converts the annual Lake Powell release to monthly release volume.

2.5.5. Water allocation of the basin states

The historic data for water withdrawal, ranging from 1971-2010 for the Upper Basin, was obtained from the Consumptive Uses and Losses Report for the Upper Colorado River Basin (USDOI, 2011b) whereas the water withdrawal data for the Lower Basin was obtained from the Decree Accounting Reports for the Lower Colorado River Basin (USDOI 2011c). The future water allocations for both the Upper and Lower Basins ranging from 2011-2035 were obtained from the Annual Depletion Schedules (USBR, 2007, Appendix C and D). The Lower Basin states have been using their complete allocation of 9.2 BCM/yr, while the Upper Basin states currently use about 5.8 BCM/yr, (out of the total allocation of 9.2 BCM/yr), with the annual withdrawal projected to be approximately 6.2 BCM in 2035 (USDOI, 2007, Appendix C).

Table 2.2 provides a description of the data types, their sources and duration of the datasets described above.

Table 2.2 Types of data, sources and length of time series of data

	Data type	Source	Duration
1	Global climate model outputs (precipitation and temperature)	CMIP3 (2007)	1970-2035
2	Potential Evapotranspiration	Vogel, R. M. and A. Sankarasubramanian (2005)	1970-1990
3	Naturalized streamflow	USDOI (2010)	1970-1999
4	Lake Mead Elevation	USDOI (2011a)	1970-1999
5	Lake Powell Elevation	USDOI (2011d)	1970-1999
6	Lake Powell Evaporation	USDOI (2011d)	2000-2010
7	Lake Mead Evaporation Coefficient	USDOI (2007, Appendix A)	2006
8	Fraction of monthly release	USDOI (2007, Appendix A)	2006
9	Water allocation of seven basin states	USDOI (2007, Appendix C & D)	1970-2035

2.6. Method

2.6.1. Model structure

The model structure consists of three different sectors that include hydrologic model sector, reservoir operation sector, and water allocation sector:

2.6.1.1. Hydrologic model sector

The hydrologic model presented by Xu et al. (1996) was used as a basis to develop this sector using SD modeling tool. This sector uses monthly precipitation, temperature, and potential evapo-transpiration to generate streamflow at the outlet of each sub-basin. Although the UCRB has eight sub-basins (USGS, 2011), for the purpose of this study, it was divided into six sub-basins, namely, (i) the Great Divide-Upper Green, (ii) the White Yampa and Lower Green, (iii) the Colorado Headwaters,

(iv) the San Yuan, (v) the Upper Colorado Dirty Devils, and (vi) the Gunnison and Upper Colorado Dolores. The sub-basins were divided based on the availability of the naturalized streamflow gauge stations at or near the outlet.

The concept of the hydrologic model is shown in Figure 2.3, based on Xu et al. (1996). Temperature threshold governs the amount of precipitation falling as snow or rain. A fraction of the snow pack melts every month, lowering the amount of snow pack. A certain fraction of total amount of available rainfall is lost due to evaporation and the remaining fraction contributes to the soil storage. A fraction of soil storage gets lost as evapotranspiration which is calculated by multiplying the potential evapo-transpiration by a fraction of evapo-transpiration. The remaining fraction of soil storage is converted into base flow and fast flow. Both base flow and fast flow contribute to streamflow at the outlet of the sub-basin.

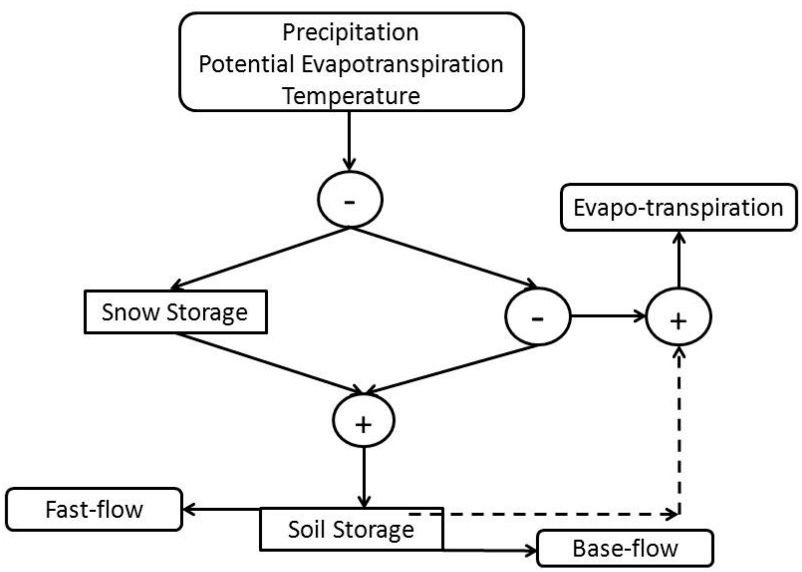

Figure 2.3. Conceptual hydrologic model (based on Xu et al., 1996)

Different components of the hydrologic model include snow accumulation and melting, actual evapotranspiration, base flow, and fast flow. Equations (1 to 11) for these components are derived from Xu et al., (1996). These are described in detail below:

1. Snow Accumulation and Melting:

Following equations represent the snow accumulation and melting component of the model:

$$s_t = Max\left(p_t\left\{1 - \exp\left[-\frac{c_t - a_1}{a_1 - a_2}\right]^2\right\}, 0\right) \tag{1}$$

Where,

s_t = snow portion of precipitation

p_t = precipitation

a_1 and a_2 = parameters to be determined for rainfall and snowfall with $a_1 > a_2$

c_t = temperature

The snow pack balance is represented as

$$sp_t = sp_{t-1} + s_t - m_t \tag{2}$$

where,

sp_{t-1}= the snowpack at the beginning of the month t and m_t is the snow melt during month t represented as following

$$m_t = Max(sp_{\ t-1}\left\{1 - exp\left[\frac{c_t - a_2}{a_1 - a_2}\right]^2\right\}, 0) \tag{3}$$

Finally, rainfall is computed as

$$r_t = p_t - s_t \tag{4}$$

2. Actual evapo-transpiration

Actual evapo-transpiration is calculated using the following equation

$$e_t = Min[\, ep_t \left(1 - a_3^{\frac{w_t}{ep_t}}\right), w_t] \quad (5)$$

Where,

a_3 = unknown parameter to be determined for evaporation, with $0 \leq a_3 < 1$

$$ep_t = PET \times [1 + a_4(c_t - c_m)] \quad (6)$$

where,

a_4 = model parameter for ET

w_t= available water = $r_t + \, max(sm_{t-1}, 0)$ (7)

where,

sm_{t-1} = available storage

3. Base flow

Base flow depends on the moisture storage of the catchment, and can be represented as the following

$$b_t = a_5 \left(Max(sm_{t-1}, 0)\right)^{b1} \quad (8)$$

where,

a_5 and b_1= parameters to be determined for base flow

4. Fast flow

Fast flow depends upon the rainfall, snowmelt, actual evapo-transpiration and the physical characteristics of the basin which are represented by the unknown parameters for the fast flow that are to be determined. Fast flow is determined using the following equation

$$f_t = a_6(Max(sm_{t-1}, 0)^{b_2}(m_t + n_t) \quad (9)$$

where,

a_6 and b_2 = unknown parameters to be determined for fast flow

n_t = active rainfall, determined as follows

$$n_t = r_t - ep_t[1 - exp(-r_t/ep_t)] \quad (10)$$

The streamflow at the outlet of each sub basin is the summation of base flow and fast flow, which is multiplied by the area of the sub basin to compute the actual volume of flow. Since some of the gauges are not located exactly at the outlet of the sub-basins, a certain percentage of area was used.

2.6.1.2. Reservoir operation sector

This sector models the regulation of water in the reservoirs of the Colorado River basin, and their scheduled deliveries to the basin states. Although the detail operation of Lake Powell was not considered in the study, major regulations governing the release of water from UCRB for the consumptive uses of Lower Basin were considered.

The runoff generated at the outlet of each sub-basin in UCRB was assumed to be stored in Lake Powell. The unregulated inflow into Lake Powell was computed as

Unregulated Inflow into Powell = Natural Inflow into Powell – Estimated Upper Basin Depletions (11)

Since no naturalized streamflow gauge station is available at the inlet of Lake Powell, natural inflow into Lake Powell was assumed to be same as the naturalized streamflow at Lees Ferry. Estimated Upper basin Depletions are the consumptive uses of the Upper Basin states.

One of the main regulations governing the release of water from Lake Powell is the mandatory release of 10.2 BCM/yr for the consumptive uses of Lower basin states and Mexico (Christensen et al., 2004). This annual release was converted into monthly release by multiplying the annual release by a fraction of monthly release (USDOI, 1985). The second regulation governing the release of water from Lake Powell is the equalization of the contents of Lake Powell and Lake Mead. An additional release from Lake Powell, above minimum regulatory release but not greater than 11.1 BCM/yr and not less than 10.2 BCM, is made to equalize the contents of both the lakes, as specified in the *Criteria for the Coordinated Long range Operations of Colorado River Reservoirs*. However, the equalization criteria were also simplified in the study. The percentage of volume in Lake Powell and Lake Mead are equalized at the end of each month in the current study, whenever water volume in Lake Powell is higher than the water volume in Lake Mead. Releases for the consumptive uses of the lower basin states and Mexico are made until water levels in Lake Powell reaches 1064 m (USDOI, 2007, Appendix B). Although releases up to 1027 m water levels in Lake Powell are possible, but only the normal operating range from 1128 m to 1064 m were considered in this study. Like Colorado River Simulation System, the study also doesnot impose shortages to the Upper Basin states.

The scheduled deliveries to the Lower Basin states are made until Lake Mead is drawn down to 327 m, then curtailments to the Lower Basin state's scheduled deliveries start (USDOI, 2007a). The curtailment criteria are based upon the "*Record of Decision (ROD, 2007)- Colorado River Interim guidelines for Lower Basin shortages and the coordinated operations for Lake Powell and Lake Mead*" USDOI(2007b). Curtailments in the scheduled deliveries are categorized into three different levels in this study. Level 3 curtailment is imposed when Lake Mead water elevation is between 327.7 and 320 m, resulting in the curtailment of approximately 395 million cubic meters per year (MCM/yr) (320,000 AFY) of Arizona's annual share, in addition, 16 MCM/yr (13,000 AFY) curtailment is made to Nevada's annual share. Level 2 curtailment is imposed when Lake Mead elevation is between 320 m and 313 m, resulting in the curtailment of 493 MCM/yr (400,000 AFY) and 21 MCM/yr (17,000 AFY) out of Arizona's and Nevada's share, respectively. Level 1 curtailment is imposed when Lake Mead elevation is below 313 m, resulting in curtailment of 592 MCM/yr (480,000 AFY) and 25 MCM/yr (20,000 AFY) from Arizona's and Nevada's annual share respectively. Since, USDOI (2007b) does not provide the information on the operation of Lake Mead when it is drawn down below 305 m, thus, the current study considered three different options for the operation of Lake Mead; (i) supply to the lower basin states are met even if Lake Mead is drawn down to 305 m; curtailments to Nevada and Arizona after 305 m water levels in Lake Mead are similar to their corresponding Level 1 curtailments, and California and Mexico experience the curtailment similar to Level 1 curtailment of Arizona; (ii) second option (considered as reservoir operation Option 1) assumes that as Lake Mead levels approach 312 m, a gradual increase in the curtailments to each of the lower basin's share is imposed above their Level 1 curtailment; and (iii) The third option, considered as reservoir operation Option 2, assumes that whenever Lake Mead is drawn below 312 m, a single percentage of curtailment is imposed on all the states. This curtailment is similar to their corresponding Level 1 curtailments for Arizona and Nevada, and the California and Mexico curtailments are similar to Level 1 curtailment of Arizona. Both options consider completely cutting off the scheduled deliveries, if necessary, so as to maintain Lake Mead above 305 m for the entire simulation period. Thus, more curtailments are imposed to each state's share in Option 1 than in Option 2 for same water levels in Lake Mead. Both Option 1 and Option 2 consider protecting Lake Mead above an elevation of 305 m.

Historical average monthly evaporation numbers were used for Lake Powell for the future simulation period. Evaporation from Lake Mead was calculated by multiplying the reservoir surface area by the monthly evaporation coefficients obtained from USDOI (1985), using following formula:

$$\text{Evaporation (t)} = \frac{1}{2} * \text{Evaporation Coefficient} * (\text{Surface area (t)} + \text{Surface area (t-1)}) \quad (12)$$

2.6.1.3. Water allocation sector

This sector computes the total allocation of each of the basin states and Mexico based on their historical withdrawal and future depletion, as mentioned in the data section.

2.6.2. Modeling approach

The model was developed using the system dynamics software STELLA (ISEE, 2011), an object oriented simulation environment. The modeling approach is described in two phases that include (i) calibration and validation, and (ii) future simulations.

2.6.2.1. Calibration and validation

The hydrologic model was calibrated for streamflow at Lees Ferry for duration of 1970 to 1999. The simulated streamflow was compared with the observed streamflow at Lees Ferry. Visual inspection of the peak flows and base flows between the observed and simulated streamflows was done for each sub-basin at their outlet; statistical performance measures were computed for streamflow at Lees Ferry for the process of calibration.

Manual calibration was done in the study and eight different hydrologic parameters were adjusted in order to get a close match between the simulated and observed streamflow. The hydrologic parameters included temperature threshold for rainfall and snowfall, parameters for evaporation and evapo-transpiration, and parameters for base flow and fast flow.

The adjusted average values of these parameters are shown in Table 2.3. The parameters for temperature threshold for rainfall and snowfall were adjusted according to the rain and snow temperature threshold mentioned by McCabe and Wolock, (1999). However, the snow temperature threshold of 0° C was used in McCabe and Wolock (1999). In this study, it was modified to -1° C. The parameter for evaporation and evapo-transpiration should range from 0 to 1 (Xu et al., 1996) and was fixed at 0.5 in the current study (Table 2.3). Xu et al. (1996) have provided the values of b_1 and b_2 to be one of the three values 0.5, 1 or 2, which fitted the study region considered in Xu et al. (1996). After testing all three values for both base flow and fast flow, one at a time, making all other values constant, the best match between the observed and simulated streamflow at the outlet of each sub-basin was obtained at a value of 0.5 for all of the sub-basins.

Table 2.3. Values of hydrologic model parameters adjusted while calibrating the hydrologic model

Parameters	Description	Average adjusted value
a_1	Temperature threshold for rainfall	5° C
a_2	Temperature threshold for snowfall	-1° C
a_3	Parameter for evaporation	0.5
a_4	Parameter for evapo-transpiration	0.5
a_5, b_1	Parameters for base flow	0.25, 0.5
a_6, b_2	Parameters for fast flow	0.06, 0.5

The calibrated hydrologic model was validated for the streamflow at Lees Ferry from 1991 to 1999 with the same set of parameters used in the calibration process. The model was also validated for Lake Mead levels from 1970 to 1999.

The period from 2000 to 2011 was not validated because the observed temperature and precipitation data are not available beyond 1999. Therefore, bias-corrected GCM outputs were used beyond 1999 that differ for each GCM and emission scenario.

2.6.2.2. Future Simulations

The calibrated model was used to run the future simulations for a period of 2012 to 2035. Future simulations were performed to compute streamflow at Lees Ferry, Lake Mead levels, the probability of supply curtailments to the Lower Basin states, and risk evaluation of the water supply to the Lower Basin. In addition, future precipitation and temperature predicted by the individual GCMs were also analyzed.

The streamflow at Lees Ferry computed for individual GCMs was compared to the actual historical naturalized streamflow from 1970 to 1999. Similarly, average monthly precipitation and temperature in the CRB for the duration of 2012 to 2035 as predicted by the individual GCMs, were compared with the GCM predicted precipitation and temperature for the duration of 1970 to 1999. Similar to Christensen and Lettenmaier (2007), this study compared the future streamflow with the historical average; however, the historical average used in this study is the observed naturalized streamflow.

Besides using GCM outputs for estimating future streamflow in the CRB, the study also used other possible ranges of flow. The range of flow is based on the other studies done in the CRB. Gober and Kirkwood (2010) used the range of Colorado River flow from 61% to 118% of the historical average flow for future. We also used the Colorado River flow varying from nearly 60% to 120% of the historical average flow (1970-1999).

In addition, different percentages of reduction in the water supply to the Lower Basin were tested varying from 5% to 30%. With such a reduction in the supply, the probabilities of lake level falling down below 327 m, 320 m and 312 m were evaluated.

Based on the water levels in Lake Mead, risk analysis for water supply to the Lower Basin was performed. Different risk analysis indices were evaluated that include reliability, average duration of failure, number of failure and average deficit per failure. Three risk analysis indices, which included, reliability, resilience, and vulnerability were originally defined by Hashimoto et al. (1982) and were modified by Zongxue et al. (1996). However, for this study, resilience and vulnerability were modified to calculate duration of failure and average deficit per failure, respectively.

Reliability measures probability of the system to meet the desired water demand and is calculated using the following formula

$$\text{Reliability} = \frac{1}{NS}\sum_{i=1}^{NS} I_i \qquad (13)$$

NS = total duration of water supply

I_i = state variable of the water supply system. It is equal to 1 if there is no deficit, and is equal to 0 if there is deficit

Average duration of failure is the average period of water deficit, calculated using the following formula

$$\text{Avg duration of faliure} = \left\{\frac{\sum_{1}^{i=1} \text{FD}}{\text{NF}}\right\} \quad (14)$$

NF = number of failures

FD = duration of failure

Average deficit per failure was computed by dividing the average deficit during the whole supply period by the average water demand during the same period, using the following formula

$$\text{Avg deficit per faliure} = \frac{\sum_{i=1}^{NF} VE_i}{\sum_{i=1}^{NF} VD_i} \quad (15)$$

VE_i= water deficit

VD_i= water demand during the deficit period

2.7. Hydrologic model evaluation

In order to evaluate the performance of the hydrologic model, four different statistical measures were applied for the calibration and the validation periods, and included R, RSR, PBIAS, and NSE.

R measures the strength of linear relationship between simulated and observed values. The value of correlation coefficient ranges from 1(perfect positive correlation) through 0 (no correlation) to -1(perfect negative correlation), which is calculated as follows

$$R = \frac{S_{so}}{\sqrt{S_s S_o}}\text{, where} \tag{16}$$

$$S_{so} = \sum_i \frac{(S_i - S_{avg})(O_i - O_{avg})}{n-1} \tag{17}$$

$$S_s = \sum_i \frac{(S_i - S_{avg})^2}{n-1} \tag{18}$$

$$S_o = \sum_i \frac{(O_i - O_{avg})^2}{n-1} \tag{19}$$

RMSE is the measure of the model precision which measures the differences between the simulated and the observed values. RSR is defined as the ratio of RMSE and standard deviation of the observed value. The value of RSR between 0.7 and 0 indicate satisfactory model performance (Moraisi et al., 2007).

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - O_{avg})^2}} \tag{20}$$

PBIAS measures whether the model output is smaller or larger than the corresponding observed values (Gupta et al., 1999). The optimal value of PBIAS is 0, with the low magnitude value indicating that the simulated value is not deviated largely from the corresponding observed values. Positive value of PBIAS indicates that the model is under-predicted while negative values indicate that the model is over-predicted (Gupta et al., 1999). PBIAS can clearly indicate the poor performance of the model (Gupta et al., 1999).

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - S_i)\times 100}{\sum_{i=1}^{n} O_i} \tag{21}$$

NSE is defined as one minus the sum of absolute square of the differences between observed and simulated values divided by the sum of absolute square of the difference between the observed values and the mean of the observed values (Nash and Sutcliffe, 1970). The value of NSE ranges from $-\infty$ to 1. A value of 1 represents the perfect match between the observed and the simulated values. A value of NSE less than zero indicates that the mean of the observed time series is able to predict better than the simulated values (Krause et al., 2005).

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - S)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \quad (22)$$

where, O and S are the observed and the simulated values.

The values of NSE between 0.5 and 1 and the values of PBIAS between 10% and 25 % indicate acceptable model performance (Moraisi et al., 2007). A value of R greater than 0.5 is acceptable (Santhi et al., 2001; Van Liew et al., 2003). Similarly, a value of RSR greater than 0.7 is considered acceptable (Moraisi et al., 2007).

In addition to the statistical measures, hydrographs, bisector plots, and boxplots were used to evaluate the model's performance.

2.8. Results

2.8.1. Calibration and validation

Figure 2.4 shows the monthly graphical measures for the calibration and the validation period. Figure 2.4 a and 2.4d show the monthly hydrographs of streamflow at Lees Ferry for both the calibration and the validation periods. The solid line represents the observed streamflow and the dotted line represents the simulated streamflow at Lees Ferry. It helps to find how well the simulated and the observed flows match. Except for some years, the simulated and observed peak flows seem to match with each other.

Figure 2.4 b and 2.4e represent bisector plots that compare the simulated values with the observed values of streamflow at Lees Ferry for both the calibration and the validation periods for monthly duration. The plots reveal whether the model is over-predicting or under-predicting the streamflow. Data points close to the 45° bisector line indicate a perfect fit between the observed and the simulated values. For the monthly bisector plots, the low flow values are observed to align themselves along the 45° bisector line; for high flows, some of the points are observed to scatter away from the bisector line, indicating that the model performs well for the low flows. Capturing accurate streamflow values for the low flows is extremely important in the Colorado River as several studies have predicted the reduction in its future streamflow.

Figure 2.4 c and 2.4f show the boxplots for the simulated and the observed streamflows at Lees Ferry for both the calibration and the validation periods. There were developed by using the simulated and the observed streamflow for the entire duration. It helps to compare the variability captured by the simulated streamflow and the observed streamflow. It was observed that for both the calibration and the validation period, the simulated data was able to capture the similar variability in the streamflow as the observed data. Overall, the hydrologic model performance could be considered satisfactory for the calibration and the validation periods.

Table 2.4 shows the monthly statistical performance measures for the calibration and the validation periods. The performance ratings were based on Moriasi et al. (2007). The values of R were computed to be 0.76 and 0.75 for the calibration and the validation periods, respectively; both were considered satisfactory. The values of RSR were computed to be 0.69 and 0.77 for the calibration and the validation periods. RSR is considered satisfactory for the calibration period as it is lower than 0.7; for the validation period, the value of RSR (0.77) is considered unsatisfactory, as it is higher than 0.70. Percentage biases for the calibration and the validation period were +9.65 % and -12.98 %. The positive value of percentage bias indicates that streamflow is underestimated in the calibration period; the negative value of PBIAS indicates that streamflow is overestimated in the validation period. Similarly, the value for the NSE was computed to be 0.53 and 0.40, respectively, for the calibration and the validation periods.

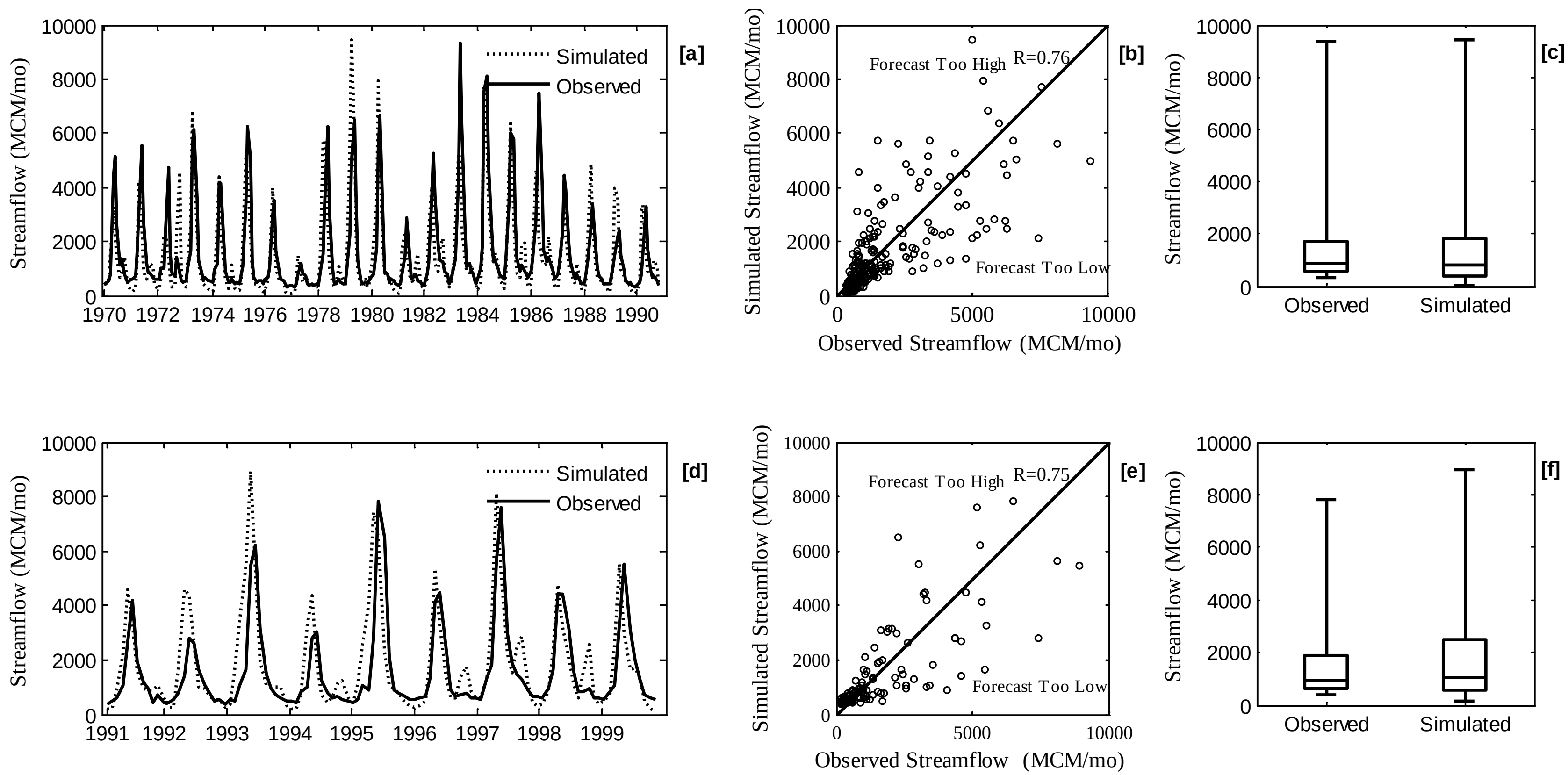

Figure 2.4. (a,d) Monthly hydrographs of streamflow at Lees Ferry for the calibration, and validation period, respectively. Dotted line represents the simulated streamflow and solid line represents the observed streamflow. (b,e) bisector plots of the observed and the simulated streamflow Lees Ferry for the calibration, and validation period, respectively. The solid line in the middle represents

45º bisector line at 1:1 slope and R represents the correlation coefficient between the observed and the simulated streamflow at Lees Ferry. (c,f) Boxplot of the observed and simulated streamflow at Lees Ferry for the calibration, and validation period, respectively. Each boxplot shows the variability in streamflow. The box represents 25th and 75th percentile values of streamflow. The solid horizontal line within box represents the median and whiskers at the lower end and the upper end represent 5th and 95th percentile values of streamflow.

Table 2.4. Values of the monthly statistical performance measures for the evaluation of the hydrologic model for both calibration and validation period (performance ratings adopted from Moriasi et al., 2007)

Performance Rating				Error type	Calibration	Evaluation	Validation	Evaluation
Very good	0≤ RSR ≤0.5	0.75< NSE ≤1	PBIAS < ± 10	R	0.76	acceptable	0.75	acceptable
Good	0.5<RSR ≤0.6	0.65<NSE ≤0.75	± 10 ≤ PBIAS < ± 15	RSR	0.69	satisfactory	0.77	unsatisfactory
Satisfactory	0.6<RSR ≤0.7	0.50<NSE ≤0.65	± 15 ≤ PBIAS < ± 25	PBIAS	9.65	very good	-12.98	good
Unsatisfactory	RSR > 0.7	NSE ≤0.50	PBIAS ≥ ± 25	NSE	0.53	satisfactory	0.40	unsatisfactory

PBIAS is in percentage

The validation of the reservoir operation, shown in Figure 2.5, was also performed by comparing the actual and the simulated Lake Mead levels for the period of 1970 to 1999. From Figure 2.5a, it is observed that the simulated lake levels were able to follow a pattern similar to the actual lake levels. The average error and the mean absolute error of about 0.28 m and 3.6 m, respectively, were observed for the actual and the simulated lake levels. Although the mean absolute error of 3.6 m seems large but considering the complex reservoir operation of the CRB, it can be regarded as satisfactory for the purpose of the study.

Similarly, Figure 2.5b and 2.5c represent the bisector plots and boxplots, respectively, for the simulated and the observed Lake Mead levels from 1970 to 1999. From Figure 2.5b, it was observed that most of the data points lie close to the 45 º bisector line, indicating a good match between the simulated and the observed streamflow. Boxplots in Figure 2.5c indicate the variability in the lake level shown by the observed and the simulated values. The boxplot for the observed lake level shows slightly more variability than that captured by the simulated values.

2.8.2. Future Simulations

The results for the future simulations are presented in three different sub-sections that include 1. Changes in precipitation, temperature and streamflow, 2. Lake Mead levels and supply curtailments to the Lower basin, and 3. Water supply risk analysis for the Lower basin.

2.8.2.1. Changes in precipitation, temperature, and streamflow

Table 2.5 shows the summary of the changes in precipitation, temperature and streamflow for future simulations for individual GCM. Precipitation is reported as the percentage change from the historical average and temperature is reported as the change (in °C) from the historical average. Similarly, streamflow at Lees Ferry is reported as the percentage change from the historical average streamflow. A minus sign indicates a reduction compared to the historical average, whereas, the numbers without a minus sign indicate an increase compared to the historical average.

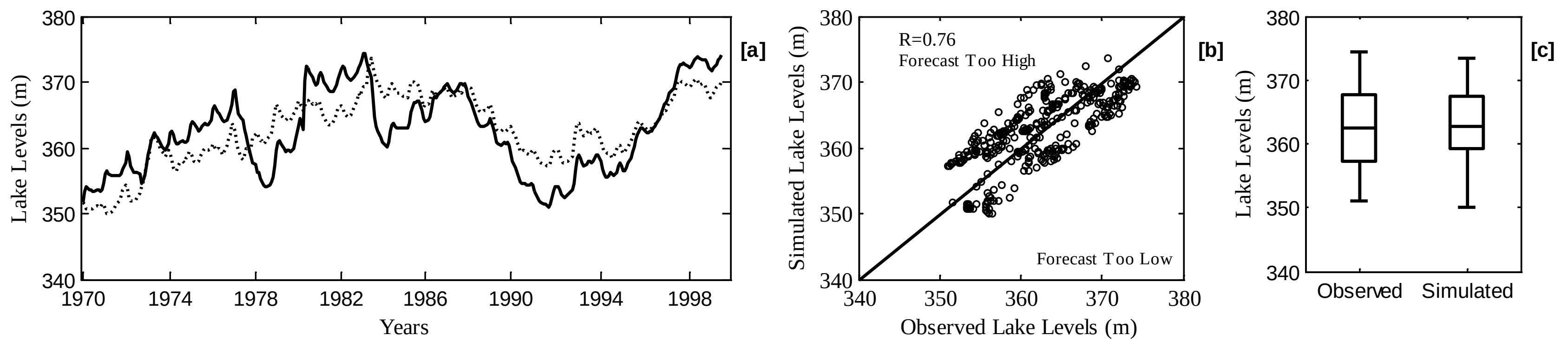

Figure 2.5. (a) Comparison between actual and simulated monthly Lake Mead levels for the duration of 1970 to 1999. The solid and the dotted lines represent the observed and the simulated Lake Mead levels. (b) Bisector plot for monthly Lake Mead levels for the duration of 1970 to 1999. The solid line in the middle represents 45º bisector line at 1:1 slope. R represents the correlation coefficient between the observed and the simulated Lake Mead levels. (c) Boxplot of simulated and observed Lake Mead levels for the duration of 1970 to 1999. Each boxplot shows the variability in Lake Mead level. The box represents 25th and 75th percentile values of lake level. The solid horizontal line within box represents the median of lake level. Whiskers at the lower end and the upper end represent 5th and 95th percentile values of the lake levels.

For A1b emission scenario, the highest decrease in precipitation, about 12.4%, was predicted by GFDL-CM2.1; the corresponding highest decrease in streamflow at Lees Ferry was about 21.0% (Table 2.5). Similarly, the highest increase in precipitation and streamflow for PCM were approximately 10.1% and 14.4%. For A2 emission scenario, highest decrease in precipitation and streamflow of approximately 8.8% and 24.0% were observed for CCSM3. Similarly, the highest increase in precipitation and the corresponding increase in streamflow of about 12.7% and 21.6% were observed for PCM. For B1 emission scenario, highest decrease in precipitation, about 7.4%, was predicted by MIROC3.2, and the corresponding decrease in streamflow by about 21.9% was estimated. For same emission scenario, the highest increase in precipitation and streamflow of about 8.1% and 15.4% were observed for PCM.

The increasing trend in temperature for the CRB is evident from Figure 2.6a, which shows the annual average temperature for A1b scenario under all GCMs. The lighter grey lines indicate the annual average temperatures for all the 16 GCMs. The darker line in the graph shows the median of the ensemble of all the GCMs. As evident from Figure 2.6a, the majority of the GCMs as well as the median of the ensemble of the GCMs show an increasing trend in temperature for the CRB.

Figure 2.6b depicts annual streamflow at Lees Ferry till 2035 for A1b scenario for all 16 GCMs. The lighter grey lines represent the annual streamflow for all the GCMs. 95th and 5th percentile values are shown by the black dotted and dotted-dashed lines, respectively. 5th and 95th percentile values respectively indicate that 5% and 95% of the flow occur below these values. The dotted horizontal line represents the long term average for the historical period. The median of the ensemble of GCMs is observed below the historical long term average for majority of future simulation periods.

Table 2.5. Comparison of precipitation, temperature and streamflow for 16 GCM and 3 emission scenarios between the historic (1970-1999) and the future (2012-2035) period. Precipitation and streamflow are reported as the percentages of the long term historical average, and temperature is reported as the change (in ºC) from the historical average

	Base year (1970-1999)															
Prcp mm/yr	405.2															
Temp (°C)	6.3															
	BCC-CMI	CGCM3.1	CNRM_CM3	CSIRO-Mk3.0	GFDL-CM2.0	GFDL-CM2.1	GISS-ER	INM-CM3.0	IPSL-CM4	MIROC3.2	ECHo-G	ECHAM5	MRI-CGCM2.3.2	CCSM3	PCM	UKMO-hadCM3
	A1b (2012-2035)															
Prcp (%)	-0.8	6.9	-4.6	-0.7	-4.3	-12.3	-3.9	7.5	7.3	0.7	-2.9	-3.0	2.4	-7.3	10.1	-9.3
Δ Temp (°C)	0.4	0.7	0.5	1.1	1.6	1.1	0.9	0.8	0.9	0.4	0.4	-0.1	1.0	1.0	0.8	1.2
Streamflow (%)	-4.9	5.5	-13.5	-0.9	-6.0	-21.0	-7.4	2.7	3.9	-9.5	-15.7	-8.9	9.3	-17.9	14.4	-21.0
	A2 (2012-2035)															
Prcp (%)	-5.3	2.2	5.1	1.3	-1.8	-0.8	4.4	9.1	0.2	0.5	-1.7	-7.9	1.9	-8.8	12.7	0.0
Δ Temp (°C)	0.7	1.6	0.8	0.4	1.0	1.0	0.7	1.4	1.2	1.4	-0.7	0.8	0.5	1.6	0.2	1.0
Streamflow (%)	-10.5	-3.1	4.7	1.6	-5.4	-4.9	4.9	8.7	-1.8	-9.5	2.9	-15.8	4.6	-24.0	21.6	-5.9
	B1 (2012-2035)															
Prcp (%)	-4.4	3.9	1.2	6.8	1.4	-8.9	-2.4	6.4	5.2	-7.4	4.9	-0.2	3.2	-1.9	8.1	7.2
Δ Temp (°C)	0.5	1.1	0.9	-0.1	0.8	0.9	1.0	1.5	1.1	1.5	0.9	0.5	0.4	1.3	0.3	1.1
Streamflow (%)	-10.5	-2.2	-1.9	12.7	0.3	-10.3	-8.5	-1.3	-0.6	-21.8	4.4	-1.8	5.8	-3.5	15.4	9.3

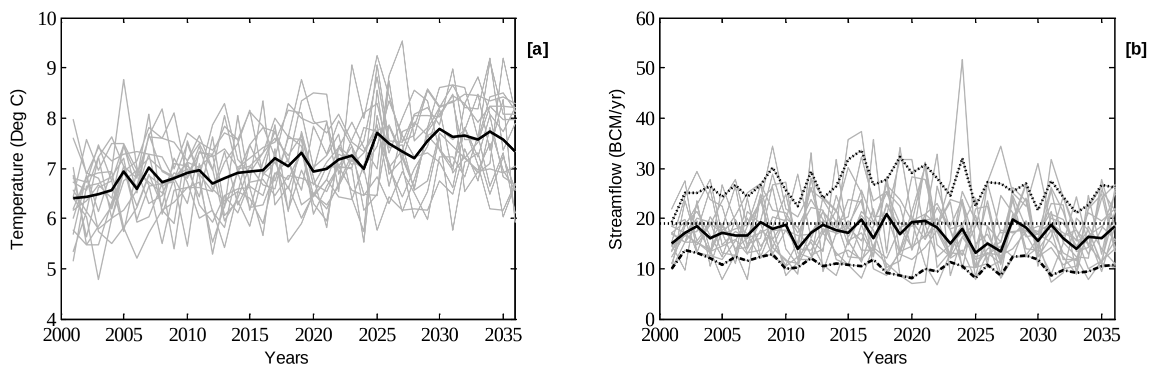

Figure 2.6. (a) Annual average temperature of CRB and (b) annual streamflow at Lees Ferry for A1b scenario for all 16 GCMs for the duration of 2000 to 2035. Lighter grey lines in Figure 6a indicate the annual average temperature predicted by individual GCMs

and dark black line in the middle indicates the median of the ensemble of GCMs. Lighter grey lines in Figure 6b indicate the annual streamflow estimated for individual GCM, the dotted and dotted-dashed line in 6b represents the streamflow value for 95th percentile and 5th percentile, respectively. The darker solid line in 6b represents the ensemble median streamflow value. Similarly, the dotted horizontal line in 6b represents the long term historical average of the observed streamflow.

Figure 2.7 show the boxplots for streamflow at Lees Ferry for all 16 GCMs and 3 emission scenarios. The boxplots help to find the variability in streamflow estimated for each GCM and the emission scenarios. Each boxplot was generated using the streamflow value for the entire future simulation period for each GCM. Under A1b scenario (Figure 2.7a), streamflow extremes at Lees Ferry range from approximately 8.3 BCM/yr to 60 BCM/ yr, with the median and average flow to be approximately 21 BCM/yr and 21.8 BCM/yr, respectively. The median flow under A1b scenario is about 2.6 BCM/yr in excess of the system demand in the CRB. System demand was calculated by adding the full allocation for the Lower Basin states and Mexico totaling 11.1 BCM/yr, the Upper Basin states' 2035 withdrawal of approximately 6.3 BCM/yr, and a reservoir evaporation of almost 1 BCM/yr (Christensen et al., 2004); this totals to about 18.4 BCM/yr.

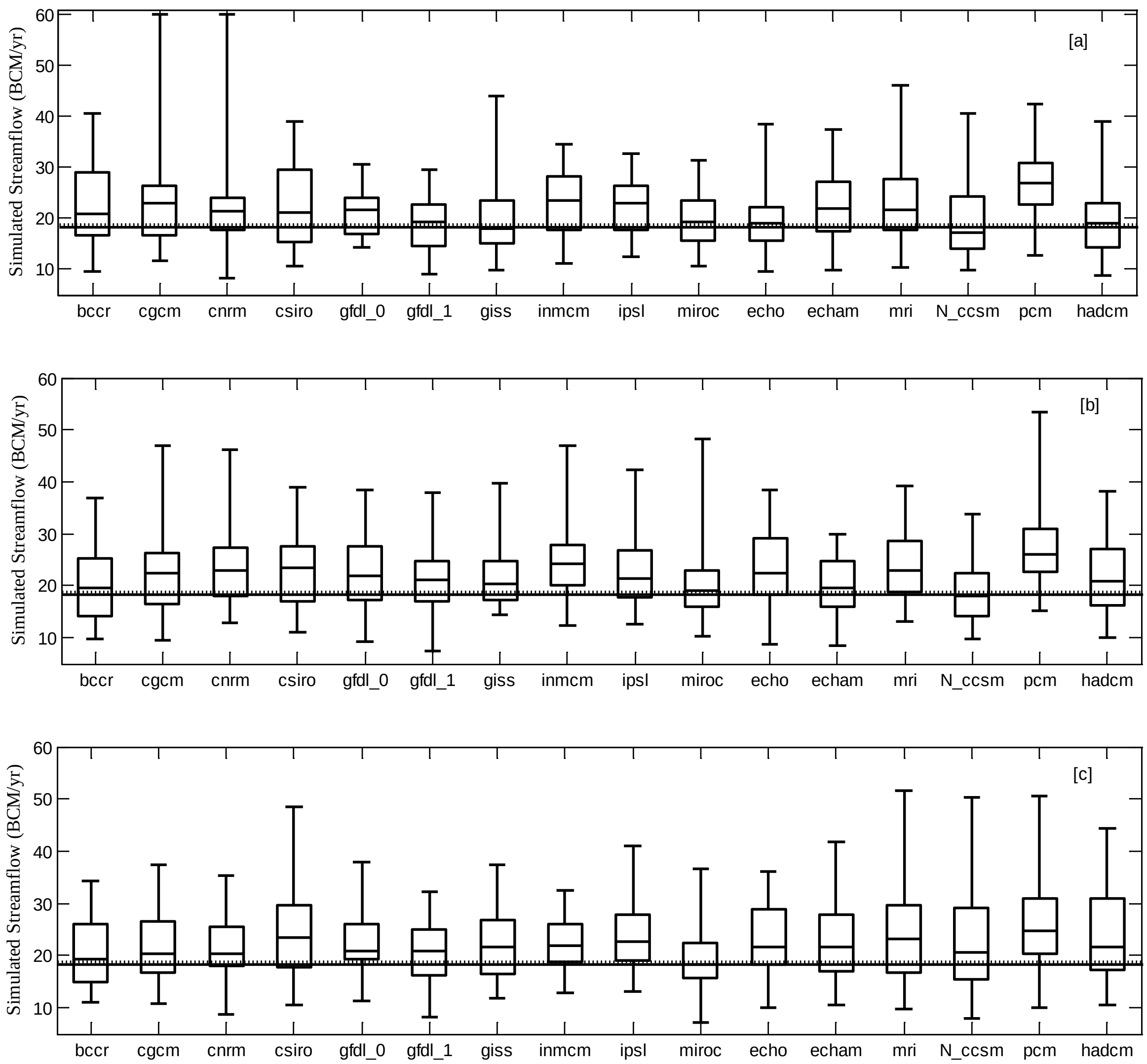

Figure 2.7. Box plots for individual GCMs for (a) A1b, (b) A2 and (c) B1 emission scenarios. Each boxplot shows the variability in streamflow simulated under each GCM. The box represents 25th and 75th percentile values of streamflow. The solid horizontal line within each box represents the median of streamflow for each GCM. Whiskers at the lower end and the upper end represent 5th and 95th percentile values of streamflow. Each boxplot represents the range of streamflow estimated for individual GCM for the duration of 2012 to 2035. The solid line represents the system demand of the CRB and the dotted line represents the mean of the observed historical flow

Figure 2.8 shows the boxplots for the ensemble of the GCMs for each of the years for all 3 emission scenarios. For each year, boxplot represents the ensemble streamflow of all the GCMs. The boxplot developed for the entire simulation period helps in determining the low and the high flow years as computed under the ensemble of the GCMs. The black dotted line indicates the average streamflow for the historical period. The streamflow in a particular year below the historical long term average can be considered the low flow (Smakhtin, 2000). Thus, the years with a median flow below the historical average flow can be referred to as low flow years while the years with medians above the historical average are the high flow years. The lower dashed and dotted line represents the system demand.

The ensemble average predicted Year 2012 to have streamflow higher than the historical average under A1b and A2 scenarios (Figure 2.8). Year 2026 was observed to be one of the lowest flow year among others compared to historical average as computed by the ensemble average for A1b and B1 scenarios while 2021 was observed to be one of the highest flow years for A2 and B1 scenarios. In Year 2035, the annual naturalized streamflow at Lees Ferry was observed to range from 15 to 25 BCM under A1b scenario, with the median flow of about 20 BCM as estimated by the ensemble of all the GCMs. This value is approximately 1.8 BCM higher than the current system demand of the Colorado River.

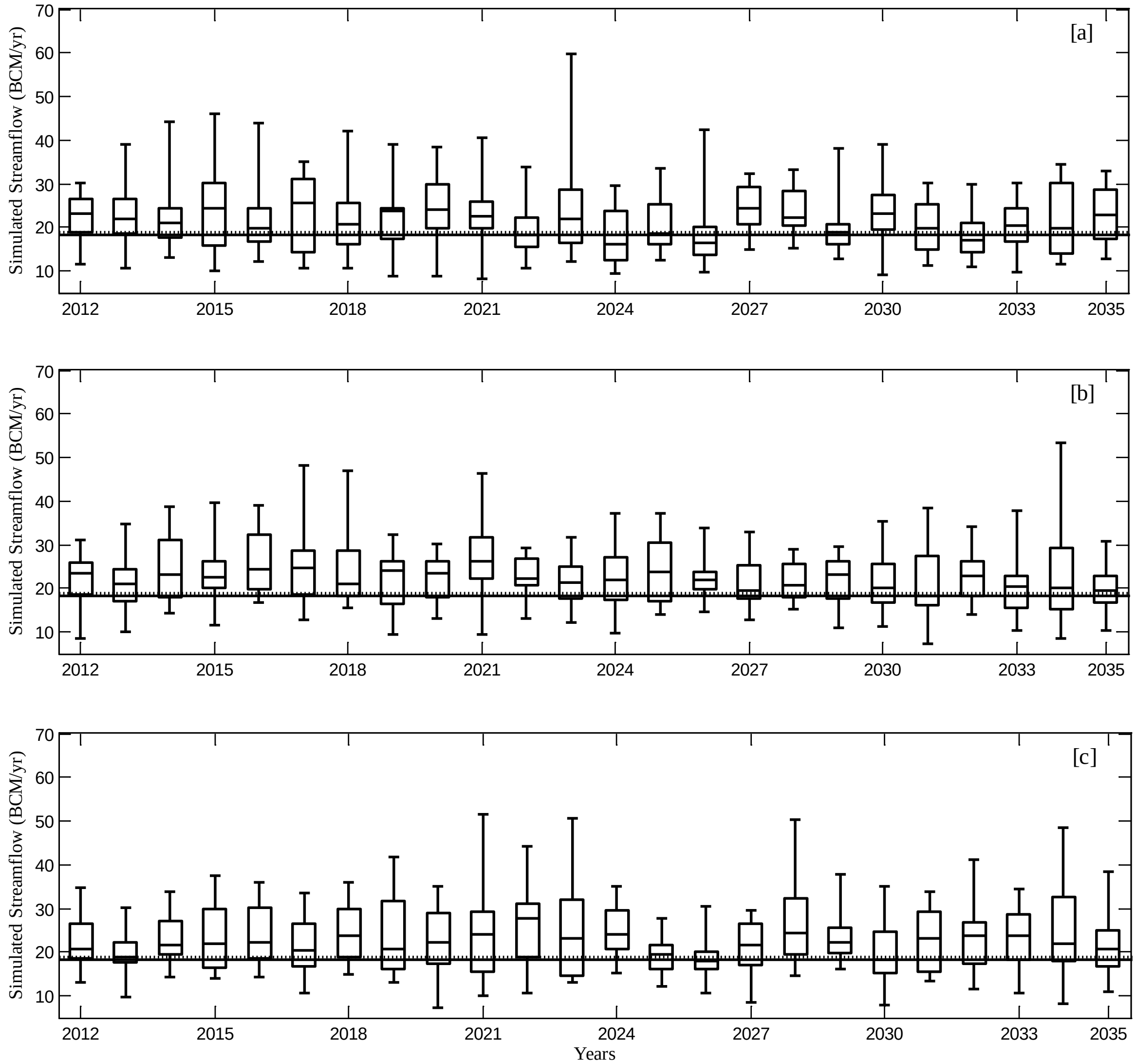

Figure 2.8. Box plots of streamflow at Lees Ferry for different years represented by the ensemble of all 16 GCMs and (a) A1b, (b) A2 and (c) B1 emission scenarios. The box represents 25th and 75th percentile values of the streamflow. The solid horizontal line within box represents the median of streamflow for each year. Whiskers at the lower end and the upper end represent 5th and 95th percentile values of the streamflow for each year. Each boxplot represents streamflow variability simulated by the ensemble of GCMs for each year from 2012 to 2035. The dotted line represents the long term average of the

observed streamflow for the duration of 1970 to 1999. The solid line indicates the system demand for the CRB

2.8.2.2. Lake Mead levels and supply curtailments

Table 2.6 shows the probabilities of Lake Mead levels to draw down below 305 m with and without different percentages of curtailments to the actual allocation if supply is continued even if lake levels drop down to 305 m. The curtailments to the allocation were imposed starting from 5% to 30% at 5% increments. With no curtailment in the water allocation, highest probability (46%) of Lake Mead level to drop down below 305 m was observed for GFDL-CM2.1. Averaged over the ensemble of GCMs for A1b scenario, a probability of about 9% was observed with no any curtailment in the allocated supply. However, with a 5% curtailment in the supply, an average probability of about 6 % was obtained. With the increase in the percentages of curtailment, the probability of Lake Mead levels to drop down below 305 m reduced accordingly. With a 30% curtailment in the allocated supply, there was no probability of Lake Mead levels to drop down below 305 m under all the GCMs for A1b scenario. Several GCMs showed a 0% probability of Lake Mead to drop below 305 m, which included BCC-CMI, CGCM3.1, CNRM-CM3, CSIRO-MK3.0, GFDL-CM2.0, INMCM3.0, IPSL-CM4, ECHAM5, MRI-CGCM2.3.3, and PCM. Thus, theses GCMs are not shown in Table 2.6.

Table 2.6. Probability (expressed as percentage) of Lake Mead levels to draw down below 305 m estimated for 16 GCMs and A1b scenario for the duration of 2012 to 2035 with and without curtailments in the allocated water supply of the lower basin states and with worst case reservoir operation option

% curtailments in water supply	GFDL-CM2.1	GISS-ER	MIROC3.2	ECHo-G	CCSM3	UKMO-hadCM3	Mean	Median
0%	46	5	17	19	15	42	9	0
5%	25	0	16	7	12	38	6	0
10%	22	0	10	0	9	24	4	0
15%	15	0	5	0	4	18	3	0
20%	3	0	2	0	0	16	1	0
25%	0	0	0	0	0	2	0	0
30%	0	0	0	0	0	0	0	0

For future simulations, the probability of Lake Mead levels to draw down below 327.7m, 320m and 312m were computed for different scenarios of streamflow conditions in the CRB, as mentioned in the modeling approach.

1. Streamflow estimated from GCM outputs

Table 2.7 shows the probabilities of Lake Mead levels to draw down below 327.7 m, 320 m, 312 m, as observed with streamflow simulated using GCM outputs and with the adoption of both Option 1 and Option 2 reservoir operations. Below 312 m[a] and 312m[b] indicate the probabilities for reservoir operation option 1 and option 2. Only probabilities of lake levels to drop down below 312 m were observed to change in these options. The average of the ensemble of the GCMs and emission scenarios showed approximately 14% and 9% probabilities for below 327.7 m and 320 m. Similarly, probabilities of lake level to drop below 312 m in two different options of reservoir operation in A1b scenario were computed to be 4% and 6%. The probability of the lake levels to drop below 312 m in reservoir operation option 1 was observed lower than in Option 2. This is because a higher curtailment in the water supply to the Lower basin is experienced in option 1 than in option 2 for the same water level in Lake Mead. It should, however, be noted that in option 1, Lower Basin states experience higher magnitude of curtailments and more often than in Option 2.

In all emission scenarios, the probabilities of Level 3 and Level 2 supply curtailments to the Lower basin are same as the probabilities of Lake Mead levels to go down below 327 m and 320 m, as shown in Table 2.7. However, the probability of Level 1 supply curtailment differs from probabilities shown in Table 2.7 for below 312 m. The probability of Level 1 supply curtailment is higher in reservoir operation Option 1 than in Option 2. The GCMs that showed a 0% probability of Lake Mead levels dropping down below 327.7 m in all 3 emission scenarios are not shown in Table 2.7.

Table 2.7. Probabilities (expressed as percentage) of Lake Mead levels to drop down below 327.7 m, 320 m and 312 m under 16 GCMs and 3 emission scenarios for the duration of 2012 to 2035 with the operation of Lake Mead in reservoir operation Option 1 and 2

Lake Mead Levels	BCC-CMI	CGCM3.1	CNRM-CM3	GFDL-CM2.1	GISS-ER	MIROC3.2	ECHo-G	ECHAM5	CCSM3	UKMO-hadCM3	Mean	Median
	A1b emission scenario											
< 327 m	0	0	28	78	29	77	42	0	38	50	21	0
< 320 m	0	0	13	61	22	34	37	0	26	45	15	0
< 312 m[a]	0	0	4	24	6	11	11	0	15	24	6	0
< 312 m[b]	0	0	8	40	11	18	19	0	18	37	9	0
	A2 emission scenario											
< 327 m	19	10	0	14	8	5	0	58	81	11	13	2
< 320 m	7	0	0	7	0	3	0	29	67	0	7	0
< 312 m[a]	3	0	0	2	0	3	0	8	34	0	3	0
< 312 m[b]	4	0	0	3	0	3	0	11	55	0	5	0
	B1 emission scenario											
< 327 m	30	0	16	30	0	62	0	0	0	0	9	0
< 320 m	16	0	4	15	0	47	0	0	0	0	5	0
< 312 m[a]	5	0	0	5	0	21	0	0	0	0	2	0
< 312 m[b]	9	0	0	8	0	30	0	0	0	0	3	0

2. Streamflow varying from 60 to 120 %

Table 2.8 shows the probabilities of Lake Mead levels to drop down below 327.7 m, 320 m, and 312 m under both reservoir operation options, if streamflow is assumed to vary from 60% to 120 % of the historical average. It is evident from Table 2.8 that with no change in current allocation of the Colorado River, none of the Lower Basin states were observed to experience the supply curtailments of any level, even for a single year, till 2035, if the streamflow in the Colorado River is equivalent to or more than 95 % of the historical average flow. The probability is 100% that Lake Mead will drop down to 327.7 m and 320 m if the future flow is equal to or below 85% of the historical flow. For Option 1, even if the future flow equals 60% of the historical streamflow, there is only an 83% probability of Lake Mead dropping below 312 m.

Table 2.8. Probabilities (expressed as percentage) of Lake Mead levels to drop down below 327.7 m, 320 m and 312 m for the duration of 2012 to 2035 with streamflow varying from 60 % to 120 % of the historical (1970 to 1999) average streamflow

	% of the historical flow												
	60	65	70	75	80	85	90	95	100	105	110	115	120
	% of time of supply curtailments												
< 327 m	100	100	100	100	100	100	38	0	0	0	0	0	0
< 320 m	100	100	100	100	100	100	22	0	0	0	0	0	0
< 312 m [a]	83	74	66	59	50	38	3	0	0	0	0	0	0
< 312 m [b]	100	100	100	100	100	82	5	0	0	0	0	0	0

2.8.2.3. Risk analysis of water supply in the Lower Basin

Table 2.9 shows the results for the risk analysis of water supply in the Lower Basin for two different options of reservoir operation, along with the mean and median values of the ensemble of the GCMs. An average reliability of about 0.86 was obtained in both the options; this indicates that there is about 86 % probability that the water supply system is in a satisfactory state during the future simulations. Average duration of failure varies from a maximum of 235 months for MIROC3.2 to not a single month for different GCMs such as BCC-CMI, CGCM3.1, CSIROMk3.0, and others. Deficit per failure was observed to vary from 0% for different GCMs to a maximum of 39.7% for MIROC3.2

(A2 emission scenario, reservoir operation Option 1). Deficit per failure was observed higher in reservoir operation Option 1 than in Option 2. This is because, in Option 1, higher curtailment to the water supply is imposed once Lake Mead is drawn down to 312 m, compared to the curtailments imposed in Option 2. Thus, if Lake Mead is operated with Option 1, there are larger curtailments to the water supply to the Lower Basin.

2.9. Discussion and Conclusion

Using a system dynamics approach, the current study modeled the effect of climate change on streamflow in the CRB and the associated challenges on the water sustainability in the Lower Basin. The effect of climate change on the streamflow was modeled using the outputs from 16 GCMs and 3 emission scenarios. The model was calibrated and validated for streamflow and Lake Mead levels. Future simulations were performed for the changes in streamflow, precipitation, temperature, and Lake Mead levels as well as risk analysis of the water supply to the Lower Basin states.

The results suggested an increase in future temperature in the CRB as apparent from majority of the GCMs. All the GCMs predicted an increase in temperature in the CRB for the future simulation period for A1b and B1 scenarios (Table 2.5). The range of increase in temperature compared to the historical average varies from 0.39 to 1.57° C among different GCMs and emission scenarios.

Table 2.9. Risk analysis of water supply system in the Lower Basin for the duration of 2012 to 2035 in both reservoir operation options

	Indices	BCC-CMI	CGCM3.1	CNRM_CM3	GFDL-CM2.1	GISS-ER	MIROC3.2	ECHo-G	ECHAM5	CCSM3	UKMO-hadCM3	Mean	Median
A1b emission scenario	Reservoir operation option 1												
	Reliability	1.00	1.00	0.72	0.22	0.71	0.23	0.58	1.00	0.62	0.50	0.79	1.00
	Avg duration of failure (months)	0	0	27	112	84	20	121	0	37	73	29.6	0.0
	No of failures	0	0	3	2	1	11	1	0	3	2	1.4	0.0
	Deficit per failure (%)	0.0	0.0	10.1	24.4	14.1	12.4	19.9	0.0	29.7	35.0	9.1	0.0
	Reservoir operation option 2												
	Reliability	1.00	1.00	0.71	0.22	0.71	0.18	0.58	1.00	0.61	0.50	0.78	1.00
	Avg duration of failure (months)	0	0	21	112	84	235	121	0	37	73	42.7	0.0
	No of failures	0	0	4	2	1	10	1	0	3	2	1.4	0.0
	Deficit per failure (%)	0.0	0.0	8.2	23.7	13.0	11.6	20.1	0.0	28.6	33.2	8.7	0.0
A2 emission scenario	Reservoir operation option 1												
	Reliability	0.81	0.90	1.00	0.86	0.92	0.95	1.00	0.42	0.19	0.89	0.87	0.98
	Avg duration of failure (months)	28	15	0	20	12	14	0	19	117	6	14.3	3.1
	No of failures	2	2	0	2	2	1	0	9	2	5	1.6	0.5
	Deficit per failure (%)	11.1	3.7	0.0	8.3	3.7	39.7	0.0	13.3	27.7	3.6	7.0	1.8
	Reservoir operation option 2												
	Reliability	0.81	0.90	1.00	0.86	0.92	0.95	1.00	0.40	0.19	0.89	0.87	0.98
	Avg duration of failure (months)	28	15	0	20	12	14	0	22	117	6	14.6	3.1
	No of failures	2	2	0	2	2	1	0	8	2	5	1.5	0.5
	Deficit per failure (%)	8.5	3.7	0.0	7.4	3.7	38.6	0.0	12.5	27.0	3.6	6.6	1.8
B1 emission scenario	Reservoir operation option 1												
	Reliability	0.70	1.00	0.84	0.70	1.00	0.38	1.00	1.00	1.00	1.00	0.91	1.00
	Avg duration of failure (months)	29	0	23	17	0	45	0	0	0	0	7.1	0.0
	No of failures	3	0	2	5	0	4	0	0	0	0	0.9	0.0
	Deficit per failure (%)	13.1	0.0	4.1	14.5	0.0	23.1	0.0	0.0	0.0	0.0	3.4	0.0
	Reservoir operation option 2												
	Reliability	0.69	1.00	0.84	0.64	1.00	0.36	1.00	1.00	1.00	1.00	0.91	1.00
	Avg duration of failure (months)	45	0	23	17	0	92	0	0	0	0	11.0	0.0
	No of failures	2	0	2	6	0	2	0	0	0	0	0.8	0.0
	Deficit per failure (%)	12.2	0.0	4.5	12.2	0.0	22.1	0.0	0.0	0.0	0.0	3.2	0.0

Averaged over all the GCMs, changes in the average annual precipitation were about -1%, +0.7%, and +1.4 % for A1b, A2 and B1 scenarios over 2012 to 2035, whereas a large variation was observed for the individual GCM (Table 2.5). The ensemble average of the GCMs and emission scenarios showed almost no any change in the magnitude of precipitation. This result can be compared with USDOI (2011) which have reported that the mean annual precipitation in the CRB will change by only small amount during the 21st century.

The increase in temperature and decrease in precipitation have a significant impact on streamflow in the CRB. Although streamflow is sensitive to the changes in both precipitation and temperature, increase in temperature alone can result in reduction in streamflow; any further reduction in precipitation results in larger decrease in streamflow as evident from Table 2.5 for MIROC3.2 (A2 scenario). This result is in agreement with the results from Nash and Gleick (1991), in which they reported that increase in temperature alone by 4° C can reduce the streamflow by 4 to 12%. A comparison between the future simulated streamflow and the historical average streamflow at Lees Ferry showed that under majority of GCMs, a reduction in streamflow was observed. An ensemble average of the GCMs for A1b, A2 and B1 scenarios, respectively suggested about 6 %, 2 % and 1% reduction in the streamflow in the CRB for the future simulation period. The results of the current study for streamflow in the CRB are in close agreement with other studies. All the previous studies consistently found that the changing climatic condition reduces the flow in the CRB. Nash and Gleick (1991) have suggested 12-31 % reduction in runoff in the CRB in future. Milly et al. (2005) have concluded the reduction in streamflow by 20 % by 2050. USDOI (2011) has reported about 8.5% reduction in streamflow at Lees Ferry till 2050s. On the contrary, Christensen and Lettenmaier (2007) have indicated only 5% reduction in flows by 2100. Compared to the reduction estimated by Christensen and Lettenmaier (2007) for the entire century, our results show a higher reduction in the streamflow for such a short time period that is until 2035. This can be attributed to the coarser resolution of the datasets used in the current study. A larger reduction in the streamflow is predicted by the models using coarser resolution datasets compared to the models using finer resolution datasets (USDOI, 2009).

The reduction in the streamflow in the CRB has a substantial effect on the water levels in Lake Mead as observed in Table 2.6. Although the median of the ensemble of all the GCMs and emission scenarios showed almost no probability of Lake Mead levels drawing down below 305 m, individual GCMs showed a large variation with regard to such a probability. Results varied from almost no probability to nearly 62 % for Lake Mead levels to drop down to 305 m among various emission scenarios if water supply to the basin states are continued, even if Lake Mead levels drop down to 305 m. However, with the adoption of reservoir operation Option 1 and Option 2, Lake Mead levels were protected above 305 m for the entire simulation period for all the GCMs and emission scenarios. Thus, it can be concluded that if some shortage responses are adopted and curtailments to the water supply are imposed, as was done with Option 1, Lake Mead can be protected above 305 m for the entire future simulation period even if there is reduction in the streamflow in the Colorado River. However, this can only be achieved by reducing the supply to the Lower Basin states. It should be noted that the water levels in Lake Mead can be controlled by the releases from Lake Powell. Although the actual operation may release water in surplus of the amount governed by the reservoir operating criteria, our model can only release the water based on the operating criteria mentioned in the reservoir operation sector.

The decrease in Lake Mead levels has a substantial effect on the water supply to the Lower Basin states, as curtailments of varying magnitude can be imposed on the allocated supply whenever Lake Mead drops below 327 m (1075 ft). Although in the short term the large storage-to-runoff ratio of the CRB reservoirs moderates the impact of the seasonal shifts in runoff to some extent, with the persistence of drought for an extended period, even the large storage capacity cannot ensure the long term reliability of water supplies to the basin states (Christensen and Lettenmaier, 2007).

The risk analysis of the water supply system in the Lower Basin (Table 2.9) indicated that with the decrease in the lake level, curtailment to the allocations of the Lower Basin states can be imposed lowering the reliability of water supply to these states. An average deficit per failure was observed to be higher in case of Reservoir Operation Option 1 than in Option 2. This is because in case of Reservoir Operation Option 1, the curtailment to the basin states starts increasing gradually, once Lake Mead levels drops down below 312 m; in addition, the supply is completely cut off so as to protect Lake Mead above 305 m. The magnitude of deficit also is higher in Option 1 than Option 2 for the same water level in Lake Mead.

The previous efforts have focused on the hydrologic implications of climate change with the use of very high resolution hydrologic models. In addition to analyzing the effect of climate change on the streamflow magnitude in the CRB, this study made an effort in finding the actual water supply risk to the Lower Basin states based on different risk evaluation indices. Unlike most of the previous studies, which have used hydrologic models that require numerous datasets such as gridded temperature, precipitation, wind speed, surface radiative and other meteorological variables, the current study has used such easily available datasets as precipitation, temperature, and potential evapotranspiration; this has produced the comparable results. In addition, the use of SD facilitated the inclusion of all the required sectors that included hydrologic model, reservoir operation, and water allocation sectors, within a single modeling framework.

It should be noted that this study used a coarser resolution (2° latitude – longitude) climate model outputs for the Colorado River basin along with a simple conceptual hydrologic model. The high resolution hydrologic models using finer resolution datasets are believed to capture the topographic and climatic variability in a better way (Hoerling et al., 2009). The downscaling of the GCM datasets can be used to represent the spatial variability to some extent (USDOI, 2011e). In addition, the Colorado River reservoir operations were simplified. However, the accurate assessment requires the thorough analysis of reservoirs operation. Not all the operational complexities of the reservoirs in the CRB were addressed in the study, both due to the lack of data and due to the complex nature of the reservoir operation criteria in the CRB. The criteria governing the surplus of water in Lake Mead were not considered in the study. However, the results may vary with the inclusion of these criteria and supply curtailments to the Lower Basin states may be experienced with lower probabilities than the results of this study. Thus, the detail operation of the Colorado River reservoir system would provide more confidence in the obtained results.

The major contributions of the study are to assess (i) the effect of climate change on the magnitude of the streamflow in the CRB by including a broad range of GCM predicted outputs, (ii) the effect of changes in the streamflow on the water supply to the basin states, and (iii) risk evaluation of water supply to the Lower Basin based on reliability, resilience and vulnerability. With the inclusion of 16 GCMs and 3 emission scenarios, which showed the most plausible range of future condition in the CRB, the study provides the broadest range of future streamflow patterns in the CRB.

The possible changes in the streamflow and its effect upon water sustainability in the basin states are of primary importance to the water managers. Furthermore, evaluation of risks of water supply system is of foremost importance to the water managers. It is expected that this study will help the policy makers by providing the range of estimates of future water availability in the CRB. This information can also help improve the water management practices by making adjustments for reduced magnitude of streamflow in the CRB.

CHAPTER 3

EVALUATING THE IMPACT OF DEMAND SIDE MANAGEMENT ON WATER RESOURCES UNDER CHANGING CLIMATIC CONDITIONS AND INCREASING POPULATION GROWTH

3.1. Introduction

Among various environmental sectors influenced by climate change, water resources are of major concern (Frederick and Major, 1997). Increasingly, climate change and its potential hydrological effects contribute to uncertainty in water resources management (Middelkoop et al., 2001). Demand increases with the increase in temperature (Arnell, 1998) and supply may decrease as a result of climate change. Changes in water demand are expected in the future as a result of several factors, including climate change, increasing population growth, and associated industrial development (Arnell and Liu, 2001). Furthermore, a study on the assessment of available water resources in the world concluded that over 50% of all the renewable and accessible water already have been apportioned to human use (Gleick and Palaniappan, 2010). Hence, the water management system can be vulnerable due to an unbalance in the supply and the demand caused by changing climatic conditions and increasing population growth.

The world population has more than doubled in the last 60 years (2.6 billion in 1950 to 6.9 billion in 2010) (USCB, 2010). This growth in global population has affected the water demand. Globally, water demand has tripled between 1950 and 2003 and is projected to double by 2035 (Tidwell et al., 2004). Approximately 1.1 billion people in the world lack access to safe water (Jackson et al., 2001) and by

2025, approximately 4 billion people are projected to live in water scarce countries with the most susceptible populations living in arid regions (Alcamo et al., 1997; Engelman et al., 2000). Because arid and semi-arid regions of the world are subject to periodic drought, managing water resources is more challenging in these regions (Gleick, 2010).

Climate change increases the frequency of extreme events, such as floods and droughts. Some arid regions, such as Western Australia, western and southwestern United States, southern Canada, Mediterranean, and the Sahel region of Africa have experienced intense multi-year droughts (Mata, 2008). The declining water table as a result of drought in the semi-arid regions in Asia and the Middle East is of particular concern as well (Seckler et al., 1999). Drought in the southern province of Algarve in Portugal has caused two major reservoirs, namely, Funcho and Arade, to completely dry up (Mata, 2008). Similarly, some of the southwestern regions of the United States, especially the Colorado River basin, has been experiencing severe, sustained drought. Thus, in the light of changing climatic conditions, bringing future demand in line with the available supplies requires sustainable water management and enhanced water conservation practices.

In the past, in order to meet the increasing demand, water managers have focused primarily on economic development and measures to increase supply. This approach, which primarily involves engineering solutions to the water problems, is termed as the “Hard” path (Gleick, 1998) or supply-side management. Supply-side management has provided massive infrastructures to meet increasing water demands, even during extreme droughts (Gleick, 1998). This approach has brought tremendous benefits to the human society with the expansion of hydropower and irrigated agriculture. Risks of flood and drought have been moderated with the construction of massive dams and reservoirs (Gleick, 2003).

However, huge infrastructures have resulted in a very expensive and irreversible social, ecological, and environmental cost (Vedwan et al., 2008; Wang et al., 2011). Thus, a shift has been occurring towards managing the demand, an approach that is often termed as the “Soft” path, or demand-side management.

The “Soft” path seeks to make the available water supply more sustainable and productive instead of trying to find other new sources (Gleick, 2003), and also investigates areas where potential water savings can be made. A shift towards demand side management practices is very important in the light of increasing population and changing climatic conditions. The current trend of population growth (USCB, 2010; Qaiser et al., 2011) and increasing drought caused by changing climatic conditions (Cayan et al., 2010; Kalra and Ahmad, 2009 and 2011) has been experienced in the parts of the Southwestern United States.

Recently, the southwestern United States has experienced a spate of dryness (Cayan et al., 2010). In particular, since 1999, the Colorado River Basin (CRB) in the Southwestern United States has experienced a multi-year, severe, sustained drought of varying magnitude (USDOI, 2011). This river basin is divided into the Upper and Lower Basin. It supplies water to seven states within United States and also to Mexico. The basin states are Wyoming, Utah, New Mexico, Colorado, Arizona, Nevada and California. The Colorado River is one of the heavily regulated and over-allocated rivers in the southwest (Christensen et al., 2004). The 1922 Colorado River

Compact allocation has exceeded the long-term average reliable supply, and the Colorado River reaches its peak renewable limit (Gleick, 2010).

Additionally, from 1920 to 2000, the population of the seven basin states dependent on the Colorado River for water supply has increased by about 7-fold; as a result, the water of the Colorado River is under continuous pressure (Gleick, 2010). This has been aggravated by human-induced climate changes. The majority of the studies suggest that increasing global warming is likely to make CRB drier and reduce runoff (Christensen et al., 2004; Mccabe and Wolock, 2007; Seager et al. 2007; Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007). Construction of large reservoirs namely- Lake Mead, created by the Hoover Dam and Lake Powell, created by the Glen Canyon Dam has been able to meet the demand of the basin states even during low flow years. Even without climate change, the hydrological pattern in CRB has been observed to have high seasonal and multiannual variability (Kalra and Ahmad, 2011), which presents additional challenges to water managers as it accentuates less dependability (Colby and Jacobs, 2007). Thus, traditional approaches to deal with water in this region are failing, and new management approaches involving demand side management are needed (Gleick, 2010).

Starting from the early 2000, a shift to demand management has occurred in the Las Vegas Valley in Southern Nevada, a region that uses the Colorado River water as its major water supply source. Because the population of this region has more than doubled in a period of 20 years, from 1990 to 2010, water demand has almost doubled while a fixed supply has been allocated from the Colorado River.

With this motivation, the current study used a systems dynamics approach to evaluate different water management policies, which include indoor-outdoor conservation and water pricing, as well as their potential role in sustainable water resources management. Previous studies for water resources management, such as Stave (2003), Tidwell et al. (2004), Ahmad and Prashar (2010), Qaiser et al. (2011), and Shrestha et al. (2011), considered water supply and demand. Those studies, however, did not take into account explicitly the effect of climate change on the water demand and the supply. With scientific evidence of global climate change, a realistic assessment of water availability in a region should incorporate the effect of changing climatic conditions. Gober and Kirkwood (2010) incorporated the effect of climate change on the assessment of water supply in Phoenix, Arizona. However, the study did not consider the effect of climate change on the water demand. The current study incorporates the effect of climate change on both the water demand and the water supply of the LVV, using the outputs from 16 global climate models (GCM) for three different emission scenarios, also referenced in the Inter-governmental Panel on Climate Change (IPCC) Fourth Assessment Report. The effect of climate change on water demand was modeled as the increase in water demand with the increase in future temperature, as predicted by different GCMs. The effect of climate change on the water supply was modeled as the change in Lake Mead water levels, a major source of water for the LVV. The change in the water levels of Lake Mead was based on the change in streamflow in the Colorado River.

The modeling horizon for this study was from 1989 to 2035. The historic period, that is, before 2011, was used to validate the water demand, and the period from 2012 to 2035 was used for simulate future demand. The model also was validated for Lake Mead levels for a period from 1970 to 1999. The model's performance was based upon mean absolute error and average error between the actual and the simulated data for the water demand and Lake Mead levels. Similarly, the performance of the hydrologic model was evaluated based on the performance measures suggested by Moriasi et al. (2007), which included correlation coefficient (R), root mean square error-observations standard deviation ratio (RSR), percentage bias (PBIAS), and Nash Sutcliff coefficient (NSE).

This study is expected to help the water managers in developing sustainable water management practices to meet the growing demand in this semi-arid region. This may facilitate making policy decisions that can achieve water sustainability in the LVV.

3.2. Las Vegas Valley and its water system

The Las Vegas Valley is located in Clark County in Southern Nevada in the southwestern United States. It is a semi-arid region at an elevation of 549 m above mean sea level (Buckingham and Whitney, 2007). It contains a drainage basin area of about 4142 square kilometers (Gorelow, 2005). The summer in the LVV is characteristic of a desert climate, with a daily average high reaching 38º C and an average low temperature of up to 21 º C, with a very low relative humidity (Gorelow, 2005). The LVV experiences an annual average rainfall of less than 13 cm. Figure 3.1 shows the map of the Las Vegas Valley study area.

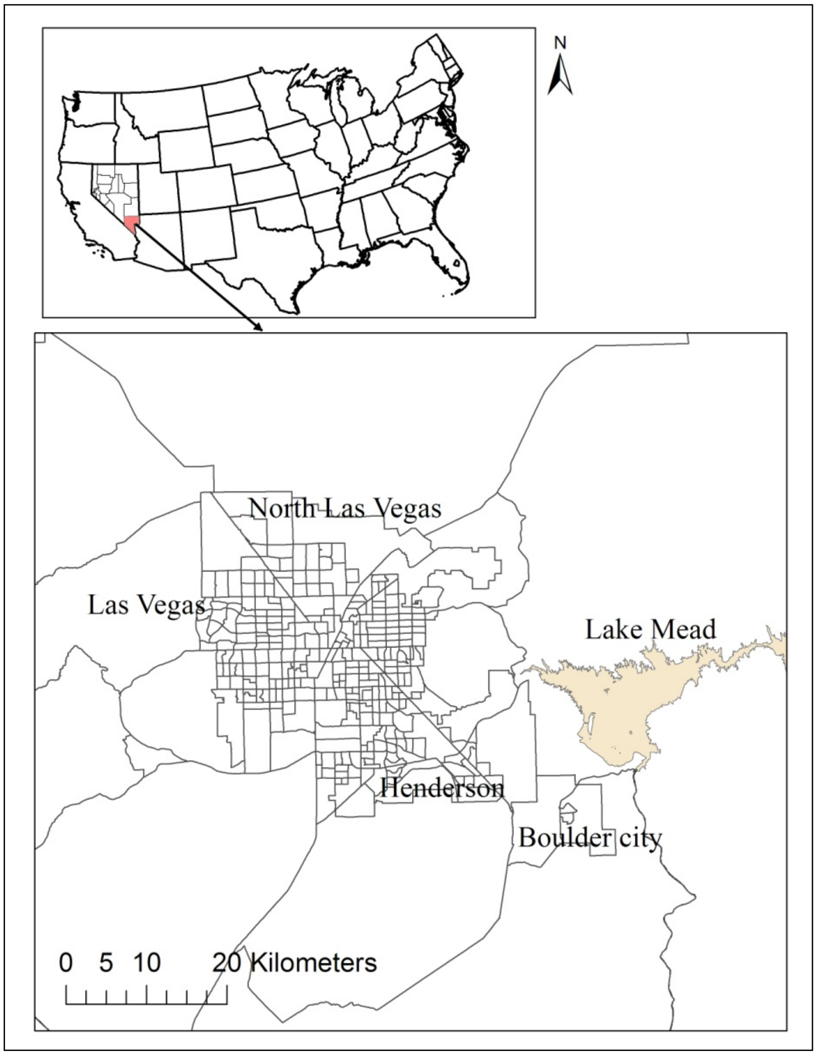

Figure 3.1. Map of the study area showing the Las Vegas Valley

The main source of water for the LVV is Lake Mead, replenished by the Colorado River. Currently, Lake Mead accounts for 90% of the LVV supply. The remaining 10% of the supply is met by ground water wells (SNWA, 2009). Apart from its annual allocation of 370 million cubic meters (MCM) from the Colorado River, an additional amount equivalent to the return flow credit is allowed to be withdrawn from Lake Mead. Return flow credit is the highly treated waste water from indoor use that is returned back to the Colorado River through Las Vegas Wash (Water

Resources Plan, 2009). Besides highly treated waste water, flows in the Las Vegas Wash consist of urban runoff, intercepted shallow ground water, and storm water (LVWCAMP, 1999); however, the LVV gets credit only for the portion of flow in the Las Vegas Wash originally from the Colorado River (LVWCAMP, 1999).

Southern Nevada Water Authority (SNWA) is the agency responsible for managing water resources in the LVV. With a growing population, increasing water demand, and changing climatic conditions, the agency has considered a wide variety of options involving both increasing the supply and decreasing the demand. Increasing supply, however, is both politically and economically expensive (Stave, 2003). With this realization, demand management of water resources is getting more attention in this region. With the demand management practices, the per capita water consumption in the LVV already has been reduced from 1191 liters per day (lpd) in 2000 to 930 lpd in 2010 (SNWA, 2009). Although, per capita water consumption has decreased, the current per capita consumption in the LVV is still high compared to other cities in the Southwest that have similar climatic conditions (Cabibi et al., 2006). This provides an opportunity for further water conservation in the LVV.

3.3. Data

The major datasets used in the study include water demand, water conservation, water pricing, water supply, global climate model outputs and population.

3.3.1. Water demand, water conservation, water pricing, and water supply

Water used by the end uses in a household was obtained from Vickers (2001) and SNWA (2008). The possible end users considered in the study include the toilet, faucet, shower, cloth washer, dish washer, bath, and leaks. The total turf area in the LVV prior 2000, about 27 million square meters, was computed from different sources, including Brandt (2009), Sovocol (2005), and SNWA (2009); Brandt (2009) estimated total turf area in the LVV in year 2008. Turf area converted to water smart landscape between 2000 and 2008 were obtained from Sovocol (2005) and SNWA (2009), and was added to the turf area estimated from Brandt (2009) in order to obtain total turf area in year 2000. The water saved with the conversion of turf to water smart landscaping was obtained from Sovocol (2005). Results from this study showed that on average, about 2271 liters per square meter could be saved per year with this type of conversion. Demand for swimming pool water was based upon the water use per unit volume of the pool and the water lost due to evaporation in an uncovered swimming pool. Total swimming pool size in the LVV (about 3.72 million square meters), and also the water saved by covering swimming pools were obtained from Cooley et al. (2007).

Water demand by golf courses was obtained from Clark County Nevada (CCN, 2000). The rate of application of reclaimed water, about 2.1 CM/yr per square meter, was obtained from CCN (2000). The current rate of reclaimed water use by the golf courses is 22 MCM/yr; this is projected to reach 47 MCM/yr by 2020 (CCN, 2000).

Water pricing has a potential to reduce the water demand. The percentage decrease in demand with a unit percent increase in water price is called price elasticity of water demand (Olmstead et al., 2007). Olmstead et al. (2007) reported that on average, the residential price elasticity of water demand is in the range of -0.3 to -0.4; therefore -0.33 was used in the current study.

Historic ground water supply data, from 1992-2008, was obtained from Nevada Division of Water Resources. Ground water supply from 1989 to 1991 was assumed to be same as the water supply in 1992 and beyond 2008, the ground water supply data was fixed at the 2008 level.

3.3.2. Global climate model outputs

This study used bias-corrected climate data for temperature and precipitation at 2° latitude-longitude, obtained from World Climate Research Programme's (WCRP) Coupled Model Inter-comparison Project phase 3 (CMIP3). Monthly temperature and precipitation data from an ensemble of 16 global climate models were used to evaluate the impact of climate change on streamflow. Similarly, from same ensembles of 16 GCMs, bias-corrected and downscaled monthly temperature values, at 1/8° latitude-longitude, were used to evaluate the impact of climate change on water demand in the LVV. In both cases, three emission scenarios namely - A1b, A2 and B1- were used in the study. These emission scenarios differ in terms of technological advances and CO_2 emission concentration by 2100. A1b scenario is categorized as the middle emission path, having a balance of technological changes across all the fossil and non-fossil energy sources, as well as a global CO_2 concentration reaching 720 ppm (Seager et al., 2007) by 2100. A2 scenario is categorized as the higher emission path and leads to higher population growth with a global CO_2 concentration reaching 850 ppm by 2100. B1 scenario is categorized as the lower emission path with a global CO_2 concentration reaching 550 ppm by 2100 (Christensen and Lettenmaier, 2007; CMIP3, 2007).

3.3.3. Population

A total population for this study included both permanent resident population in the LVV as well as the tourist population.

Total historic and projected future permanent resident populations, from 1989 to 2035, were obtained from Center for Business and Economic Research at the University of Nevada, Las Vegas (CBER, 2010). The total resident population in the LVV during 2010 was about 2.04 million (CBER, 2010). Residential population was divided by the number of person per house, to obtain the number of houses in the LVV. Each home was considered to be occupied by 2.56 residents; this was calculated from the population and houses data obtained from CBER (2010).

The total number of monthly tourists in the LVV, for a period from 1989 to 2010, was obtained from a report from the Las Vegas Convention Center (LVCC). In 2010, nearly 37.3 million tourists visited LVV (LVCC, 2011). Tourist numbers remained almost stable (approximately 37 million) from 2005 to 2010, with highest in 2007 at about 39 million. Future tourist numbers were assumed to remain at 2010 levels.

3.4. Method

3.4.1 System Dynamics modeling

In order to evaluate the water conservation policies, systems dynamics (SD) was used in this study. SD is the study of the system in terms of stocks and flows, which affect each other through the feedback loops and time delays (Sterman 2000). The system structure consists of the causal relationship among the variables. A more detail description on the theoretical background of SD can be found in Forrester (1996), Sterman (2000), and Ford (1999).

Over the years, SD has been used for a number of water resources management studies. Winz et al. (2009) provides a good review of SD applications in water resources. Tidwell et al. (2004) developed a community-based SD model for water resources management in the Middle Rio Grande basin of New Mexico, which involved stakeholders and general public in the decision making process. Madani and Marino (2009) used SD to simulate complex water management in Zayandeh-Rud River Basin in Iran, which used trans-basin water diversion as one of the techniques to solve the water shortages in Iran. Ahmad and Prashar (2010) developed a simulation model to evaluate the implications of municipal water conservation policies in South Florida; this model captured the complex inter-relationships between available water and the demand for municipal, agricultural, and environmental purposes. Gober et al. (2010) used SD to model the interaction between changing climatic conditions and the increasing population as well as their effect on future water supply in Phoenix, AZ. Other applications of SD for water resources include reservoir operations (Ahmad and Simonovic, 2000), flood management (Li and Simonovic, 2002; Ahmad and Simonovic, 2004 and 2006), and flood evacuation emergency planning (Simonovic and Ahmad, 2005).

In the LVV, Stave (2003) developed a model to facilitate the stakeholder's participation in water resources management; Venkatesan et al. (2011a and 2011b) developed models for salinity load estimation and water reuse, respectively; Shrestha et al. (2011) developed a SD model to estimate the carbon footprint associated with two water supply options; and Qaiser et al. (2011) used SD to evaluate the impact of water conservation on the fate of outdoor water use in the arid region.

3.4.2. Model structure

A dynamic simulation model was developed in a system dynamics framework to model the combined effect of population growth, climate change, and water conservation, and water pricing policies on water demand and supply in the LVV. A simplified schematic of the SD model is shown in Figure 3.2.

The model consists of different sectors that include (1) a hydrologic water balance sector, (2) a reservoir operation sector, (3) a water demand sector, and (4) a water supply sector.

3.4.2.1. Hydrologic water balance sector

This sector computes monthly streamflow in different sub-basins of the Upper Colorado River Basin (UCRB), which covers an area of 46,102 square kilometers. For this study, the UCRB is divided into six different sub-basins, namely, (i) the Great Divide-Upper Green, (ii) the White Yampa and Lower Green, (iii) the Colorado Headwaters, (iv) the San Yuan, (v) the Upper Colorado Dirty Devils, and (vi) the Gunnison and Upper Colorado Dolores. The streamflow generated in each sub-basin is accumulated at the outlet of the UCRB at Lees Ferry. The hydrologic water balance sector developed in this study was adopted from Xu et al. (1996); this sector uses monthly precipitation, mean monthly air temperature, and monthly potential evapotranspiration (PET) as inputs and generates monthly streamflow as output. The details of the hydrologic model components and the equations involved can be found in Xu et al. (1996).

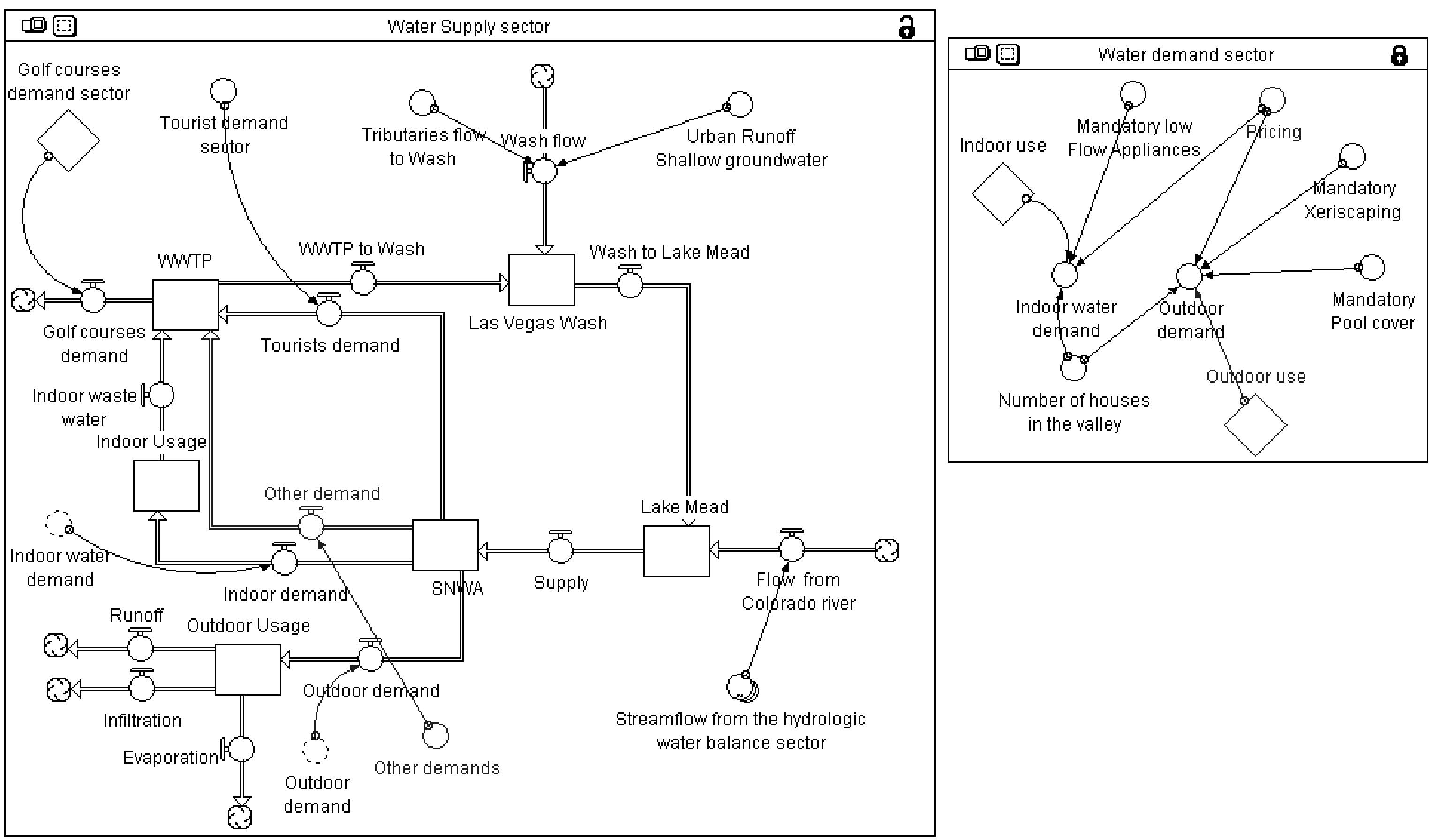

Figure 3.2. Simplified conceptual diagram of system dynamics model developed for the Las Vegas Valley

The hydrologic water balance model was calibrated and validated for streamflow at Lees Ferry for duration of 1970 to 1990 and 1991 to 1999, respectively. The values of R, RSR, PBIAS, and NSE for the calibration period were 0.76, 0.69, 9.65%, and 0.53, respectively; all these values were considered within the satisfactory range.

3.4.2.2. Reservoir operation sector

This sector regulates the release of water from UCRB and Lake Mead to the basin states. Based on the reservoirs operating criteria, runoff generated in the UCRB is assumed to be stored in Lake Powell and released to the Upper Basin states and Lake Mead. These operating criteria were simplified in the current study. The volume of flow equivalent to the naturalized flow at Lees Ferry was assumed to inflow into Lake Powell. The major criteria affecting the release from Lake Powell are (i) mandatory release of 10.2 billion cubic meters (BCM) per year from the Glen Canyon Dam for the consumptive use of Lower Basin states and (ii) equalization of contents in Lake Mead and Lake Powell (Christensen et al., 2004). Equalization of contents in these reservoirs was also simplified in the study. At the end of each month whenever Lake Powell volume is larger than Lake Mead volume, the contents of the reservoirs were equalized so that the percent of water volume was same in both the lake. In addition, in order to equalize the contents in the reservoirs, a release not exceeding 11.1 BCM per year but larger than 10.2 BCM per year was made from Lake Powell. From Lake Mead, allocations of each of the Lower Basin states and Mexico were released. Scheduled deliveries to the Lower Basin states from Lake Mead were met until Lake Mead had drawn down to 327.7 meters (USDOI, 2007b). Thus, curtailments started at a Lake Mead level of 327.7 m.

The curtailment criteria were based on the "*Record of Decision (ROD) - Colorado River Interim guidelines for Lower Basin shortages and the coordinated operations for Lake Powell and Lake Mead*" (USDOI 2007b). About 4.33%, 5.66% and 6.66% curtailments were made from the annual share of Nevada as Lake Mead was drawn below 327.7 m, 320 m, and 312 m respectively. Since the operating criteria of Lake Mead after an elevation of 305 m is not specified in USDOI (2007b), the scheduled deliveries to Nevada's annual share was assumed to be curtailed by 5.76%, similar to the curtailment below lake levels of 312 m. It should be noted that the existing SNWA water system intakes (Intakes No. 1 and No. 2) become inoperable as soon as water levels in Lake Mead drop down to 320 m (1050 ft) and 305 m (1000 ft), respectively. However, a third intake is under construction, which can further withdraw water from Lake Mead even if water levels drop down below 305 m (1000 ft) (Feroz et al., 2007).

The reservoir operation sector was validated for Lake Mead levels for a period of 1970 to 1999.

3.4.2.3. Water demand sector

The water demand sector computes the water demand for residential, tourist, golf course and other.

Residential demand: This accounted for the highest water use, about 59%, in the LVV (SNWA 2008). Residential demand was modeled in detail by further dividing into indoor and outdoor demands.

For indoor demand, water used by each end use was considered. For each end use, water use volume was calculated by multiplying the frequency of use with the water consumed per use. Indoor demand per house was computed by summing up the volume of water used by all the end uses multiplied by number of residents in a house. The total indoor demand was calculated by multiplying the indoor demand per house with total number of houses. Water savings obtained with each end use was estimated by subtracting the efficient use from the non-efficient use.

The outdoor demand primarily consisted of water demand by landscaping and swimming pools. The landscape water demand was calculated by multiplying the average lawn size per household in the LVV and water used per square meter for lawn irrigation. The water savings was obtained by converting turf grass into water-smart landscapes. Water demand by swimming pools was calculated by multiplying the average swimming pool volume with the water required per unit volume, along with water lost from the uncovered swimming pool due to evaporation. The current study considered that water in the swimming pool was changed once a year. Use of a cover in a swimming pool was considered as an option to save water loss due to evaporation. Thus, the water savings was the amount of water lost due to evaporation in an uncovered swimming pool. Water lost due to excess irrigation runoff, obtained from Qaiser et al. (2011), was also considered as another component of outdoor water demand.

Tourist demand: Tourist demand was calculated by multiplying the number of monthly tourists with the per capita tourist water demand. The average per capita tourist water demand of about 100 liters per capita per day (lpcd) was used in the current study. In absence of other information on the per capita consumption for tourists, the average per capita for tourists was so adjusted in order to obtain the total tourist water demand, which was about 16 % of the total demand (SNWA, personnel communication). About 80 % of the tourist demand was considered to be used indoors, and the remaining 20 % was for outdoor use, as obtained from Cooley et al. (2007).

Golf courses demand: The water demand for golf courses was obtained by multiplying the total area for golf courses with the water application rate. Currently, about 30% of the total water demand for golf courses is met with reclaimed water, 56 % of the demand is met with potable water from municipal sources, 11% is met from ground water wells, and 3% is met from untreated water (CCN, 2000). For a future projection of golf courses demand, it was considered that by 2035, 60% of the total golf courses demand will be fulfilled with reclaimed water, as estimated in a study by Clark County, Nevada (CCN, 2000).

Other demands: Other demands include commercial and industrial, school and parks, common areas, among other uses (SNWA, 2008). In the absence of information available on the fraction of "other" demands for indoor and outdoor use, 29 % was considered to be used indoors and the remaining 71% outdoors. The split was made in order to calibrate the return flow credit in 2010.

In the current study, residential outdoor water demand and golf courses water demand were considered to be affected by climate change. A study by Bisgrove and Hadley (2002) concluded that about a 1.1° C increase in temperature would cause an increase in outdoor garden water demand by 4 %. Though climatic settings vary, in the absence of any other estimates, estimates from Bisgrove and Hadley (2002) were used for the outdoor landscape water demand and golf courses water demand. The increase in water demand with the increase in evaporation rate was considered for swimming pools. The future evaporation rate was calculated by using evaporation and temperature relationships provided by the Blaney-Criddle method (Brouwer and Heibloem, 1986). Since the Blaney-Criddle method underestimates the evapo-transpiration in windy, dry, sunny areas by about 60 % (Brouwer and Heibloem, 1986), a correction factor was applied to the evaporation rate estimated with this method; this resulted in an average evaporation rate of 1.98 m/yr in LVV. The same adjustment factor was applied for the future, and the additional water required due to the increase in evaporation rate was calculated.

Similarly, the impact of climate change on the hydrologic model was evaluated using future temperatures predicted by the GCMs. The effect of increase in temperature caused greater evaporation and earlier melting of snow pack.

3.4.2.4. Water supply sector

The water supply sector computes the water to be supplied to the LVV based on estimates from the water demand sector. Water supplied to the LVV is used either indoors or outdoors. All the water used indoors is passed to one of the three waste water treatment plants (WWTPs) located in the LVV. Water is treated to a tertiary level in the WWTPs and is finally discharged into Lake Mead through the Las Vegas Wash. An average loss of 10 % was assumed for the WWTPs, and was calculated as the difference between the total indoor water entering the WWTP and that flowing out into the Las Vegas Wash. A portion of the treated waste water was supplied to golf courses within the LVV, as indicated by golf courses demand for reclaimed water.

A portion of water used outdoors is lost to the atmosphere through evaporation and evapotranspiration; in addition most of the outdoor water contributes to shallow sub-surface ground water or flows to the Las Vegas Wash as urban runoff (Stave, 2003). An average evaporative loss from outdoor use, obtained from Qaiser et al. (2011), accounts for about 30% of the total outdoor use. About 66 % of the total outdoor water is infiltrated into ground and about 4% is runoff (Qaiser et al., 2011). Approximately 6.2% of total outdoor use contributes to shallow ground water and urban runoff (Qaiser et al., 2011).

Water withdrawal from Lake Mead is based upon the current allocation of Colorado River water to Nevada and also on different curtailment criteria once the lake level draws down below 327 meters (USDOI, 2007). Storage in Lake Mead is estimated using the following equation:

$$\text{Storage}\ (t) = \text{Storage}(t - dt) + (\ Rf + I - E - Rel) \times dt \qquad (1)$$

where,

Storage (t)   Lake Mead storage at time 't'

Storage(t − dt)   Lake Mead storage at previous time step

Rf   Return flow credit at time 't'

I and E   Inflow into Lake Mead and Evaporation loss from Lake Mead, respectively

Rel   Release from Lake Mead to fulfill the downstream requirements at time t

3.4.3. Modeling approach

The system dynamics software STELLA (ISEE, 2011) was used to develop the model. The modeling approach consists of model validation and future simulations.

3.4.3.1. Validation

The model was validated using multiple tests, as described by Sterman (2000), which included structure assessment, dimensional consistency, extreme conditions and behavior reproduction. Structure assessment tests the model's structure against the real system.

Dimensional consistency ensures uniformity in the units of measurement of all the variables in the model. Extreme condition tests the model's responses under extreme values of the inputs or extreme conditions of policy implementations. Behavior reproduction test checks the model's ability to replicate the behavior of the real system. The model performed satisfactorily under all these tests. Similarly, different integration methods were tested that include Euler, 2nd order Runga-Kutta (RK), and 4th order RK. Euler's method of integration was selected. Similarly, the model was tested for different time steps and 0.25 was used. Model was validated for water demand in the LVV from 1989 to 2010 and for Lake Mead levels from 1970 to 1999, by comparing model output with the observed data.

3.4.3.2. Future Simulation

The validated model was used to generate the water demand and the water supply for future simulations from 2012 to 2035. Multiple future simulations were performed to test various water demand management policies in the LVV.

3.4.3.2.1. Water demand and supply

For evaluating the water demand and water supply, two different policy scenarios were tested;

(i) Status quo population growth, no policy implementation, and with climate change, and

(ii) Status quo population growth, with policy implementation, and with climate change.

For both the scenarios, water demand and water supply were affected by climate change. The scenarios tested the water demand model's sensitivity to policy implementation and climate change.

The first scenario was called Status Quo. In this scenario, population growth proceeds through 2035 at rates consistent with that projected by the CBER. This scenario further assumes that there are no additional policies implemented for the conservation of water.

The second scenario, called the Conservation Policy Scenario, considered status quo population growth and implementation of different policies. Here policies refer to (i) indoor conservation, (ii) outdoor conservation, (iii) indoor and outdoor conservation, (iv) water pricing, and (v) combination of the aforementioned policies with conservations in hotels/casinos. Indoor conservation involved mandating low-flow appliances in houses constructed after 2012 and retrofitting a selected percentage of existing homes with low-flow appliances. Outdoor conservation involved mandating the conversion of turf grass into desert landscape and the use of covers for residential swimming pools constructed after 2012 along with retrofitting a selected percentages of existing houses. With these policies adopted for conservation, 50% of the older non-conserving houses were assumed to be retrofitted for the future simulation. The delay in behavioral responses of people in retrofitting efforts was modeled using a delay function. Water pricing was assumed to be effective from 2012, and was assumed to affect the residential water demand only.

For both policy scenarios, the impact of population growth was tested by considering (i) a growth in population only 50 % of the projected growth rate and (ii) no population growth.

3.4.3.2.2. Risk Analysis

Risk analysis of the water supply to the LVV from the Colorado River was computed based on the request for water demand sent to Lake Mead and on the maximum supply that could be obtained from Lake Mead. Risk analysis was based on reliability, number of failures, average duration of failure, and average deficit per failure. Reliability, resilience, and vulnerability for the water supply system were originally defined by Hashimoto et al. (1982) and were modified by Zongxue et al. (1996). The definition of resilience and vulnerability were modified in this study to calculate the average duration of failure and average deficit per failure.

Reliability, which measures the probability of the system to meet the desired water demand, is calculated using the following formula:

$$\text{Reliability} = \frac{1}{NS}\sum_{i=1}^{NS} I_i \tag{2}$$

where

NS = total duration of water supply

I_i = state variable of the water supply system. It is equal to 1 if there is no deficit, and is equal to 0 if there is deficit.

The average duration of failure is calculated as the total duration of failure divided by the number of failure, using the following formula

$$\text{Avg duration of failure} = \left\{\frac{\sum_{1}^{i=1} FD}{NF}\right\} \tag{3}$$

NF = number of failures

FD = duration of failure

The average deficit per failure is computed by dividing the average deficit during the whole supply period by the average water demand during the same period using the following formula

$$\text{Average deficit per failure} = \frac{\sum_{i=1}^{NF} VE_i}{\sum_{i=1}^{NF} VD_i} \tag{4}$$

VE_i= water deficit

VD_i= water demand during the deficit period

The value of average deficit per failure generally lies between 0 and 1. Its value increases with the increase in water deficit.

3.4.3.2.3. Lake Mead levels

The water levels in Lake Mead were also computed for all the GCMs and emission scenarios for the future simulation.

3.5. Results

3.5.1. Validation

The model was validated for the total water demand in the LVV from 1989 to 2010. Figure 3.3 shows the comparison between the actual water demand and the simulated water demand. The drop downs seen in the actual data are due to the water conservation efforts. There were mean absolute error and average error of approximately 2% and 1.4%, respectively between the actual and the simulated water demand during the model validation period. Overall, the results indicated satisfactory model performance and model was able to replicate the trend of actual water demand within the LVV.

For the purpose of validation of the water demand, water pricing was also considered. Although water pricing started in the LVV beginning from 1991 (SNWA, personnel communication), the actual information of the increase in price in different years is not available. Also, the tier pricing system is hard to represent because of the structural complexities of the different components of water demand in the LVV. Thus, it was assumed in the model that the 40% increase in water price started in 1991. The effect of water pricing was assumed to decrease to about 85% of the original effect after four years, and 75% after another four years. Furthermore, it was assumed that there was no effect of the original price increase after 2012.

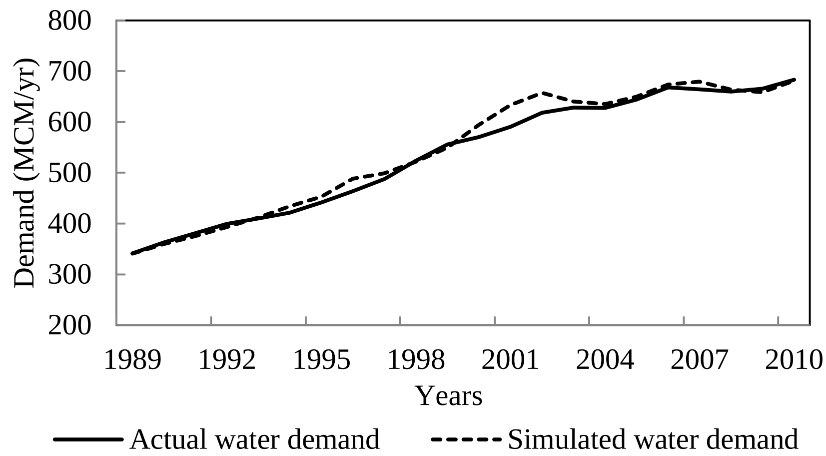

Figure 3.3. Comparison between actual and simulated water demand in the LVV (1989 to 2010)

Similarly, the model was validated for Lake Mead levels from 1970 to 1999. Figure 3.4 shows a comparison between the actual and the simulated Lake Mead levels. From Figure 3.4a, it can be observed that the simulated lake levels follow the pattern similar to the actual lake levels. During the validation period, the mean absolute error and average error of about 3.6 m and 0.28 m, respectively, were obtained between the actual and the simulated lake levels. Although 3.6 m seems higher in magnitude, considering the complex nature of reservoir operation of the CRB and since all the operational complexities of the system cannot be represented in the model, the overall performance of the reservoir operation sector of the model can be considered satisfactory. Figure 3.4b shows that the data points align themselves close to 45° bisector line, with the correlation coefficient of 0.76. Similarly, the boxplot in Figure 3.4c shows almost similar variability for the simulated and the observed Lake Mead levels.

3.5.2. Future simulation

For future simulation, the water demand and water supply were computed for two policy scenarios mentioned in the modeling approach section. The results are shown for each scenario for the individual GCM and A1b emission scenario (Figure 3.5 -3.13).

3.5.2.1. Water demand

1. Status quo scenario:

Under this scenario, water demand reached approximately 1069 MCM in 2035 (Figure 3.5), an excess of about 699 MCM per year over current Colorado River allocation. An increase in water demand by about 43% was observed between 2012 and 2035 (744 MCM in 2012 to 1069 MCM in 2035). With the population growth only 50% of the projected growth, water demand reached 916 MCM in 2035 (Figure 3.5), a reduction of about 14% from status quo population growth. Similarly, in no population growth scenario, demand reached 742 MCM in 2035 (Figure 3.5), a reduction of about 30.5% from status quo population growth.

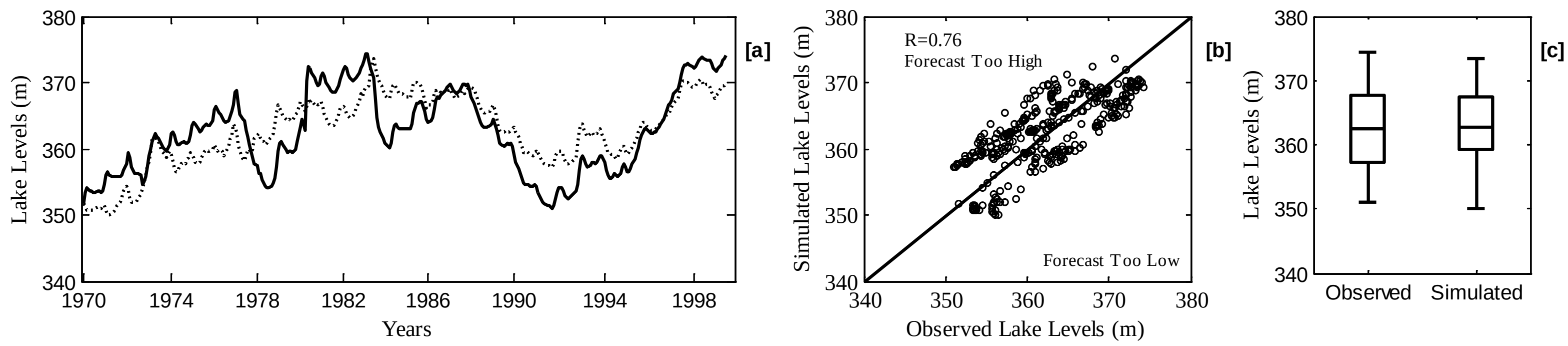

Figure 3.4. (a) Comparison between actual and simulated monthly Lake Mead levels (1970 to 1999). The solid line indicates the actual lake levels and the dotted line represents the simulated lake levels. (b) Bisector plot for monthly Lake Mead levels for the duration of 1970 to 1999. The solid line in the middle represents 45° bisector line at 1:1 slope. R represents the correlation coefficient between the observed and the simulated lake levels. (c) Boxplot of observed and simulated Lake Mead levels for the duration of 1970 to 1999. Each boxplot shows the variability in the lake levels. Whiskers at the ends represent 5^{th} and 95^{th} percentile values of the lake levels.

The per capita consumptions in status quo population growth, growth in population only 50% of the projected growth, and no growth in population were computed to be 919 lpd (243 gpd) , 971 lpd (257 gpd), and 968 lpd (256 gpd), respectively in 2035.

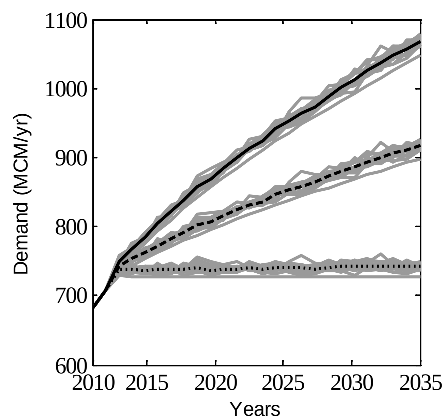

Figure 3.5. Comparison of the water demand in status quo population growth (solid line), population growth only 50% of the projected growth (dash line), and no population growth (dotted line). Grey lines indicate water demand for 16 individual GCMs and A1b emission scenario

Water demand was compared with and without considering the impacts of climate change for all 3 emission scenarios. The results of the comparison are shown in Table 3.1. A maximum increase of 3.27% in demand was observed for MIROC3.2 in B1 scenario. For A1b scenario, maximum increase in water demand was observed for UKMO-hadCM3 (about 2.99%), and for A2 scenario, BCC-CM showed the maximum increase in demand by 3%. Minimum increase in water demand was observed for PCM under all three emission scenarios. The ensemble average of all the GCMs showed an increase in demand by 1.9%.

Table 3.1. Increase in water demand (expressed as percentage) for 16 GCMs and 3 emission scenarios compared to no climate change

	BCC_CM	CGCM3.1	CNRM_CM3	CSIRO-Mk3.0	GFDL-CM2.0	GFDL-CM2.1	GISS-ER	INM-CM3.0	IPSL-CM4	MIROC3.2	ECHO-G	ECHAM5	MRI-CGCM2.3.2	CCSM3	PCM	UKMO-hadCM3	Mean	Median
A1b	1.53	1.53	2.02	1.88	2.70	2.48	1.49	2.81	2.37	2.06	2.74	1.28	1.47	2.49	0.01	2.99	1.99	2.04
A2	3.00	1.53	1.13	1.87	2.03	2.35	2.22	2.65	1.68	2.81	2.27	2.13	0.62	2.56	0.01	1.55	1.90	2.08
B1	1.92	2.77	1.31	0.35	1.08	1.39	1.62	1.68	2.35	3.27	2.51	0.89	1.28	2.21	0.01	2.25	1.68	1.65

2. Conservation policies scenario:

Figure 3.6 presents the result under this scenario for the individual GCMs and A1b scenario. Results are shown for status quo population growth only.

Under status quo population and with indoor conservation that includes both retrofitting the old appliances with water smart appliances and mandating the houses built after 2012 to be water smart, a reduction in demand by about 75 MCM was obtained in 2035. With outdoor conservation, water demand in 2035 reduced by about 167 MCM. With indoor and outdoor conservation together, water demand reduced by approximately 243 MCM in 2035 (Figure 3.6 a). Different price rise options were tested in the model varying from increasing price by 25%, 50%, 75%, and 100%. This resulted in water demand reduction by about 53, 106, 159, and 212 MCM, respectively. Water demand with the price rise by 50% is shown in Figure 3.6 b. Similarly, the combination of policies resulted in water demand reduction by about 327 MCM in 2035 (Figure 3.6c), which is about 48% of the water demand in 2010.

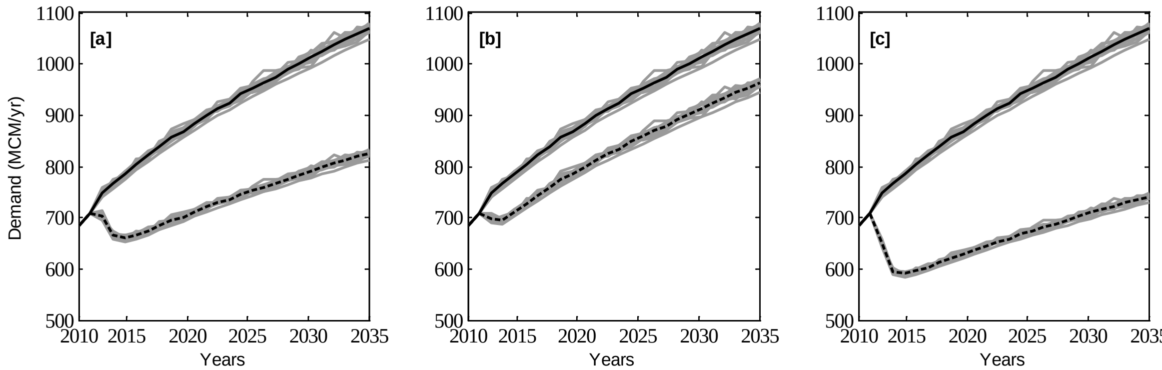

Figure 3.6. Water demand (a) with indoor and outdoor conservation, (b) with 50% price rise, (c) with the combination of policies for status quo population growth. The solid lines indicate water demand without any policies implemented, and the dotted line indicates water demand with policies implemented. Grey lines indicates the water demand for 16 individual GCMs and A1b emission scenario

With growth in population only 50% of projected growth and with no growth in population, three policies were tested (i) Indoor and outdoor conservation, (ii) Price rise and (iii) Combination of policies. The results are summarized in Table 3.2. It indicates the results of median of the ensemble of GCMs for A1b scenario. The reduction in demand obtained with each policy was compared the water demand in status quo scenario in 2035 which was obtained to be 1069 MCM. Different price rise options were tested, starting from 25% to 100%. With the combination of policies demand reduced by about 408 MCM and 511 MCM in population growth only 50% of the projected growth and in no population growth, respectively.

Table 3.2. Summary of annual water demand and reduction in water demand in 2035 with different policies implemented under different population growth rates. Water demand in status quo scenario is 1069 MCM in year 2035. Average of the ensemble of all the GCMs for A1b emission scenario are reported

Description	Demand (MCM)	Demand reduction (MCM)	% demand reduction
Status quo population growth			
Indoor only	994	75	7.0
Outdoor only	902	167	15.6
Indoor and Outdoor	826	243	22.7
Price rise (25%)	1016	53	5.0
Price rise (50%)	963	106	9.9
Price rise (75%)	910	159	14.9
Price rise (100%)	857	212	19.8
Combination scenario	742	327	30.6
Growth in population only 50% of the projected growth			
Indoor and Outdoor	736	333	31.2
Price rise (50%)	829	240	22.5
Combination scenario	660	408	38.2
No population growth			
Indoor and Outdoor	625	444	41.6
Price rise (50%)	673	396	37.1
Combination scenario	558	511	47.8

3.5.2.2. Water supply

Water supply to the LVV from the Colorado River was computed for different GCMs and A1b scenario and was compared with demand request sent to the Colorado River. This helps in computing the water deficit/surplus for each policy. Thus, deficit refers to the condition when the maximum available supply from the Colorado River is not able to meet the demand request sent to the Colorado River.

1. Status quo scenario:

Figure 3.7 presents the result for this scenario. With status quo population growth and no conservation and pricing policies, the model forecasted that the demand exceeds the supply in near future i.e. in 2013 (Figure 3.7 a) with ensemble average deficit of about 200 MCM in 2035.

With growth in population only 50% of the projected growth, the demand exceeds the supply in 2013 (Figure 3.7 b), with ensemble average deficit of about 112 MCM in 2035. Similarly, with no growth in population, demand was never observed to exceed supply till 2035, for majority of the GCMs. However, for some of the GCMs, demand was observed to exceed supply in year 2028 with approximately 3 MCM deficit in year 2035(Figure 3.7 c). This is because, with climate change water demand increases and water supply decreases.

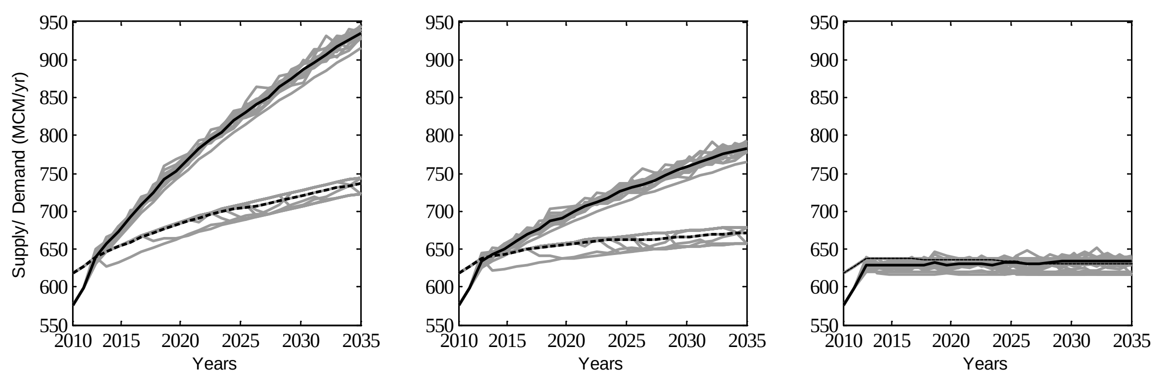

Figure 3.7. Water demand and supply from the Colorado River without policy implemented under (a) status quo population growth, (b) population growth only 50% of projected growth, and (c) no population growth. The solid line represents the water demand and the dotted line represents the water supply. Grey lines indicate the water demand and supply for 16 individual GCMs and A1b emission scenario.

2. Conservation policies scenario:

With status quo population growth and with indoor conservation, it was observed that demand exceeds the available supply in 2014. The water deficit of about 180 MCM was computed in 2035. With outdoor conservation, water demand was forecasted to exceed the available supply in 2028. In this case, the water deficit of about 36 MCM was obtained in 2035. With both indoor and outdoor conservation, the demand was seen to exceed the available supply in year 2029 (Figure 3.8a), with ensemble average deficit of about 25 MCM in 2035. With 50% price rise, the demand was observed to exceed the available supply in 2016 (Figure 3.8b), with deficit of about 143 MCM in 2035. With the combination of the policies, the demand was never observed to exceed the available supply (Figure 3.8c), with water surplus of about 10 MCM in 2035.

With growth in population only 50% of projected growth and indoor and outdoor conservation, the demand was never observed to exceed the available supply till 2035 (Figure 3.8d). The water surplus of about 20 MCM was computed in 2035. Under the same population growth and price rise by about 50%, the demand was observed to exceed the available supply in year 2020 (Figure 3.8e). The water deficit of about 66 MCM was computed in 2035 in this case. With the combination of the policies, it was observed that the demand never exceeds the available supply till year 2035 (Figure 3.8f). The ensemble average water surplus in 2035 was computed to be about 53 MCM under this scenario.

Similarly, with no growth in population and with indoor and outdoor conservation, water demand was never observed to exceed the available supply till 2035 (Figure 3.8g). The water surplus of about 87 MCM was observed in 2035 under this scenario. Under the same population projection and price rise by about 50%, demand was never observed to exceed the available supply (Figure 3.8h), with water surplus of about 34 MCM in year 2035. Similarly, with the combination of policies, demand never exceeded the available supply till 2035 (Figure 3.8i). The water surplus was computed to be about 117 MCM in 2035.

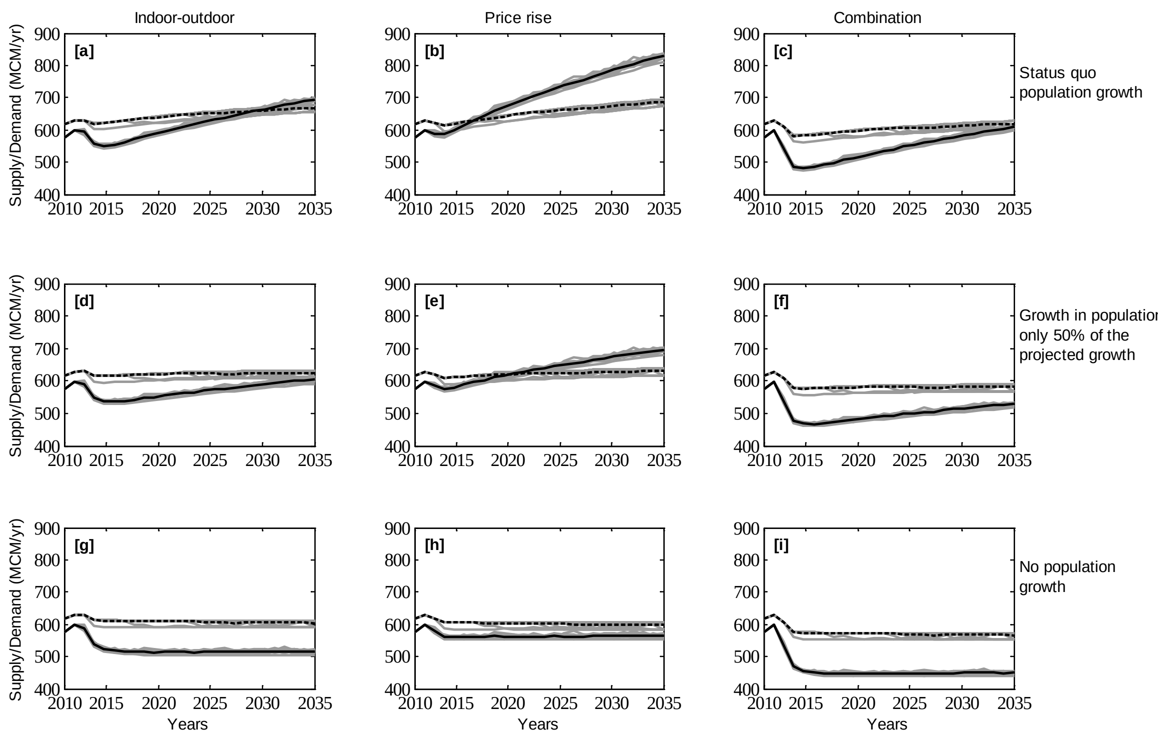

Figure 3.8. Water demand and supply from the Colorado River for different policies (shown on the top) and population growth conditions (shown on the right side). The black solid line represents the water demand request send to the Colorado River and the black dotted line represents the water supply from the Colorado River. Grey lines indicate the water demand and supply for 16 individual GCMs and A1b emission scenario

Table 3.3 summarizes the water deficit/surplus under different GCMs and emission scenarios with and without conservation policies scenarios for different population growths. The numbers are expressed as the percentage of the corresponding demand. Table 3.3 shows that with the combination of polices adopted for the conservation of water, water demand never exceeds the water supply in all three population growth conditions. However, for status quo population growth and combination of policies, there are some of the GCMs, where supply from the Colorado River is not able to meet the requested demand.

Table 3.3. Summary of water deficit/surplus from the Colorado River (expressed as percentage of water demand) for 16 GCMs and emission scenarios in year 2035 with and without conservation policies for different population growth rates. Grey color and minus sign indicate water deficit. Numbers without minus sign indicate water surplus

	BCC-CMI	CGCM3.1	CNRM_CM3	CSIRO-Mk3.0	GFDL-CM2.0	GFDL-CM2.1	GISS-ER	INM-CM3.0	IPSL-CM4	MIROC3.2	ECHO-G	ECHAM5	MRI-CGCM2.3.2	CCSM3	PCM	UKMO-hadCM3	Mean	Median
	Status quo scenario																	
A1b	-20.1	-20.1	-22.8	-20.4	-21.1	-23.3	-22.3	-21.2	-20.8	-20.6	-23.4	-19.8	-20.0	-23.2	-18.7	-23.6	-21.3	-20.9
A2	-22.4	-20.1	-20.1	-20.5	-20.4	-22.4	-20.9	-20.0	-21.2	-23.0	-20.5	-23.4	-19.8	-22.4	-20.9	-18.7	-21.0	-20.7
B1	-23.0	-20.1	-20.1	-20.5	-20.4	-23.2	-20.9	-20.0	-21.2	-23.1	-20.5	-21.1	-19.8	-20.0	-20.9	-18.7	-20.8	-20.5
	Status quo population growth (indoor and outdoor conservation)																	
A1b	-1.9	-1.9	-5.5	-2.3	-3.0	-5.9	-5.0	-3.1	-2.7	-2.5	-6.2	-1.7	-1.9	-5.9	-0.5	-6.4	-3.5	-2.9
A2	-5.1	-1.9	-2.4	-2.3	-3.0	-4.6	-1.9	-3.1	-2.7	-5.4	-3.1	-4.8	-1.9	-5.9	-0.5	-3.3	-3.3	-3.1
B1	-5.6	-1.9	-1.9	-2.4	-2.3	-5.9	-2.8	-1.9	-3.1	-5.8	-2.5	-3.1	-1.7	-1.9	-2.8	-0.5	-2.9	-2.4
	Status quo population growth (price rise by 50%)																	
A1b	-15.9	-15.9	-18.9	-16.2	-17.0	-19.3	-18.4	-17.1	-16.7	-16.4	-19.6	-15.6	-15.8	-19.3	-14.4	-19.8	-17.3	-16.8
A2	-18.5	-15.9	-16.3	-16.2	-17.0	-18.2	-15.8	-17.1	-16.7	-18.8	-17.0	-18.3	-15.8	-19.3	-14.4	-17.2	-17.0	-17.0
B1	-17.8	-15.9	-16.3	-16.2	-17.0	-19.1	-15.8	-17.1	-16.7	-19.0	-17.0	-15.6	-15.8	-16.8	-14.4	-17.2	-16.7	-16.7
	Status quo population growth (combination scenario)																	
A1b	3.5	3.5	-0.5	3.1	2.3	-1.0	0.0	2.2	2.7	3.0	-1.2	3.8	3.6	-1.0	5.1	-1.5	1.7	2.5
A2	-1.5	3.5	3.5	3.0	3.1	0.3	2.5	3.5	2.2	-0.7	3.0	-1.2	3.8	0.0	2.5	5.1	2.0	2.7
B1	0.9	3.5	3.0	3.1	2.3	-0.7	3.5	2.2	2.7	-0.6	2.3	3.8	3.6	2.5	5.1	2.0	2.5	2.6
	Growth in population only 50% of the projected growth (combination scenario)																	
A1b	12.0	12.0	7.4	11.6	10.6	6.9	8.1	10.5	11.0	11.4	6.6	12.4	12.1	6.9	13.9	6.3	10.0	10.8
A2	8.0	12.0	11.5	11.6	10.6	9.1	12.1	10.5	11.0	7.6	10.6	8.3	12.1	6.9	13.9	10.3	10.4	10.6
B1	7.3	12.0	12.0	11.5	11.6	6.9	10.9	12.1	10.5	7.0	11.4	10.6	12.4	12.1	10.9	13.9	10.8	11.4
	No population growth (combination scenario)																	
A1b	28.4	28.4	23.0	27.9	26.8	22.3	23.7	26.7	27.3	27.7	22.0	28.8	28.5	22.4	30.5	21.7	26.0	27.0
A2	23.6	28.4	27.7	27.9	26.8	27.1	28.5	26.7	27.3	23.5	26.8	23.9	28.5	22.4	30.5	26.4	26.6	27.0
B1	22.9	28.4	28.4	27.7	27.9	22.5	27.1	28.5	26.7	22.5	27.7	26.8	28.8	28.5	27.1	30.5	27.0	27.7

3.5.2.3. Risk Analysis

Table 3.4 shows the risk analysis of water supply system based on reliability, average duration of failure, and deficit per failure. For no population growth and no policies adopted for water conservation in no climate change, reliability was computed to be 1. A reliability of 1 indicates that for whole future simulation period, water demand of the LVV can be met from the Colorado River. However, for the same population growth, no policies adopted for further conservation, and for climate change, reliability decreases to an ensemble average value of 0.61. This can be attributed to the increase in water demand and decrease in water supply due to climate change.

Table 3.4. Risk analysis of water supply from the Colorado River for no climate change and for 16 GCMs (A1b emission scenario) for the duration of 2012 to 2035 with and without conservation policies for status quo population growth, growth in population only 50% of the projected growth, and no population growth

Indices	No climate change	BCC-CMI	CGCM3.1	CNRM_CM3	CSIRO-Mk3.0	GFDL-CM2.0	GFDL-CM2.1	GISS-ER	INM-CM3.0	IPSL-CM4	MIROC3.2	ECHO-G	ECHAM5	MRI-CGCM2.3.2	CCSM3	PCM	UKMO-hadCM3	Mean	Median
	Status quo scenario																		
Reliability	5.9	4.2	3.5	3.8	3.5	4.5	3.1	4.5	2.8	3.1	2.1	3.1	4.5	4.9	3.8	6.3	3.5	3.8	3.6
Avg failure duration	67.8	46.0	55.6	69.3	34.8	68.8	69.8	55.0	56.0	55.8	94.0	55.8	68.8	54.8	46.2	67.5	69.5	60.5	55.9
No. of failures	4.0	6.0	5.0	4.0	8.0	4.0	4.0	5.0	5.0	5.0	3.0	5.0	4.0	5.0	6.0	4.0	4.0	4.8	5.0
Avg deficit per failure	11.8	13.0	13.5	14.1	12.8	13.5	15.7	14.2	13.9	13.5	15.7	14.5	13.3	12.9	14.9	11.9	15.4	13.9	13.7
	Growth in population only 50% of the projected growth (no policies)																		
Reliability	12.2	9.4	7.6	9.7	7.3	8.7	6.6	7.6	5.9	7.6	3.5	6.9	9.0	8.3	7.6	12.5	6.3	7.8	7.6
Avg failure duration	28.1	37.3	38.0	28.9	26.7	32.9	44.8	29.6	33.9	26.6	69.5	29.8	32.8	29.3	33.3	36.0	38.6	35.5	33.1
No. of failures	9.0	7.0	7.0	9.0	10.0	8.0	6.0	9.0	8.0	10.0	4.0	9.0	8.0	9.0	8.0	7.0	7.0	7.9	8.0
Avg deficit per failure	6.6	7.9	8.4	9.3	7.6	8.4	10.9	9.1	8.8	8.5	10.7	9.5	8.1	7.6	10.0	6.7	10.4	8.9	8.6
	No population growth (no policies)																		
Reliability	100.0	77.8	64.6	57.6	76.0	71.2	29.9	55.6	62.2	65.6	26.0	50.3	74.7	79.9	45.8	99.3	34.4	60.7	63.4
Avg failure duration	0.0	1.9	2.1	2.9	1.7	2.3	6.1	3.2	2.0	1.9	6.0	3.7	1.8	2.1	3.5	1.3	4.8	3.0	2.2
No. of failures	0.0	33.5	47.5	42.0	40.5	36.5	33.0	40.0	55.0	51.0	35.5	38.5	39.5	28.0	44.0	1.5	39.0	37.8	39.3
Avg deficit per failure	0.0	2.3	2.2	2.6	1.6	2.0	3.3	2.7	2.3	2.1	3.3	3.0	1.8	1.9	3.1	0.3	3.2	2.4	2.3
	Status quo population growth (combination scenario)																		
Reliability	100.0	98.6	97.6	95.5	98.3	98.3	88.2	90.3	96.9	97.2	92.7	89.9	99.7	99.7	89.6	100.0	87.5	95.0	97.0
Avg failure duration	0.0	1.1	1.6	3.3	0.9	1.1	2.3	2.5	1.3	1.2	1.4	2.5	0.7	0.0	2.3	0.0	3.3	1.6	1.4
No. of failures	0.0	4.0	7.0	13.0	5.0	5.0	34.0	28.0	9.0	8.0	21.0	29.0	1.0	1.0	30.0	0.0	36.0	14.4	8.5
Avg deficit per failure	0.0	2.1	1.8	1.7	1.1	0.7	2.2	1.5	1.0	1.1	1.6	2.4	0.1	1.1	2.2	0.0	2.3	1.4	1.5
	Growth in population only 50% of the projected growth (combination scenario)																		
Reliability	100.0	99.7	99.7	100.0	100.0	100.0	100.0	100.0	99.3	100.0	99.7	99.7	100.0	100.0	99.7	100.0	98.6	99.8	100.0
Avg failure duration	0.0	0.7	0.7	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.7	0.7	0.0	0.0	0.7	0.0	1.1	0.4	0.0
No. of failures	0.0	1.5	1.5	0.0	0.0	0.0	0.0	0.0	1.5	0.0	1.5	1.5	0.0	0.0	1.5	0.0	3.5	0.8	0.0
Avg deficit per failure	0.0	0.1	1.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	1.5	1.0	0.0	0.0	0.0	0.0	1.7	0.4	0.0
	No population growth (combination scenario)																		
Reliability	100.0	100.0	99.7	100.0	100.0	100.0	100.0	100.0	99.3	100.0	99.7	99.7	100.0	100.0	100.0	100.0	99.3	0.0	0.0
Avg failure duration	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
No. of failures	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	0.3	0.0
Avg deficit per failure	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.8	0.0	0.0	0.0	0.0	0.0	0.2	0.0

3.5.2.4. Lake Mead Levels

Table 3.5 compares the probability of lake levels to draw down to 305 meters under different GCMs and emission scenarios without policies implementation for future simulation. A high variability was observed among different GCMs regarding the probability of Lake Mead levels to drop down below 305 m. For example, CCSM3 under A2 scenario showed a probability of about 65% of Lake Mead falling below 305 m for about 187 months till 2035. Whereas, under B1 scenario for MIROC3.2, a probability of 23 % for lake levels to drawn down to 305 m for about 66 months was observed. On the contrary, all three emission scenarios for GCMs such as PCM, CGCM3.1, INM-CM3.0 showed no probability of Lake Mead levels to fall below 305 m till 2035. The average of the ensemble of the GCMs under A1b, A2 and B1 emission scenarios concluded about 9%, 5% and 2% probabilities of lake levels to draw down to 305 m. The median of the ensemble average of the GCMs under all three scenarios showed no probabilities of Lake Mead levels to draw down below 305 m for the future.

Table 3.5. Probability (expressed as percentages) of Lake Mead levels to drop down below 305 m (1000 ft) for 16 GCMs and 3 emission scenarios for the duration of 2012 to 2035

	BCC-CMI	CGCM3.1	CNRM_CM3	CSIRO-Mk3.0	GFDL-CM2.0	GFDL-CM2.1	GISS-ER	INM-CM3.0	IPSL-CM4	MIROC3.2	ECHO-G	ECHAM5	MRI-CGCM2.3.2	CCSM3	PCM	UKMO-hadCM3	Mean	Median
A1b	0	0	0	0	0	46	5	0	0	17	19	0	0	15	0	42	9	0
A2	3	0	0	0	0	0	0	0	0	1	0	5	0	65	0	0	5	0
B1	4	0	0	0	0	11	0	0	0	23	0	0	0	0	0	0	2	0

The results shown in Table 3.5 are also observed in Figure 3.9. Figure 3.9 depicts the cumulative distribution function (CDF) of Lake Mead levels for the entire future simulation period under different climate models for A1b, A2 and B1 scenarios. It helps to visualize the variation in the probability of different lake levels observed for individual

GCMs. For A1b scenario, MRI-CGCM2.3.2, PCM, IPSL-CM4, INM-CM3.0, CGCM3.1 showed very little to no probabilities of lake level falling below 305 m (Figure 3.9). On the contrary, GFDL-CM2.1, showed a 46% probability of lake level falling down below 305 m. Thus, a considerable variability was observed among the GCMs regarding the probability of Lake Mead levels drawing down to or below 305 m.

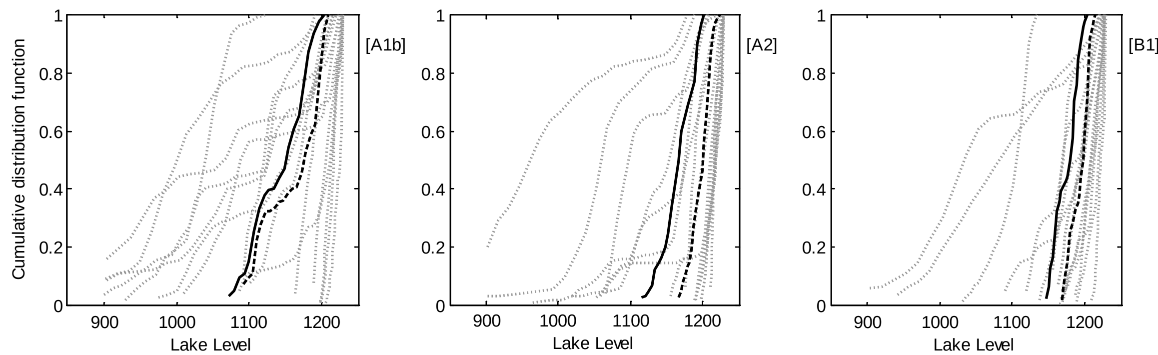

Figure 3.9. Cumulative distribution function (CDF) of Lake Mead levels for 16 GCMs and 3 emission scenarios for the duration of 2012 to 2035. The lighter dotted lines indicate the CDF of lake levels for the individual GCM. The black solid line and the black dash line represent the mean and the median CDF of the lake levels for the ensemble of the GCMs, respectively

3.6. Discussion and Conclusion

This study used a system dynamics model to capture the effects of the interaction among changing climatic conditions, increasing population growth, and policies adopted for water conservation in the LVV to influence the future water demand and water supply until 2035. The reduction in water demand was analyzed using water conservation and water pricing policies. Conservation policies that were tested included retrofitting conventional appliances with water smart appliances, building new homes as water smart, converting turf landscape into water smart landscapes, and covering swimming pools in the residential homes. The water demand and water supply were compared under all the policies and with different population growth conditions. Similarly, risk analysis was conducted of the water supply from the Colorado River to the LVV. In addition, Lake Mead levels and the chances and duration of supply curtailments to the LVV were analyzed.

The results of this study suggest the importance of demand management to achieve the long term sustainability of water in the LVV. Indoor conservation has a relatively minor impact, since the water deficit experienced in 2035 only reduced by about 20 MCM. This is because in case of the LVV, credit is obtained when more water is used indoors. Since indoor conservation reduces return flow credit, the supply reduces accordingly. However, it should be noted that return flow credit requires pumping water from Lake Mead, which results in more energy use that has an associated carbon foot print. The decision to reuse water or pump more water from Lake Mead as return flow credit should be based upon both an economic and an environmental assessment.

Outdoor conservation was more effective in conserving water compared to indoor conservation. Outdoor conservation bought 14 more years of sustainable water supply in the future compared to a scenario without any conservation. This result is in agreement with the study by Stave (2003), which concluded that outdoor conservation is more effective than indoor conservation. Additionally, compared to indoor conservation, outdoor conservation has no impact on reducing the return flow credit, which is one of the important sources of water supply to the LVV.

The combination of indoor and outdoor conservation was helpful to ensure that the current available water supply lasts until 2030. Thus, the combination of indoor and outdoor conservation provided 17 more years of sustainable water supply compared to a scenario without any conservation.

A price rise up to 50% helped to reduce the deficit to about 143 MCM in 2035 and the water demand exceeded the supply in 2016, provided the population grows as predicted. Price rise is also one of the efficient options in conserving water; however, the range of price rise makes a huge difference in determining the best policy option.

The combination of conservation and pricing policies helps to provide a sustainable water supply until the study time frame and to delay the impending water crisis in the LVV. Thus, results suggest a strong need to implement the actions using combined policies. Although, with a combination of policies adopted for water conservation, water demand can be met till 2035, but the water surplus obtained with such policies is not very significant. Thus, only demand management policies tested in the study may not be enough to obtain the water sustainability in long run.

The effect of slowing the population growth in reducing the water deficit in 2035 is evident from the results of this study, as a reduction in the water deficit in year 2035 was obtained with slower population growth rate. Although, the assumption that the population will remain constant may not be realistic in case of the LVV, which has been growing at an average rate of about 4.4% per year for the last 10 years (2000 to 2010). In spite of this, running the model for no growth and increase in population only 50% of the projected growth helps to understand the role of population growth rate on water demand.

Water demand in the LVV due to the changing climatic conditions was observed to be very insignificant, compared to water demand due to population growth. The results of the current study were based only upon an increase in temperature. Because of the very low annual rainfall in the LVV, the effect of change in precipitation to reduce the outdoor water demand was assumed to be very insignificant. Also, previous studies have shown that residential water demand increases with increasing temperatures (Brandes and Kriwoken 2006). However, there has not been any previous study done in the LVV that looked at climate change impacts upon the outdoor water demand; therefore our results cannot be compared with other studies. However, it should be noted that the same results may not be equally significant in other arid regions where outdoor use accounts for a larger fraction of the total water use.

The use of 1/8° latitude-longitude GCM predicted temperature data was used for the climate impact studies on water demand, which used the statistical method of downscaling. However, a study by Chen et al., (2011) showed that different downscaling methods showed different results for the climate impact studies using global climate model outputs. Thus, the use of GCM dataset using a different downscaling method may produce result different than our current study.

The value of reliability increased with a decrease in population growth rate, and with the adoption of polices for water conservation. The reliability of meeting water demand from the Colorado River was observed to be very low, about 0.06, for status quo population growth and about 0.12 for growth in population only 50% of the projected growth; both scenarios with no policies implemented. However, if no population growth and no climate changes are considered, the Colorado River is able to meet the demand of LVV for the entire duration in the future. The effect of climate change, however, decreased the reliability of water supply, even in no population growth. This is because there is an increase in water demand and at the same time, there is a decrease in water supply as a result of climate change.

The water levels in Lake Mead, as estimated from the ensemble average of the GCMs under A1b scenario, showed a 9% probability of drawing down below 305 m for nearly 26 months till 2035. The implementation of policies to conserve water in the LVV does not make much difference in maintaining Lake Mead levels above 305 m. This is because the current allocation of Nevada, compared to other Lower Basin states, is very small (4% for NV compared to 37.3% for AZ and 58.6 % for CA). A broad study that includes conservation in the other Lower Basin states is needed to draw a further conclusion.

For the ease of comparison with the study done by Barnett and Pierce (2008), we evaluated the risk of lake level going down below 305 m by 2021 for all the GCMs. Although, the ensemble average of all the GCMs showed almost no probability of Lake Mead levels going down by 2021, MIROC3.2 was selected as it showed the highest probability of about 21% for Lake Mead levels drawing down below 305 m by 2021. The study by Barnett and Pierce (2008) concluded that there is 50% chance that both Lake Powell and Lake Mead may deplete by year 2021. However, the results from Barnett and Pierce (2008) were for the combined storage of Lake Mead and Lake Powell. Compared to Barnett and Pierce (2008), our study indicates a lower likelihood of Lake Mead falling below 305 m (1000 ft).

The previous studies focused on evaluating the water demand based on the population growth and water conservation policies (Stave 2003; Tidwell 2004; Ahmad and Prashar 2010; Qaiser et al. 2011; Shrestha et al. 2011). Those studies, however, did not model the effect of climate change on the water demand and supply. The current study explicitly modeled the effect of climate change on water demand and water supply by using 16 GCMs and 3 emission scenarios. Thus, compared to previous efforts to model the water sustainability in a region, the current study has made an improvement towards relating the climate change to the water demand and supply.

It should be noted that this study considered only the effect of change in temperature as a major contributor to change the water demand. The change in water demand as a result of change in precipitation was not accounted for in the study. It should also be noted that the study used the increase in outdoor water demand with the increase in temperature from the study done in United Kingdom because of the absence of regional data. Similarly, the Colorado reservoir operations were simplified to a larger extent. The water demand sector is largely data intensive. To incorporate the houses being retrofitted with the water smart appliances in the recent years, water demands by the end uses for houses built prior and after 1994 were averaged. Due to the limitation of the data for the end uses in the residential houses in the LVV, national data was used. The actual values may vary for the LVV.

Some of the assumptions in the study include (i) the supply of groundwater remains constant in future, (ii) no further supply augmentation measures are considered, and (iii) number of person per household remains constant at 2.56.

The major contributions of this study are to analyze (i) the effect of population growth in increasing the water demand of the LVV, (ii) the effect of an increase in temperature due to the changing climatic conditions on the water demand (iii) the effect of changes in temperature and precipitation as a result of changing climatic condition on the water supply, (iv) the potential of various water management policies in making water resources sustainable, (v) the risk evaluation of water supply system in the LVV (vi) the effect of climate change on the water levels in Lake Mead, and (vii) the probability and duration of years of unsustainable water supply in the LVV as a result of decrease in Lake Mead levels.

The effect of climate change on the water demand and water supply is of foremost importance to water managers. In addition, the possible responses to water shortages caused by the changing climate and increasing population also are of primary concern to water managers. Thus, the model was developed as a part of long term effort to engage water managers and policy makers on the broad choices of policies that can be used to influence water use behavior. Significant changes in the water use pattern and the life style of the residents may be required in the future. Changing water use pattern can be encouraged by providing incentives for lower residential water use.

Though the study focused on the LVV, the findings are applicable to other arid regions as well. Demand management policies used in the study can be applied to other regions to obtain the long term sustainability of water resources.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

The study explored the effect of climate change on streamflow in the Colorado River and its impact on the water resources management in the Las Vegas Valley (LVV) with the use of system dynamics approach. The study also explored the effect of changing climatic conditions on the water supply and water demand in the LVV. In addition, the study explored the effect of population growth on the water demand in the LVV. Demand management was modeled as the primary method of conserving the available water in response to population growth and climate change. Different model sectors were built within system dynamics framework that includes hydrologic water balance model sector, water demand sector, water supply sector, and Colorado River reservoir operation sector. The hydrologic water balance model sector was calibrated and validated for streamflow at Lees Ferry for the duration of 1970 to 1990 and 1991 to 1999, respectively. Similarly, water demand sector was validated for total water demand in the LVV for the duration of 1989 to 2010. Colorado River reservoirs operation sector was validated for Lake Mead levels for duration of 1970 to 1999. Future simulations were run for the duration of 2012 to 2035.

Two major tasks were performed in this study. The objective of Task# 1 was to determine the effect of climate change on the magnitude of streamflow in the Colorado River basin and its implications on the water supply to the Lower Basin states. For this objective, it was hypothesized that the changing climatic conditions affect the magnitude of streamflow in the CRB; this may decrease the water supply to the Lower Basin states. The major conclusions that can be drawn from Task# 1 are summarized as follows:

- Almost all the GCMs predicted an average increase in temperature in the CRB by 2035. Ensemble average of the GCMs showed an increase in CRB temperature by about 0.84°C. A maximum increase in CRB temperature (about 1.57ºC) was predicted by CCSM3 for A2 scenario. Decrease in future temperature by about 0.08ºC and 0.68ºC were predicted by ECHAM5 (for A1b scenario) and ECHO-G (for A2 scenario), respectively.
- A maximum increase in the magnitude of future precipitation (by about 12%) was predicted by PCM (for A2 scenario). While, a maximum decrease in the magnitude of future precipitation (by about 12.4%) was predicted by GFDL-CM2.1 (for A1b scenario). However, almost no change in the magnitude of precipitation was observed across the ensemble of GCMs and emission scenarios.
- Majorities of the GCMs showed a reduction in streamflow in the Colorado River by 2035. A maximum reduction in streamflow (by about 21.01%) was estimated for UKMO-hadCM3 (A1b scenario). This can be attributed to the decrease in precipitation by about 9.34% and increase in temperature by about 1.18°C, predicted by UKMO-hadCM3. PCM showed a maximum increase in the future streamflow (about 21.57%) under A2 scenarios resulting from an increase in future precipitation by about 12.66% The changes in the magnitude of streamflow varied significantly across the individual GCM. Ensemble average of the GCMs showed an average reduction in streamflow in the Colorado River by about 3% by 2035. Increase in temperature alone has a potential to reduce the streamflow, as observed in case of

IPSL-CM4 (A2 scenario). The reduction in streamflow by 1.84% for IPSL-CM4 (A2 scenario) can only be attributed to the increase in temperature by 1.17°C, as almost no change in the magnitude of precipitation was observed for this GCM.

Reduction in streamflow in the CRB resulted in decreasing water levels in Lake Mead. Approximately 14% chance of Lake Mead levels dropping down below 327.7 m (1075 ft) was observed from the ensemble average of the GCMs. An average probability of 4% for Lake Mead levels to draw down below 312 m was obtained, if Lake Mead is operated with option 1(in option 1, a gradual increase in the supply curtailments to Nevada (NV) and Arizona (AZ) was considered as Lake Mead drops down below 312 m; curtailments to California (CA) and Mexico were considered similar to the curtailment of AZ). If lake was operated with Option 2, an ensemble average probability of about 6% for Lake Mead to draw down below 312 m was observed. In option 2, a constant percentage of curtailment (6.66% for NV, and 17.14% for AZ, CA, and Mexico) was imposed. Probability of Lake Mead levels to drop down below 312 m was observed higher in Option 2 than in Option 1, because supply curtailment in option 1 is higher than in Option 2 for same water level.

If supply to the basin states was continued even if Lake Mead was drawn down to 305 m, an average and median probability of about 5% and 0% for lake levels to draw down below 305 m were obtained for the ensemble of all the GCMs and emission scenarios. However, varying probabilities were observed among individual GCM ranging from 0 to 65%.

- A 30% reduction in the water supply to the Lower Basin states resulted in 0% probability of Lake Mead levels to drop down below 305 m under all GCMs.

- With the reduction in future streamflow below 85% of the historical average, Lake Mead levels were observed to be below 327.7 m (1075 ft) for the entire duration of future simulations. With the adoption of reservoir operation Option 1, the probability of Lake Mead levels to drop down below 312 m (1025 ft) was observed to be 38%, if future streamflow is 85% of the historical average.
- Ensemble average reliability of approximately 0.86 was obtained in both the options of reservoir operation. Ensemble average water deficit per failure was higher in reservoir operation option 1 than in Option 2. This is because relatively more supply curtailment is experienced in Option 1 than in Option 2 for same water level in Lake Mead. A reliability of 1 was obtained for majority of the GCMs in A1b emission scenario that included BCC-CMI, CGCM3.1, CSIRO-Mk3.0, GFDL-CM2.1, INM-CM3.0, ECHAM5, IPSL-CM4, MRI-CGCM3.2, and PCM.

The results from Task# 1 confirmed the hypothesis that the changing climatic conditions affect the magnitude of streamflow in the CRB, as the ensemble average of all the GCMs and emission scenarios showed a reduction in streamflow by 3% till 2035. The results further confirmed the hypothesis that the reduction in streamflow may reduce the supply to the Lower Basin states, as an ensemble average probability of Lake Mead levels to drop below 327.7 m (1075 ft) was about 14% till 2035.

The objective of Task# 2 was to determine the effects of changing climatic conditions and increasing population growth on the water demand and supply in the LVV. It also focused on investigating the potential of different water management options in conserving water in the LVV. To accomplish this objective, it was hypothesized that the changing climatic conditions and increasing population growth increase the water demand in the LVV. At the same time, climate change may reduce the supply of water from the Colorado River. It was also hypothesized that the demand management policies have a potential to conserve water and help in providing sustainable water supply in the LVV for a longer duration of time.

The results from Task# 2 showed that the increase in population increased the water demand in the LVV by about 43 % between 2012 to 2035. Under status quo population growth and no further policies adopted for water conservation, water demand in the LVV in 2035 was computed to be about 1069 MCM under A1b emission scenario. With the increase in population only 50 % of the projected increase, water demand was computed to be 916 MCM. With no growth in population, the water demand was 742 MCM in 2035.

The reduction in demand obtained with different demand management policies were computed and compared with the water demand in status quo scenario, which is 1069 MCM. The results are summarized as follows:

- Indoor conservation reduced water demand by about 7%.
- Outdoor conservation reduced water demand by about 15.6%
- Indoor and outdoor conservation reduced water demand by about 22.6%.
- Price rise by 50% reduced water demand 9.9%.
- Combination of policies includes indoor, outdoor conservation, price rise by 50% and conservation in hotels and casinos. With the combination of polices, demand reduced by about 30.6%.

▪ Increase in temperature caused by the changing climatic conditions increased the water demand by approximately 1.9 % (averaged over the ensemble of GCMs and emission scenarios). The effect of climate change did not increase the water demand by a significant amount; this is because of the reduced outdoor demand.

- Water demand from the Colorado River and maximum water supply that can be obtained from the Colorado River were computed for different scenarios of population growth, and policies implemented for water conservation under changing climatic conditions. The results are briefly summarized as follows:
    - With status quo population growth and no policies adopted for water conservation, water supply from the Colorado River was not observed to meet the water demand in the LVV beyond year 2013. The deficit in 2035 was computed to be 200 MCM.
    - With growth in population only 50% of the projected growth, the demand was observed to exceed the supply in 2013, with ensemble average deficit of about 112 MCM in 2035. Similarly, with no growth in population, demand was never observed to exceed supply till 2035, for majority of the GCMs. However, for some of the GCMs, demand was observed to exceed supply in year 2028 with a deficit of approximately 3 MCM in year 2035. This is because, with climate change water demand increases and water supply decreases.
    - With policies adopted for water conservation, supply from the Colorado River was observed to fulfill the water demand in the LVV some more years into future. With status quo population growth and indoor-outdoor conservation, demand was seen to exceed the available supply in year 2029, with ensemble average deficit of about 25 MCM in 2035. With 50% price rise, the demand was observed to exceed the available supply in 2016, with deficit of about 143 MCM in 2035. With the

combination of the policies, demand was never observed to exceed the available supply, and water surplus of about 10 MCM was computed in 2035.

Thus, demand management of water was observed to be very important to obtain the long term sustainability of water resources in the LVV given population growth and climate change. A combination of conservation and pricing is essential for providing sustainable water supply in future.

The results from Task# 2 confirmed the hypothesis that the changing climatic conditions and the increasing population growth increase the water demand in the LVV. The results further strengthened the hypothesis that the demand management policies help in conserving water and providing sustainable water supply in the LVV.

4.2. Recommendations

Based on the results of the study, some of the major recommendations include:

- The combination of conservation and pricing policy is most effective in providing sustainable water resources in the LVV. Hence, the combination of policies should be adopted while planning for future water resources in LVV.
- Different demand management policies were tested in the study that includes indoor, outdoor conservation, increasing price of water. Among these, outdoor conservation was observed most effective in conserving water among all other policies.
- The slower population growth can also reduce the water deficit in the future simulation period. Thus, if politically feasible, the water management policies should also be coupled with growth management policies in the LVV.

- With some adaptive management e.g., water banks (not considered in this study) and curtailment, it may be possible to maintain Lake Mead above 305 m for the entire future simulation period, even if there is reduction in the streamflow in the Colorado River.

4.3. Future works

Based on the research experience, recommendations for the future work include:

- The use of regional climate models (RCM) should be considered in modeling the effect of climate change on the hydrology of the Colorado River flow. Studies have shown that RCMs are able to better capture the topographical complexities in the CRB than their host GCMs (Gao et al., 2011). Similarly, the coarser resolution (2 degree latitude by longitude) global climate model datasets (precipitation and temperature) were used in the study. However, the highly variable climatic nature of the CRB is believed to be better captured by the finer resolution datasets (Hoerling and Eschied, 2007). Thus, the use of finer resolution datasets can be included in the future study. In addition, the choice of method for downscaling the coarser resolution datasets should also be so selected, that the results are consistent in majority of the selected downscaling methods. Climate change impact studies using different downscaling methods for the GCM outputs have shown different results (Chen et al., 2011).
- The Colorado River reservoir operation sector should include the detail operation of Lake Powell and Lake Mead, which may help in the deterministic analysis of the duration and magnitude of the years of supply curtailments to the Lower Basin states,

which are of primary concern to the water managers. It may also improve the result of the supply curtailments to the Lower Basin states. Curtailments to the basin states should also be based on the entitlement priority systems. In addition, the operation of CRB reservoirs should also address the hydropower production as it is one of the other most important aspects of reservoir operation besides supply to the basin states. All the operational criteria of the reservoir system mentioned in the Colorado River Simulation System cannot be modeled in the study partly because of the unavailability of the data and also because of the complex nature of the operation.

- Decrease in the streamflow in the Colorado River is associated with the increase in the salinity load in the river basin. Thus, the effect of such a reduction in streamflow to increase the salinity load in the CRB should also be incorporated in the future studies.
- The potential of demand management policy options in reducing the water demand should also be based on income elasticity of water demand in addition to price elasticity. Similarly, the use of block price rate structures can be used besides using a single marginal price rate structure.
- A detail assessment of the future projection of residential house numbers in the valley should be done using land use plans. The current study assumed that each residential house is occupied by a 2.56 residents throughout the whole duration of the study. This number may vary depending on the economic condition in the LVV.
- The potential of demand management policies in conserving water should also be explored in industrial and commercial areas, as there is a large potential of conserving water in these areas.

- The effect of climate change on the water demand in the LVV should include the effect of both the change in the magnitude of precipitation and temperature. In addition, the use of regional data for the impact of climate change on water demand should be used. Similarly, the effect of changing climatic conditions in the water demand in industries should also be investigated. The impact of climate change on the agricultural water demand, particularly in the states of Arizona and California, can also be modeled. Ecological water demand with the change in climatic conditions can also be investigated.
- A detail assessment of groundwater permits available for future withdrawal should be considered. This may help in extending the sustainable water supply farther into future.
- Although, the combination of demand management policies, used in the study was able to provide the sustainable water supply till 2035, however, the water surplus obtained in year 2035 was too small to just depend on the demand side management for meeting the increasing water demand. Thus, suitable supply augmentation measures are required to be explored.

References

ACWA & CRWUA (2005). Colorado River Basin Climate. Colorado River Water Users Association and Association for California Water Agencies.

Ahmad, S., & Simonovic, S. P. (2000). System dynamics modeling of reservoir operations for flood management. *Journal of Computing in Civil Engineering, 14*(3), 190-198.

Ahmad, S., & Prashar, D. (2010). Evaluating municipal water conservation policies using a dynamic simulation model. *Water Resources Management, 24*(13), 3371-3395.

Ahmad, S., & Simonovic, S. P. (2004). Spatial system dynamics: New approach for simulation of water resources systems. *Journal of Computing in Civil Engineering, 18*(4), 331-340.

Ahmad, S., & Simonovic, S. P. (2006). An intelligent decision support system for management of floods. *Water Resources Management, 20* (3), 391-410.

Alcamo, J, Doll, P., Kaspar, F., & Siebert S. (1997). Global change and global scenarios of water use and availability: An application of WaterGAP. *Center for Environmental Systems Research.*

Arnell, N. W. (1998). Climate Change and Water Resources in Britain. *Climatic Change, 39*(1), 83-110.

Arnell, N., & Liu, C. (2001). Hydrology and Water Resources. In Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, by McCarthy J.J., O.F. Canziani, N.A. Leary, D.J., Dokken and K.S. White (eds.). Cambridge University Press, Cambridge.

Barnett, T.P., & Pierce, D. W., (2008). When will Lake Mead go dry? *Water Resources Research, 44.*

Barnett, T. P., & Pierce, D. W. (2009). Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences of the United States of America, 106*(18), 7334-7338.

Bisgrove, R., & Hadley, P. (2002). Gardening in the Global Greenhouse: The impacts of climate change on Gardens in the United Kingdom. A technical report submitted to the Center for Horticulture and Landscape, School of Plant Sciences, The University of Reading.

Brandes, O. M., & Kriwoken, L. (2006). Changing perspectives - changing paradigms: Taking the "soft path" to water sustainability in the Okanagan Basin. *Canadian Water Resources Journal, 31*(2), 75-90.

Brandt, J. (2009). *Using Aerial Imagery to Benefit Turf Reduction Programs in the Las Vegas Valley*. WaterSmart Innovations Conference 2009. Retrieved from <http://www.watersmartinnovations.com/2009/PDFs/F-1012.pdf> on June, 2011

Brouwer, C., & Heibloem, M., (1986). *Irrigation water management: Irrigation water needs.* Retrieved from http://www.fao.org/docrep/S2022E/s2022e00.htm#Contents on June, 2010.

Buckhingham, S.E., & Whitney J.W. (2007). GIS Methodology for quantifying channel change in the Las Vegas Valley. *Journal of the American Water Resources Association 43*(4), 888-898.

Cabibi H.T., Miller, B. & Schwartz, A. (2006). *Water in the Urban Southwest: An Updated Analysis of Water Use in Albuquerque, Las Vegas Valley and Tucson*. A report by Western Resource Advocates.

Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M., & Gershunova, A. (2010). Future dryness in the southwest US and the hydrology of the early 21st century drought. Proceedings of the National Academy of Sciences of the United States of America, 107(50), 21271-21276.

CBER, Center for Business and Economic Research-University of Nevada, Las Vegas (2010). *Population Forecast through 2050*. Retrieved from <http://www.accessclarkcounty.com/depts/comprehensive_planning/demographics/Documents/FinalPopforecast.pdf> on October 2010

Chen, J., Brissette, F.P., & Leconte R. (2011). Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology, 401,* 190-202.

Christensen, N. S., & Lettenmaier, D. P. (2007). A multi-model ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrology and Earth Science System, 3*, 3727-3770.

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, *62*(1-3), 337-363.

Clark County, Nevada (CCN) (2000). *Area wide reuse study Las Vegas Valley study area*. http://www.accessclarkcounty.com/depts/daqem/epd/ waterquality/Documents/AreaWideReuseStudy.pdf

CMIP3 (2007). *Bias corrected and spatially downscaled climate projections derived from CMIP3 data* and served at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ described by Maurer et al., (2007).

Colby, B.G. & Jacobs, K.L. (2007). *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*. Resources for the future (RFF) Press, Washington DC

Cooley, H., Cabibi, T.H., Cohen, M., Gleick, P.H., & Herberger, M. (2007). *Hidden Oasis: Water conservation and efficiency in Las Vegas*. Pacific Institute

Dai, A. (2006). Precipitation Characteristics in Eighteen Coupled Climate Models. *Journal of Climate, 19,* 4605-4630.

Engelman, R., Cincotta, R. P., Dye, B., Gardiner-Outlaw, T., & Wisnewski J. (2000). *People in the Balance: Population and Natural Resources at the Turn of the Millennium*. Population Action International, Washington D.C.

Feroz, M., Jensen, M., & Lindell, J. E. (2007). The Lake Mead intake 3 water tunnel and pumping station, Las Vegas, Nevada, USA. Paper presented at the *Rapid Excavation and Tunneling Conference - 2007,* 647-662.

Ford, A. (1999). *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems*. Island Press, Washington, DC.

Forrester, J.W. (1996). System dynamics, system thinking, and soft OR. *System dynamics review, 10.*

Frederick, K. D., & Major, D. C. (1997). Climate change and water resources. *Climatic Change, 37*(1), 7-23.

Gleick, P. H., (1985). Regional Hydrologic Impacts of Global Climate Changes. A paper presented at the *International Research and Development Conference; Arid Lands:*

Today and Tomorrow, Tucson, AZ, Office of Arid Land Studies, University of Arizona.

Gleick, P. H. (1987). Regional Hydrologic Consequences of increases in Atmospheric Carbon Dioxide and other Trace Gases. *Climatic Change*, *10* (2), 137–161.

Gleick, P. H. (1998). Water in crisis: Paths to sustainable water use. *Ecological Applications*, *8*(3), 571-579.

Gleick, P. H. (2003). Global freshwater resources: Soft-path solutions for the 21st century. *Science*, *302*(5650), 1524-1528.

Gleick, P. H. (2010). Roadmap for sustainable water resources in southwestern North America. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(50), 21300-21305.

Gleick, P. H., & Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(25), 11155-11162.

Goa, Y., Vano, J.A., Zhu, C., & Lettemaier, D. (2011). Evaluating climate change over the Colorado River Basin using Regional Climate Models. *Journal of Geophysical Research*, *116*, D13104, 20.

Gober, P., & Kirkwood, C.W. (2010). Vulnerability Assessment of water induced water shortage in United States. *Proceedings of National Academy of Sciences of the United States of America.*

Gober, P., Wentz, E. A., Lant, T., Tschudi, M. K., & Kirkwood, C. W. (2010). WaterSim: A simulation model for urban water planning in Phoenix, Arizona, USA. *Environment and Planning B: Planning and Design*, *38*(2), 197-215.

Gorelow, A.S. (2005). *Climate of Las Vegas, Nevada updated November 2005*. Retrieved from http://www.wrh.noaa.gov/vef/climate/index.php on January, 2011.

Hashimoto, T., Stedinger, J.R., & Loucks, D.P. (1982). Reliability, resilience, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research, 18* (1), 14-20.

Hoerling, M., & Eischeid, J. (2007). Past peak water in the Southwest. *Southwest Hydrology, 6*(1), 18-19.

Hoerling, M., Letteinmaier, D.P, Canyan D., & Udall B., (2009). Reconciling Projections of Colorado River Stream flow. *Southwest Hydrology. 20*

Intergovernmental Panel on Climate Change, IPCC, (2007). Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate, 996, Cambridge Univ. Press, New York.

Inter-governmental Panel on Climate Change, IPCC, (2008). Climate Change and Water. Retrieved from http://www.ipcc.ch/meetings/session28/doc13.pdf on January, 2011.

ISEE (2011). Stella, *Systems Thinking for Education and Research*. Retrieved from <http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx> on September, 2010

Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., & Running, S. W. (2001). Water in a changing world. *Ecological Applications, 11*(4), 1027-1045.

Kalra, A., & Ahmad, S. (2009). Using oceanic-atmospheric oscillations for long lead time streamflow forecasting. *Water Resources Research, 45*, W03413.

Kalra, A., & Ahmad, S. (2011). Evaluating changes and estimating seasonal precipitation for Colorado River Basin using stochastic non-parametric disaggregation technique, *Water Resources Research, 47,* W0555.

Las Vegas Convention Center, LVCC (2011). *Visitor's statistics*. Retrieved from <http://www.lvcva.com/press/statistics-facts/index.jsp> on October 2010.

Las Vegas Wash Comprehensive Adaptive Management Plan, LVWCAMP (1999) *Colorado River water return flow credits.* Retrieved from <http://www.lvwash.org/assets/pdf/resources_lvwcamp_appendices.pdf> on July, 2010.

Lettenmaier, D. P., Brettman, K. L., Vail, L. W., Yabusaki, S. B., Scott, M. J., (1992). Sensitivity of Pacific Northwest Water Resources to Global Warming. *Northwest Environmental Journal*, *8*(2), 265–283.

Li, L., & Simonovic, S.P (2002). System dynamics model for predicting floods from snowmelt in North American prairie watersheds. *Hydrological Processes. 16*, 2645-2666.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *Journal of Geophysical. Res., 99*(D7), 14415–14428.

MacDonald, G. M. (2010). Water, Climate Change, and Sustainability in the Southwest. *Proc. Natl. Acad. Sci. U. S. A., 107*(50), 21256-21262.

Madani, K., & Marino, M. A. (2009). System dynamics analysis for managing Iran's Zayandeh-Rud river basin. *Water Resources Management, 23*(11), 2163-2187.

Mata, L.J., (2008). *Influence of climate change on Droughts and Water Scarcity in Dry Regio*n. A report prepared for the World Bank.

McCabe, G. J., & Wolock, D. M. (1999). General-circulation-model simulations of future snowpack in the western united states. *Journal of the American Water Resources Association, 35*(6), 1473-1484.

McCabe, G. J., & Wolock, D. M. (2007). Warming may create substantial water supply shortages in the Colorado River basin. *Geophysical Research Letters, 34*(22)

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J. C. J., Lang, H., Parmet, B.W.A.H ., Schadler, B., Schulla, J., & Wilke, K. (2001). Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. *Climatic Change, 49*(1-2), 105-128.

Milly, P. C. D., Dunne, K. A., Vecchia, A. V., (2005). Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate. *Nature, 438*(7066), 347-350.

Molle, F., & Turral H. (2004). Demand management in a basin perspective: is the potential for water saving overrated? *A paper presented at the International Water Demand Management Conference,* June 2004. Dead Sea, Jordan.

Moriasi, D.N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers, 50*(3), 885−900.

Nash, L. L., & Gleick, P. H. (1991). Sensitivity of streamflow in the Colorado River basin to climatic changes. *Journal of Hydrology, 125*(3-4), 221-241.

Nash, L. L., Gleick, P., (1993). The Colorado River Basin and Climate Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation, EPA, Policy, Planning and Evaluation. EPA 230-R-93–009.

National Research Council (2007). *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic variability*. Washington D.C: National Academics Press.

Nijssen, B., Lettenmaier, D.P., Liang, X., Wetzel, S.W., & Wood, E.F. (1997). Streamflow simulation for continental-scale river basins, *Water Resources Research, 33*, 711–724.

Olmstead, S. M., Hanemann, M. W., & Stavins, R. N. (2007). Water Demand under Alternative Price Structures. *Journal of Environmental Economics Management 54*(2), 181-198.

Peters, H. L., Pratt, B., & Chang, H. (2010). Effects of Urban Spatial Structure, Socio-demographics, and Climate on Residential Water Consumption in Hillsboro, Oregon. *Journal of the American Water Resources Association, 46*(3), 461–472

Postel, S. L., Daily, G.C., & Ehrlich, P. R. (1996).Human Appropriation of Renewable *Fresh Water Science, 271*(5250), 785-788

Prairie, J., & Callejo R. (2005). Natural flow and salt computation methods, U.S. Department of the Interior USDOI, Bureau of Reclamation.

Qaiser, K., Ahmad, S., Johnson, W., & Batista, J. (2011). Evaluating the impact of water conservation on fate of outdoor water use: A study in an arid region. *Journal of Environmental Management, 92*(8), 2061-2068.

Rajagopalan, B., Niwak, K., Prairie, J., Hoerling, M., Harding, B., Barsugli, J., Ray, A., Udall B., (2009). Water supply risk on the Colorado River: Can management mitigate? *Water Resources Research, 45*, W08201.

Regonda, S.K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle shifts in Hydroclimatology over the Western United States. J. *Climate, 18*(2), 372-384

Rijsberman, F. R., 2006. Water scarcity: Fact or fiction? *Agricultural Water Management, 80*(1-3), 5-22.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H., Harnik, N., Leetmaa, A., Lau, N., Li, C., Velez, J., & Naik, N. (2007). Model projections of an imminent transition to a more arid climate in southwestern North America. *Science, 316*(5828), 1181-1184.

Seckler, D., Amarasinghe, U., Molden, D.J., R. de Silva, R. B. (1998). World Water Demand and Supply, 1990 to 2025: Scenarios and Issues. IWMI Research Report 19. IWMI, Colombo, Sri Lanka.

Seckler, D., Barker, R., & Amarasinghe, U. (1999). Water scarcity in the twenty-first century. *International Journal of Water Resources Development, 15*(1-2), 29-42.

Sharp, D. (2010). An Inventory of Approaches to Climate Modeling and Downscaling. A paper presented at the *PUMA workshop*.

Shrestha, E., Ahmad, S., Johnson W., Shrestha P., & Batista, J.R. (2011). Carbon Footprint of water conveyance verses Desalination as alternatives to expand water supply. *Desalination* (in press).

Simonovic, S. P., & Ahmad, S. (2005). Computer-based model for flood evacuation emergency planning. *Natural Hazards, 34*(1), 25-51.

Smakhtin, V., Revenga, C., Doll, P. (2004). A Pilot Global Assessment of Environmental Water Requirements and Scarcity, *Water International*, *29*(3), 307- 317.

Smakhtin, V.U., (2000). Low flow hydrology: A review. *Journal of Hydrology*, *240*(3-4), 147-186.

SNWA, Southern Nevada Water Authority (2008). *Water Use facts*. Retrieved from <http://www.snwa.com/html/cons_waterfacts.html> on October, 2010.

SNWA, Southern Nevada Water Authority (2009). *Conservation plan 2009 – 2013*. Retrieved from <http://www.snwa.com/assets/pdf/cons_plan_intro.pdf> on October, 2010.

SNWA, Southern Nevada Water Authority (2011). *Resource Plan*. Retrieved from <http://www.snwa.com/assets/pdf/wr_plan.pdf> on October, 2010.

Sovocol, K. A. (2005). *Xeriscape Conversion Study: Final Report*. A report submitted to Southern Nevada Water Authority, Las Vegas.

Stave, K. A. (2003). A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *Journal of Environmental Management*, *67*(4), 303-313.

Sterman, J. D. (2000). *Business Dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill, NY.

Stewart, I.T., Cayan D.R., & Dettinger M.D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, *18*, 1136-1154.

Tidwell, V. C., Passell, H. D., Conrad, S. H., & Thomas, R. P. (2004). System dynamics modeling for community-based water planning: Application to the middle Rio Grande. *Aquatic Sciences*, *66*(4), 357-372.

U.S. Census Bureau (2010). *State population data*. Retrieved from <http://quickfacts.census.gov/qfd/index.html. > on October, 2010.

U.S. Department of Interior (USDOI), Bureau of Reclamation, (1985). *Colorado River Simulation System: System Overview*. Retrieved from <http://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html> on September 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation, (2007). *Final Environment Impact Statement*. *Appendix A, C and D*. Retrieved from <http://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html> on October, 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation, (2007a). *Record of Decision, Colorado River Interim guidelines for Lower Basin shortages and the coordinated operation for Lake Powell and Lake Mead*. Retrieved from <http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf> on October 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation, (2007b). *Record of Decision, Colorado River Interim guidelines for lower basin shortages and the coordinated operation for Lake Powell and Lake Mead*. Retrieved from <http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf> on October, 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation, (2009). *Literature Synthesis on Climate Change Implications for Reclamation's Water Resources*.

Retrieved from <http://www.usbr.gov/research/docs/climatechangelitsynthesis.pdf> on September, 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation, (2010). *Natural flow and salt computation methods*. Retrieved from <http://www.usbr.gov/lc/region/g4000/NaturalFlow/documentation.html> on September 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011). *Drought in the Upper Colorado River Basin*. Retrieved from <http://www.usbr.gov/uc/feature/drought.html> on September, 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011a). *Lake Mead at Hoover Dam, Elevation.* Retrieved from <http://www.usbr.gov/lc/region/g4000/hourly/mead-elv.html> on October 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011b). *Colorado River System Consumptive uses and losses reports*. Retrieved from <http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html> on September 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011c). *Decree accounting reports*. Retrieved from

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011d). *Monthly summary report*. Retrieved from <http://www.usbr.gov/uc/water/rsvrs/ops/monthly_summaries/index.html> on September 2010.

U.S. Department of the Interior USDOI, Bureau of Reclamation (2011e). *Secure Water Act Section 9503(c)- Reclamation Climate Change and Water.*

U.S. Geologic Survey USGS (2011). *Science in your watershed*. Retrieved from <http://water.usgs.gov/wsc/reg/14.html> on June, 2011.

U.S. Census Bureau, (2010). *State population data*. Retrieved from <http://quickfacts.census.gov/qfd/index.html> on June 2010.

Vedwan, N., Ahmad, S., Wilhelm, F.M., Broad, K., Letson, D., & Podesta, G. (2008). Institutional Evolution in Lake Okeechobee Management in Florida: Characterstic, Impacts, and Limitations. *Water Resources Management, 22*, 699–718.

Venkatesan, A. K., Ahmad, S., Johnson, W., & Batista, J. R. (2011a). Salinity reduction and energy conservation in direct and indirect potable water reuse. *Desalination, 272*(1-3), 120-127.

Venkatesan, A. K., Ahmad, S., Johnson, W., & Batista, J. R. (2011b). System dynamic model to forecast salinity load to the Colorado River due to urbanization within the Las Vegas Valley. *Science of the Total Environment*, *409*, 2616-2625.

Vickers, A. (2001). *Handbook of water conservation and water use*. Water Plow Press, Amherst, Massachusetts.

Vogel, R. M., Sankarasubramanian, A. (2005). *USGS Hydro-Climatic Data Network (HCDN): Monthly Climate Database, 1951-1990*. Retrieved from http://www.daac.ornl.gov from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A on October, 2010.

Vorosmarty, C. J., Green, P., Salisbury, J., Lammers, R. B. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science, 289*(5477), 284-288.

Wang, X., Zhang, J., Liu, J., Wang, G., He, R., Elmahdi, A., & Elsawah, S. (2011). Water resources planning and management based on system dynamics: A case study of Yulin city. *Environment, Development and Sustainability*, *13*(2), 331-351.

Water Resources Plan 09 (2009). *A report submitted to Southern Nevada Water Authority, Las Vegas*. Retrieved from <http://www.snwa.com/assets/pdf/wr_plan.pdf > on October, 2010.

Winz, I., Brierley, G., & Trowsdale, S. (2009). The use of system dynamics simulation in water resources management. *Water Resources Management*, *23*(7), 1301-1323.

World Health Organization (WHO) (2009). Water scarcity.

Xu, C., Seibert, J., & Halldin, S. (1996). Regional water balance modeling in the NOPEX area: Development and application of monthly water balance models. *Journal of Hydrology*, *180*(1-4), 211-236.

Zongxue, X., Jinno, K., Kawamura, A., Takesaki, S., Ito, K. (1998). Performance Risk Analysis for Fukuoka Water Supply System. *Water Resources Management, 12*, 13-30.

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