THESIS

MODELING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

CASE STUDY: ARKANSAS RIVER BASIN IN COLORADO

Submitted by

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ABSTRACT

MODELING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES
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There is mounting evidence that amount of carbon dioxide is being increased which can lead to changing the global climate drastically during this century. Climate change can have important effect on the water resources and water demand like urban and agriculture uses. The effects of climate change have been explored in the Arkansas River Basin in Colorado which is one of the major rivers in Colorado that provides water for 650,000 people a year and irrigates around 280,600 acres of agriculture areas. The aim of this research is to project precipitation and temperature in smaller temporal and spatial scale by MAGICC/SCENGEN tool and model the impact of climate change on the water resources by water Evaluation and Planning (WEAP) software to provide results for the water managers and policy makers.

Two climate scenarios (A2 and B2) and a 550 ppm policy were used to project future temperature and precipitation in the Arkansas River Basin for the period of 2013 to 2040. Based on the results from the two climate scenarios, a warmer and drier climate is anticipated for the region. Three adaptation scenarios (new irrigation technology scenario, new irrigation technology along with crop change scenario, and new irrigation technology along with reducing crop area scenario) were analyzed to consider their effects to mitigate the negative impact of climate change in the Arkansas River Basin. The results of the simulation of these scenarios showed that all three have a relatively short term impact. This indicates that globe warming is a potentially very serious problem for water management in the Arkansas River Basin.

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CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Water supply is threatened by increasing population growth and climate change. Since the last century, the population of the world has increased three times, use of nonrenewable energy has increased by a factor of 30, and industrial production has increased 50 times. This means demand for water is increasing and resources with suitable quality are depleting because of urban, agriculture, and industrial uses (Karamouz et al., 2011). In the United States, 41% of the water supply is consuming by irrigated farmlands and that represents nearly 81% of the total water demand (Solley et al., 1993). Since 1980, surface water supplies have been decreasing in the Great Plains of the United States and this has resulted in a reduction of 12% of the irrigated farmland (Dugan et al., 1994). By decreasing surface water supplies, groundwater consumption has been quickly expanded which has resulted in aquifer depletion. For instance, about 16.6 million acre-feet have been pumped from the Ogallala aquifer since 1940 without sufficient recharge (Rosenberg et al., 1999). By adding another factor, climate change, the competition between water demands (e.g. urban development, agriculture, hydropower, industry) is becoming more severe.

Based on research done by scientists and scholars, increasing amounts of carbon dioxide (CO2) can lead to changing the global climate drastically during this century (IPCC, 2001). By increasing amounts of carbon dioxide and concentration of greenhouse gases, the average temperature of earth’s atmosphere and the levels of the oceans have been rising since the 19th century. This is known as the global warming phenomenon. Global warming can have important effects on the water resources and water demands like urban and agriculture uses. Precipitation and evapotranspiration, two important hydrologic variables, can be altered by changing temperature. Understanding the interaction of climate and water resources can help scientists and policy makers to mitigate the negative effects of global warming by introducing proper water management scenarios.

There is anticipation that water resources will be increasingly stressed by climate change therefore the gap between water supply and demand for water will expand. In general, with warmer weather, water demand is anticipated to increase while water supply is anticipated to decrease (Peterson and Keller, 1990). For instance, agriculture consumption, which is the major demand for water supply, will be increased due to both decreasing precipitation and increasing evapotranspiration. In water-stressed basins, where the water demand is already approaching the available supply, the impacts of climate change can be especially severe.

1.2 Problem Statement

The United Nations has acknowledged that climate change is happening due to human-caused (or anthropogenic) factors (Fung, C et al., 2011) (Figure1.1). Effects of climate change on the water resources can be significant by causing changes in quantity, type (snow or rain), and timing of precipitation (Figures 1.2 and 1.3).

Different climate and water balance models have been developed to estimate potential impacts of climate change. But many of these models are not precise because of their coarse spatial and temporal resolution (Elgaali, 2005). In addition, the climate models use different initial boundary conditions and their results are quite different from each other.

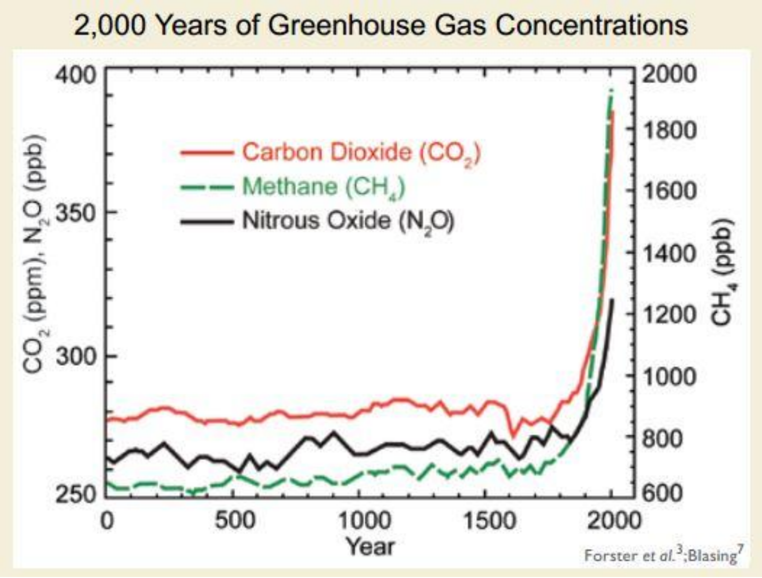


Figure 1. 1 : Increasing gas concentrations since 1970, concentration units are parts per million (ppm) or parts per billion (ppb) (source: Forster et al. 2007; Blasing et al. 2008)

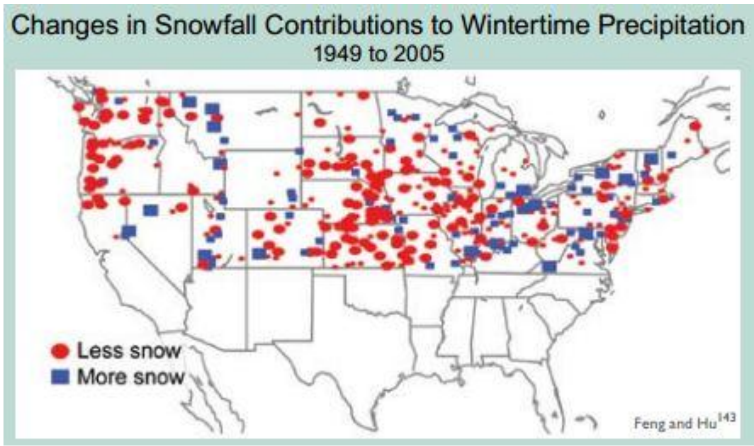


Figure 1. 2: Change of ratio of winter snow to total precipitation from 1949 to 2005. Red and blue circles indicate less and more snow respectively (source: Feng, S. and Q. Hu et al. 2007)

This research seeks to estimate the impacts of global climate change downscaled to a basin scale. A modeling framework is used to estimate the effects of climate change and evaluate water management scenarios to potentially mitigate the negative impacts. The modeling framework used in this research consists of applying climate change models and a river basin model.

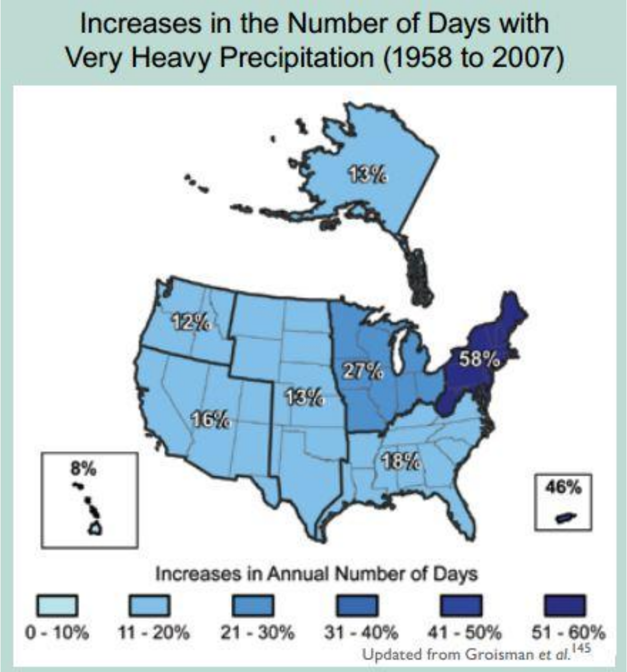


Figure 1. 3: Increasing percentage of average number of days with very heavy precipitation from 1985 to 2007 (source: Groisman et al., 2005)

The MAGICC/SCENGEN tool (Wigley, 2007) was used to project precipitation and temperature changes for the case study river basin based on climate change scenarios which are developed by the Intergovernmental Panel on Climate Change (IPCC). This tool was selected because of its higher spatial resolution of (2.5° X 2.5° longitude and latitude) and temporal (monthly) resolution which can lead to more precise results at a specific location. The developed precipitation and temperature data from this tool were used as inputs to a model of the water resources of the case study basin (Arkansas River Basin). The water resources model used the Water Evaluation and Planning (WEAP) software (Sieber. J and D. Purkey, 2011) developed by the Stockholm Environment Institute. Based on the historical data, the WEAP model was calibrated and validated and then was used to analyze the impacts on the basin's water resources due to the different climate change scenarios. The model was then used to evaluate the impacts of potential water resources management adaptation scenarios.

1.3 Study Objectives

The overall study goal is to demonstrate the use of the modeling framework to assess the impacts of climate change on a water-stressed basin. Specifically for the selected case study area of the Arkansas River Basin in Colorado, the study objectives were:

- Apply the MAGICC/SCENGEN tool to project precipitation and temperature changes for the Arkansas basin based on selected climate scenarios.
- Simulate historical data within the Arkansas basin by calibrating the WEAP model for this basin.
- Simulate the projected precipitation and temperature changes using the WEAP model.
- Compare the current and future simulations of the Arkansas basin to assess the impact of climate change on water resources in the basin.
- Analyze potential water management adaptation scenarios designed to mitigate the negative impacts of climate change.
- Estimate the length of time that the adaptation scenarios might be effective.

1.4 Case Study Area

1.4.1 Location

The Arkansas River is one of the major tributaries of Mississippi River. It flows from the Collegiate Peaks in Colorado towards the east and southeast and it passes through the states of Colorado, Kansas, Oklahoma, and Arkansas. This is the sixth longest river in the United States with a length of 1,469 miles (2,346 km). The origin of Arkansas River is in the Rocky Mountains in Lake County, Colorado, near Leadville, and the mouth of the Arkansas River is located at Napoleon, Arkansas. This river has a drainage basin of 160,000 sq mi (414,398.098 km^2) (England, J. F et al., 2006).

The focus of this study is a part of the Arkansas River Basin which is known as Arkansas valley in southeastern Colorado. The Arkansas valley is bounded by the Rocky Mountains on the west and by Kansas, New Mexico and Oklahoma states on the east and south. Approximately, 72, 724 km2 (28,415 sq miles), nearly 27 percent of the state of Colorado, is covered by the Arkansas valley. The length (east to east) and width (north to south) of the valley are about 400 km (250 miles) and 240 km (150 miles) respectively (Elgaali, 2005).

1.4.2 Climate

Temperatures within the basin vary in response to topographic locations. The range of average annual temperature is between 2^o C (35.5^o F) and 12^o C (53.6^o F) at Leadville in the Rocky Mountains and Lamar in the lower valley (Elgaali, 2005).

Distribution of precipitation is uneven throughout the year and it ranges from about 45 inches per year in the highest mountains, 16 - 20 inches in the western part of the region and 9 - 12 inches in the middle and eastern part of the region. The type of precipitation at high elevations is snow which constitutes the major portion of the runoff for the Arkansas River (Elgaali, 2005). Figure 1.4 shows the distribution of average annual precipitation throughout the Arkansas basin.

1.4.3 Water Resources

1.4.3.1 Surface Water

The snowpack in the mountains at the western border of region constitutes the major runoff in the basin so water supply varies from year to year. In general, more than 60 percent of the runoff occurs between April and July and 20 percent occurs between August and October. A trans-basin diversion also transports water from the west side of Continental Divide to the Arkansas Basin. The trans-basin diversion consists of a system of reservoirs, tunnels, and canals for collecting and transporting water (Figure 1.5).

There are reservoirs and lakes in the basin and their functions to control natural water are important. The reservoirs are using to store water to meet demand. The peak runoff generally is during May and June due to snow melt while the peak demand for water usually is during July and August because of demand from the agricultural sector. Furthermore, there are some reservoirs and lakes that are used for recreation, fisheries and wildlife habitat, and flood control purposes.

1.4.3.2 Groundwater

There are six aquifers inside of the basin, as described comprehensively in the final report of Water Supply and Needs report for the Arkansas River Basin (2006). These aquifers are divided into alluvial, bedrock (Raton Basin, Dakota-Cheyenne), and designated basin (High Plains) (Figure 1.6).

The unconfined alluvial aquifer contains glacial silts to large boulders. The main sources of recharge for this aquifer are infiltration of surface water from the river, irrigation and the ditches and canals. This aquifer is the main source of supplemental groundwater for irrigation. The Raton Basin consists of aquifers recharged by runoff from the Sangre de Cristo Mountains,

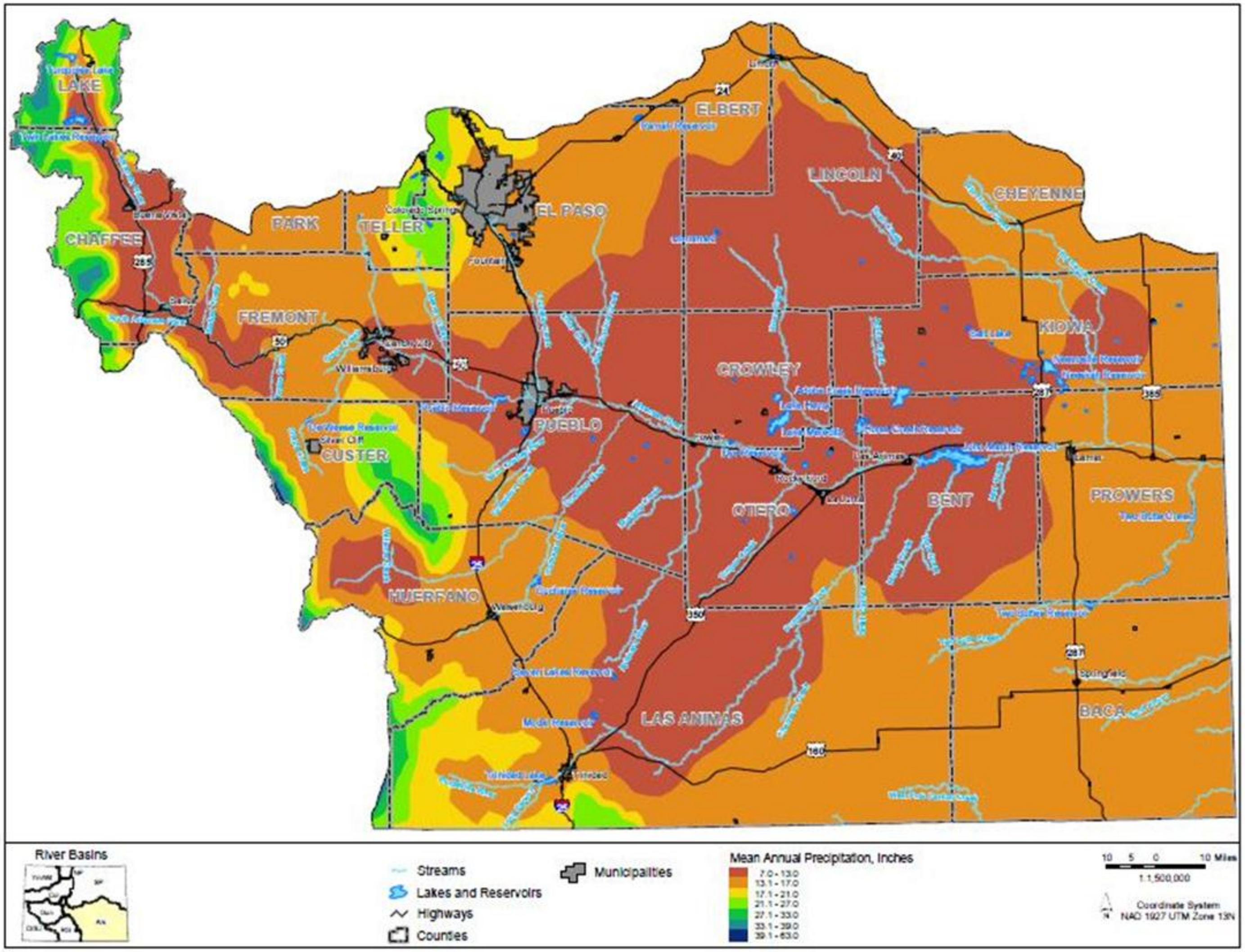
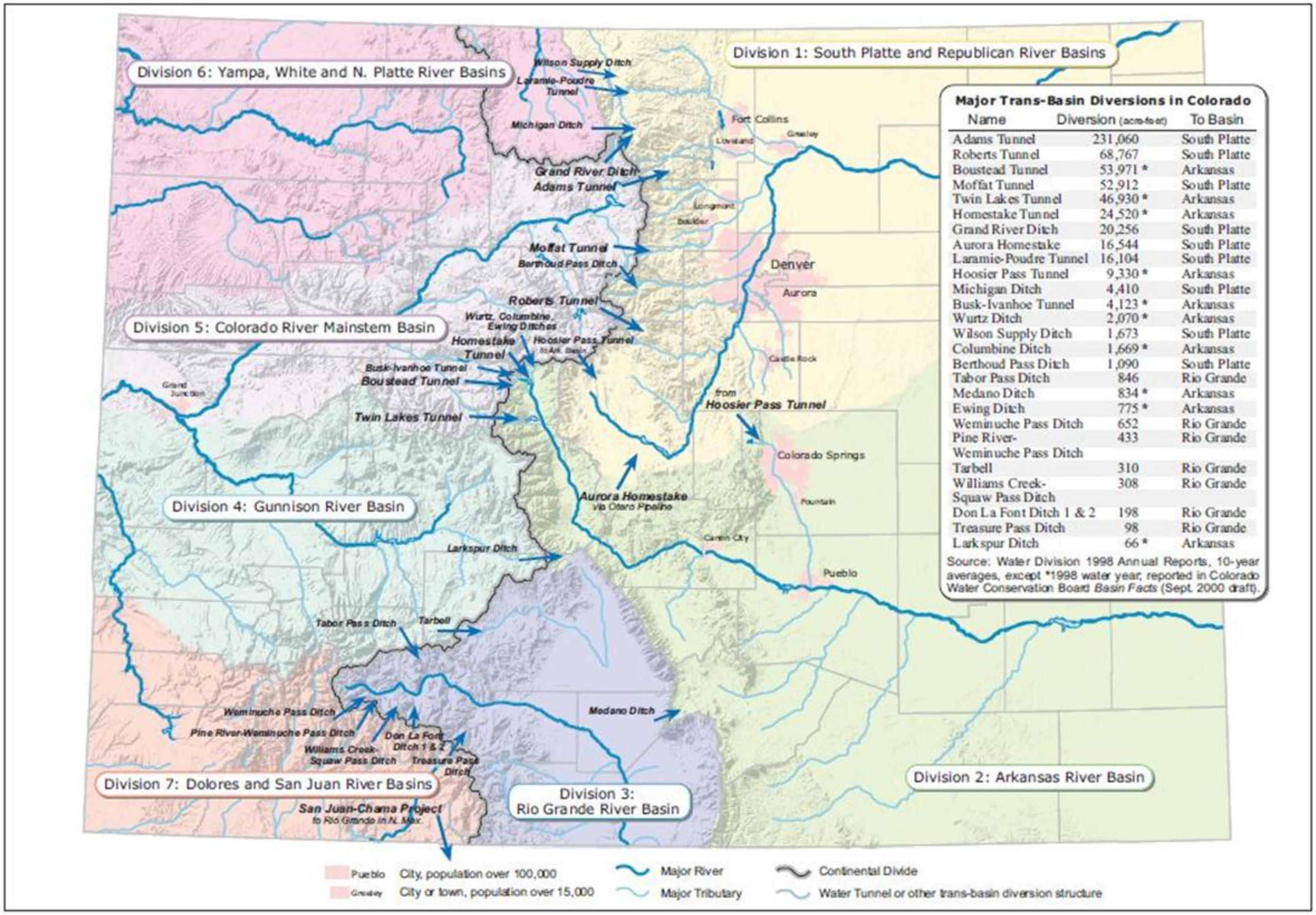


Figure 1. 4: Distribution of average annual precipitation

(Source: Water Supply and Needs report for the Arkansas River Basin, Colorado Department of Natural resources)


Major Trans-Basin Diversions in Colorado

Name	Diversion (acre-feet)	To Basin
Adams Tunnel	231,060	South Platte
Roberts Tunnel	68,767	South Platte
Boustead Tunnel	53,971 *	Arkansas
Moffat Tunnel	52,912	South Platte
Twin Lakes Tunnel	46,930 *	Arkansas
Homestake Tunnel	24,520 *	Arkansas
Grand River Ditch	20,256	South Platte
Aurora Homestake	16,544	South Platte
Laramie-Poudre Tunnel	16,104	South Platte
Hoosier Pass Tunnel	9,330 *	Arkansas
Michigan Ditch	4,410	South Platte
Busk-Ivanhoe Tunnel	4,123 *	Arkansas
Wurtz Ditch	2,070 *	Arkansas
Wilson Supply Ditch	1,673	South Platte
Columbine Ditch	1,669 *	Arkansas
Berthoud Pass Ditch	1,090	South Platte
Tabor Pass Ditch	846	Rio Grande
Medano Ditch	834 *	Arkansas
Ewing Ditch	775 *	Arkansas
Weminuche Pass Ditch	652	Rio Grande
Pine River-Weminuche Pass Ditch	433	Rio Grande
Tarbell	310	Rio Grande
Williams Creek-Squaw Pass Ditch	308	Rio Grande
Don La Font Ditch 1 & 2	198	Rio Grande
Treasure Pass Ditch	98	Rio Grande
Larkspur Ditch	66 *	Arkansas

Source: Water Division 1998 Annual Reports, 10-year averages, except *1998 water year, reported in Colorado Water Conservation Board *Basin Facts* (Sept. 2000 draft).

Figure 1. 5: Major Trans-Basin Diversions (Sources: Colorado Division of Water Resources, Office of the State Engineer; Colorado Water Conservation Board; U.S. Bureau of Reclamation; U.S. Geological Survey. Map by Thomas Dickinson)

and infiltration from precipitation, stream, and lakes. The composition of the Dakota-Cheyenne aquifer underlying the major part of the Arkansas Basin is from well-sorted sandstone to fine-grained shale. The major use of this aquifer is for irrigation and domestic water.

1.4.4 Land

The material of soils within the basin are weathered materials, wind deposits, and alluvial. Based on a general map developed by the Colorado Water Conservation Board (CWCB) and the US Department of Agriculture (USDA), the dominant soil is loamy (Elgaali et al., 2005). The geology of the southern Rocky Mountain province, which is located at the western part of the Arkansas River Basin, is Precambrian metamorphic schist and gneisses. The eastern part of basin, the Great Plains province, is dominated by multiple layers of sedimentary rocks, and Quaternary alluvium (Water Supply and Needs Report for the Arkansas River Basin, 2006). Land use in the Arkansas River Basin is displayed in figure 1.7. Most of the land in the Basin is used as grassland (67%), forest (13%), and planted/cultivated areas (9%). The other land uses including shrub land, barren land, open water, and wetlands. The non-irrigated crops like winter wheat, forage and grain sorghum are used mostly in the eastern part of the Basin, which are about two thirds of the Basin.

Figure 1.8 shows the major farmlands along the Arkansas River that are irrigated. The major irrigated crops are alfalfa, corn for grain and silage, grass hay, beans, vegetables, barley, and wheat. The methods of irrigation are open furrow, sprinkler, and drip. There are a complex of canals and ditches that distribute and provide water for irrigation along with wells pumping from alluvial deposits (SCS-USDA, 1981).

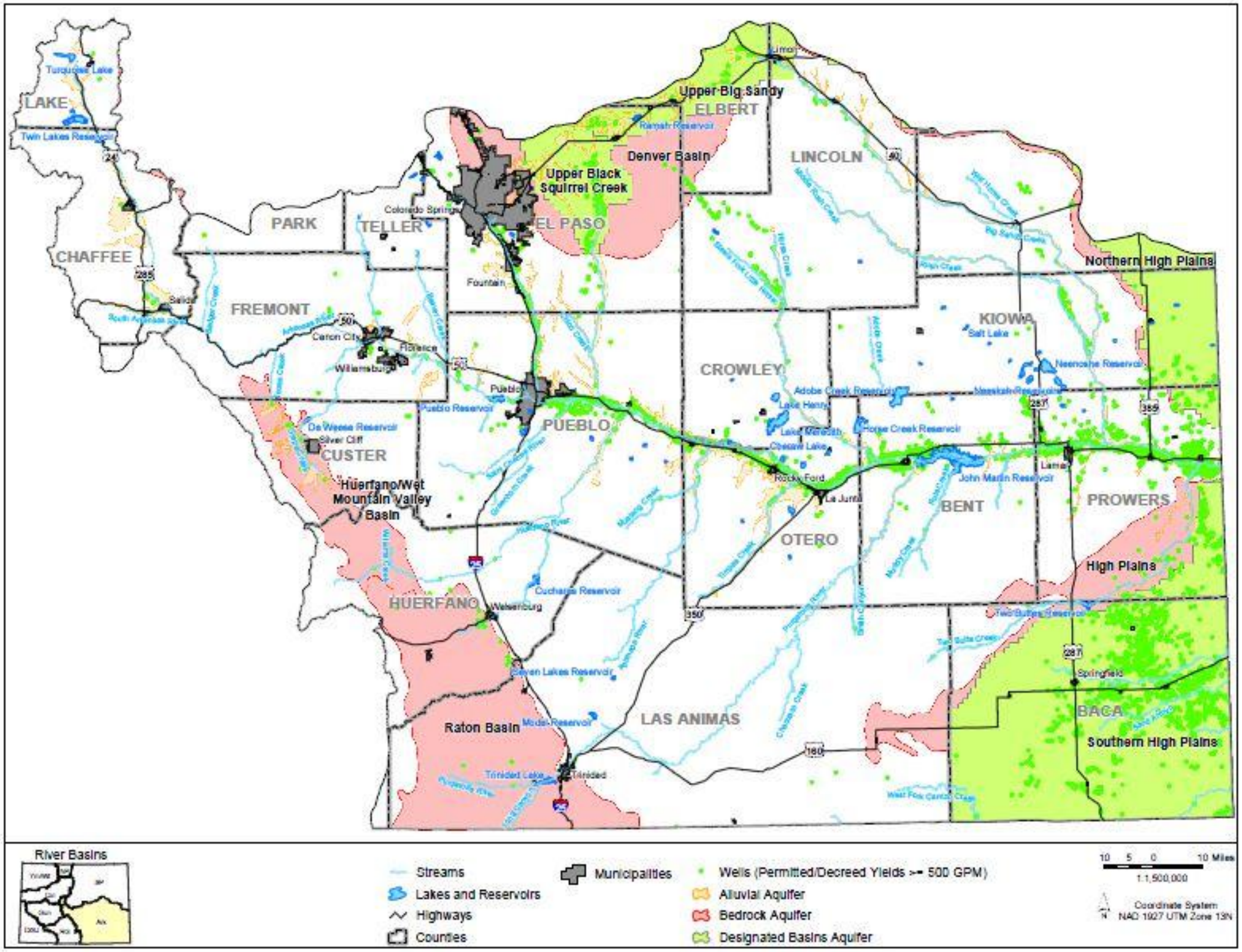


Figure 1. 6: Major aquifers inside of the Arkansas Basin

(Source: Water Supply and Needs Report for the Arkansas River Basin, Colorado Department of Natural resources)

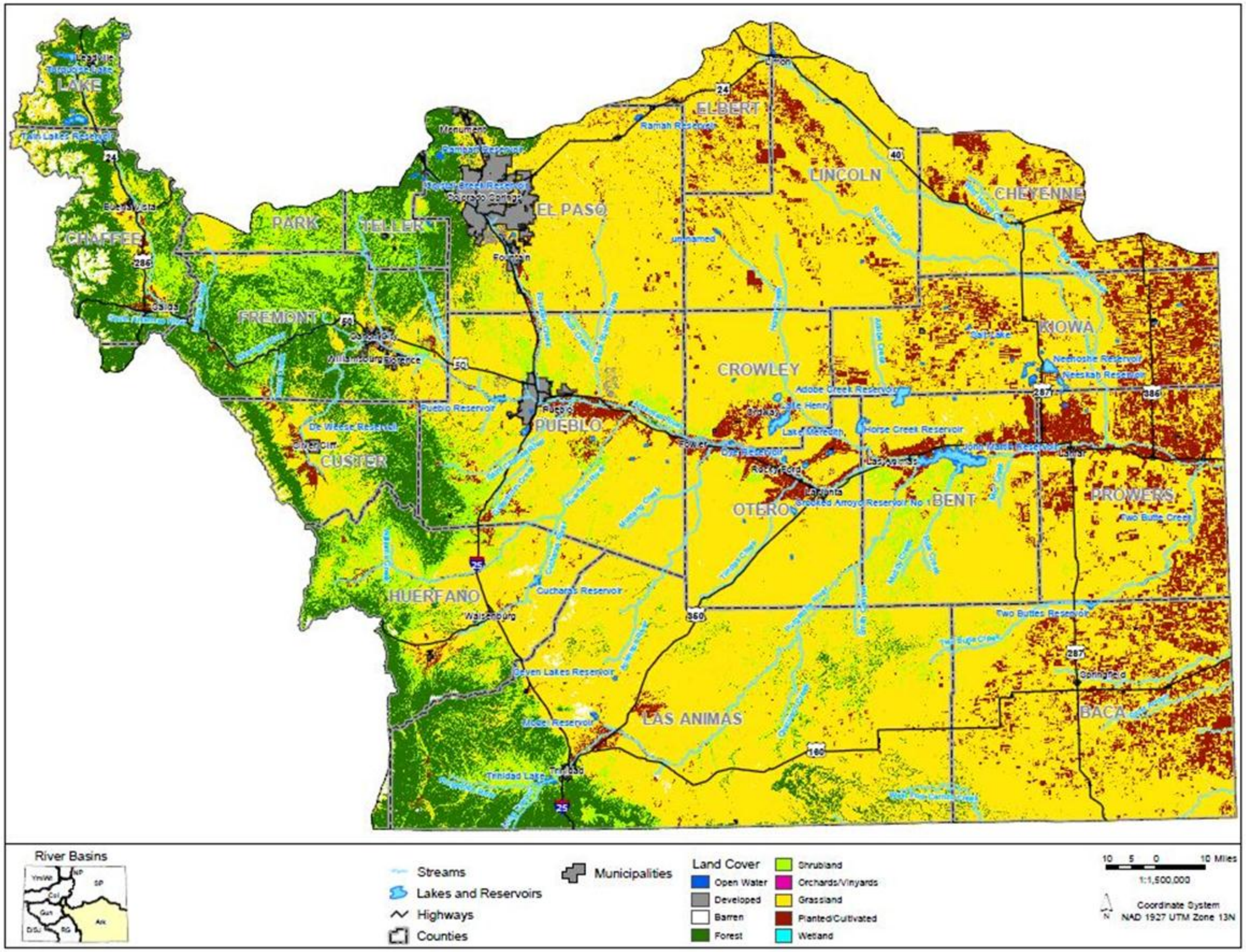


Figure 1. 7: Land use in the Arkansas River Basin (source: U.S. Geological Survey, 1992)

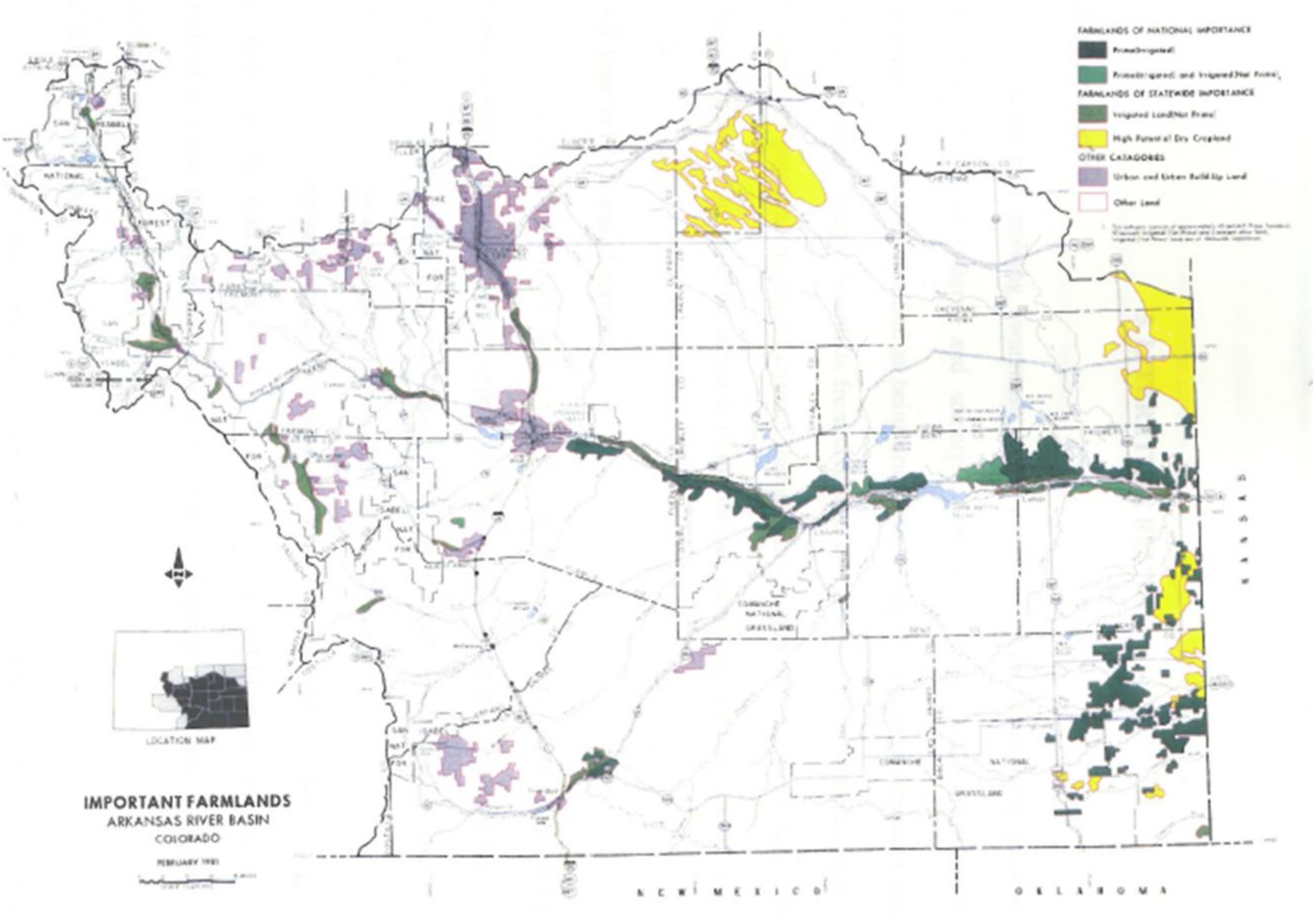


Figure 1. 8: Major farmland along Arkansas River Basin (source: SCS-USDA, 1981)

CHAPTER TWO: LITERATURE REVIEW

2.1 Aspects of Climate Change

The awareness of the extent to which change of climate can affect the environment, society, and economy is increasing. Long-term climate change has been observed at continental, regional, and ocean basin scales, due to increasing concentration of greenhouse gases particularly carbon dioxide. These include changes in precipitation amounts and timings, arctic temperatures, wind patterns, and aspects of extreme weather like heavy precipitation, drought, and heat waves (IPCC, 2007).

The pattern of precipitation is not distributed evenly across the world and is governed by atmospheric circulation patterns and moisture availability. These two factors are impacted by temperature so the pattern of precipitation is expected to change due to changing temperature. The changes include the type of precipitation, the amount, the intensity and the frequency. Precipitation has increased in eastern North America, southern South America, and northern Europe and decreased in the Mediterranean, most of Africa, and southern Asia (Trenberth, K.E et al., 2007).

Increasing global average air and ocean temperature can change the type of precipitation during the winter season (IPCC, 2007). The pattern of precipitation is changing from snow to rain in Northern regions and mountainous area so that heavy precipitation events have increased even in places where total rain amounts have decreased (Barnett, T.P., et al., 2008). All these changes are associated with increasing global temperature since warmer air can hold and carry more water vapor (Santer, B.D., et al., 2008, Willett, K.M et al., 2007, and Santer, B.D., et al., 2007).

2.2.1 Water Resources

One of the key components of water resources is runoff. Runoff will be impacted by climate change, especially in the midwestern and southwestern of portions of the United States. Runoff is affected by changing of temperature and precipitation. Due to importance of runoff for water supply a lot of research has been conducted to quantify the effects of climate change on runoff.

Runoff represents only a portion of precipitation. The magnitude of this portion depends upon temperature, humidity, solar intensity, vegetation, wind speed, and soil moisture. Therefore the change in runoff is not necessarily the same as the change in precipitation. Frederick and Gleick (1999) have simulated impacts of a range of temperature and precipitation changes on runoff in various river basins to explore the impact of climate change on water supply. They found that by increasing temperature by 2^{o}C and decreasing precipitation by -10%, the amount of runoff within the Great Basin Rivers, Upper Colorado, Lower Colorado, and Colorado River will decrease by -17% to -28%, -35%, -56%, and -40% respectively.

Seager, R. et al., 2007, Bates, B.C. t al., 2008, Kundzewicz, Z.W. et al., 2007, and Lettenmaier, D. et al., 2008 projected runoff using climate models. Based on their projection, California and other parts of the West will experience decreased runoff, while runoff will be increased in the East.

Bates, B.C. et al., 2008 and Mote, P. et al., 2008 studied the impacts of higher temperature on the snowpack. They found the production of runoff as streamflow in summer will be earlier in the East and some areas of the Northeast. They found the reduction of snowpack is widespread particularly in lower elevation mountains in California, the Northeast, and the Northwest.

There is evidence that precipitation is transitioning from snow to rain more in the West and Northwest over the last 50 years (Feng, S. and Q. Hu, 2007, Knowles, N.et al., 2006, and Huntingtonton T.G. et.al., 2004) and runoff is occurring up to 20 days earlier in the West and up to 14 days earlier in the Northwest due to earlier melting snow (Stewart, I.T. et al., 2004 and 2005). Other studies in snowmelt-dominated basins in the West and East show earlier spring runoff by up to 60 days in the West and up to 14 days in the East (Stewart, I.T. et al. 2004 and Rauscher, S.A. et al., 2008, Hayhoe, K. et al., 2007). Earlier melting snowpack will produce earlier runoff, there will be less summer streamflow, and this will put more pressure on humans and the environment due to less available water and higher air and water temperatures.

2.3 Assessment of Climate Change Effects

The Intergovernmental Panel on Climate Change (IPCC, 2007: Summary for Policymakers) developed four climate scenarios to project emission gases and temperatures for the future. These scenarios are used by researchers and policy makers to assess potential future conditions and compare them to baseline conditions in the absence of climate change. These scenarios can also be used to analyze adaptation scenarios to mitigate the negative effects of climate change.

2.3.1 Climate Change Scenarios

Based on state of the Special Report on Emissions Scenarios (SRES) (IPCC, 2000), climate change scenarios are not the prediction or forecast of the future but rather they are potential future scenarios and each of scenario represents a way in which the future might unfold. The four scenarios describe future demographic conditions, environmental conditions, social conditions, economic conditions, technologies, and policies. The four scenarios are described by the IPCC (2007) as follows:

- **A1 Scenario**: “This scenario describes a future of world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B).”

- **A2 Scenario:** “The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.”

- **B1 Scenario:** “This scenario describes a convergent world with the same low population growth as in the A1 scenario, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives."

- **B2 Scenario:** "The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels."

There are also some climate change mitigation scenarios that show possible futures where global warming can be reduced by planned actions such as using green energies. For example, one of the climate change mitigation scenarios can be defining a long-term goal of desired carbon dioxide concentration and selecting the actions to reach the goal such as limiting international and national emissions of greenhouse gases. Climate change mitigation scenarios can also be compared by the other climate change scenarios like A2 and B2 to have insight about their impacts on reducing the global warming.

The concentration of carbon dioxide has reached about 375 ppm (Pacalal. S., and R. Socolow, 2004). Limitation of emission of carbon dioxide has a lot of issues such as cost which can make it hard to reach an agreement between governments and agencies. So the 550 ppm policy is one of the feasible policies that can be considered by policy makers and scientists to project temperature.

2.3.2 Climate Change Approaches

During the past decade, various approaches have been used to assess the impact of climate change. The approaches, described comprehensively in the final report of Climate Change Characterization and Analysis in California Water Resources Planning Studies 2010, are as follows:

- **Relative Change Approaches**: In this approach a parameter of interest was added or subtracted by a defined quantity or a defined percentage to assess the potential change due of climate change. These approaches are dependent on results from the other studies that defined the general direction and order of magnitude of the expected changes. For instance, an assessment of climate change on flood peaks in the Central Valley of California indicates that flood peaks will increase compared to the levels that have historically occurred. Since the exact level of increase is unknown, a factor of safety or perturbation would be used to model larger extreme flood events by increasing the historical peak flow. Then the increased peak flood flow values can be used in analysis or design studies.

- **Qualitative Approaches:** These approaches, like the relative approaches, are dependent on results from the other studies that defined the general direction and order of magnitude of the expected changes due to climate change. This approach does not use quantitative numbers to define impact, but qualitatively analyzes and explains how expected changes in temperature, precipitation, evaporation, and hydrology can impact the resources of interest in the study.

- **Ensemble-Informed Approaches:** "These approaches use data from a large array of future climate simulation instead of a selected small subset of simulations. Using various statistical methods, the results from the full array of GCM simulations are aggregated to develop a set of ensemble-informed simulation. Sub-ensemble simulations may also be developed to highlight potential conditions represented by simulations that agree on one or more climate parameters, such as precipitation and temperature" (Climate Change Characterization and Analysis in California Water Resources Planning Studies, 2010).

2.4 Water Evaluation and Planning (WEAP)

2.4.1 Background

The Water Evaluation and Planning (WEAP) software is advanced, integrated modeling software that simulates and models water supplies, water demands and environmental requirements as well as considering effects of policies on water quantity, water quality and the ecosystem. Supply preferences and demand priorities are considered by WEAP to solve the water allocation problem using a combination of linear programming and heuristics (Sieber. J and D. Purkey, 2011).

Using WEAP a water planner can analyze a full range of water issues through a scenario-based approach. Scenarios could include climate variability and change, watershed condition and changes, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure (Yates, 2005).

2.4.2 Water Evaluation and Planning (WEAP) Applications

Holger Hoff et al. (2011) applied WEAP to analyze the management of transboundary water resources in the Jordan River basin which is a very complex situation due to political conflicts in the region. Using WEAP and a dynamic consensus database, they tested various unilateral and multilateral adaptation options considering climate and socio-economic change.

Overexploitation of the large aquifer in Spain's central arid region and the degradation of wetlands have been caused by exhaustive groundwater mining for irrigation which gave rise to notable social conflicts in recent years. WEAP was used to analyze water and agricultural policies to conserve groundwater resources and maintain rural livelihoods in the basin (Consuelo Varela-Ortega et al., 2011).

Jesus Efren Ospina et al. (2011) used WEAP to make some baseline and adaptation strategy scenarios for water supply and demand in the Sinú-Caribe river basin in Colombia and project potential impacts of climate change in the basin.

The Niger River basin encompasses biosphere reserves, parks with a variety of wildlife, an important livestock activity, very fertile land for agriculture and a growing industrial sector. Management of water in the basin is very complicated due to socio-cultural, ecological and economic issues. Zakari Mahamadou Mounir et al. (2011) used WEAP to optimize and allocate present and future Niger River resources between competing water demands.

G. Sanchez-Torres Esqueda et al. (2010) assessed the impacts of climate change on the variation of water availability in the irrigation districts in the Guayalejo-Tamesí River Basin in Tamaulipas, México. They used WEAP to define vulnerability of the water resources in the case study river basin, considering the effects of climate change on water availability in the municipal, industrial, and agricultural sectors.

Erick Akivaga Mugatsia (2010) applied WEAP to assess the effect of proposed water infrastructure developments, policy and regulation under various scenarios in view of Water Act

2002 in Kenya. Using WEAP, the author divided the catchment into three sub-basins and developed two main scenarios that were compared to a reference scenario to assess the changes.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

The models and methods that were used for this research are discussed. Projection of precipitation and temperature used the MAGICC/SCENGEN models, and hydrological analysis and water management simulation used the WEAP software. Figure 3.1 illustrates the steps that were carried out to analyze and evaluate impacts of climate change.

3.2 MAGICC/SCENGEN TOOL

The MAGICC/SCENGEN tool was used to obtain climate change scenarios, based on Global Circulation Models (GCMs), for the Arkansas River Basin. The MAGICC/SCENGEN tool consists of two models. MAGICC, Model for the Assessment of Greenhouse-gas Induced Climate Change, is a gas-cycle/climate model that drives SCENGEN (SCENario GENerator) which is a spatial climate-change model (Figures 3.2 and 3.3). The Intergovernmental Panel on Climate Change (IPCC,) has used the MAGICC model since 1990 as one of the main models to project sea level rise and future global-mean temperature.

MAGICC is based on the energy balance and upwelling-diffusion relationships. It generates outputs of global and hemispheric-mean temperature along with oceanic thermal expansion. The MAGICC model is linked to a variety of gas-cycle models that can project concentrations of key green-house gases (Wigley, 2007).

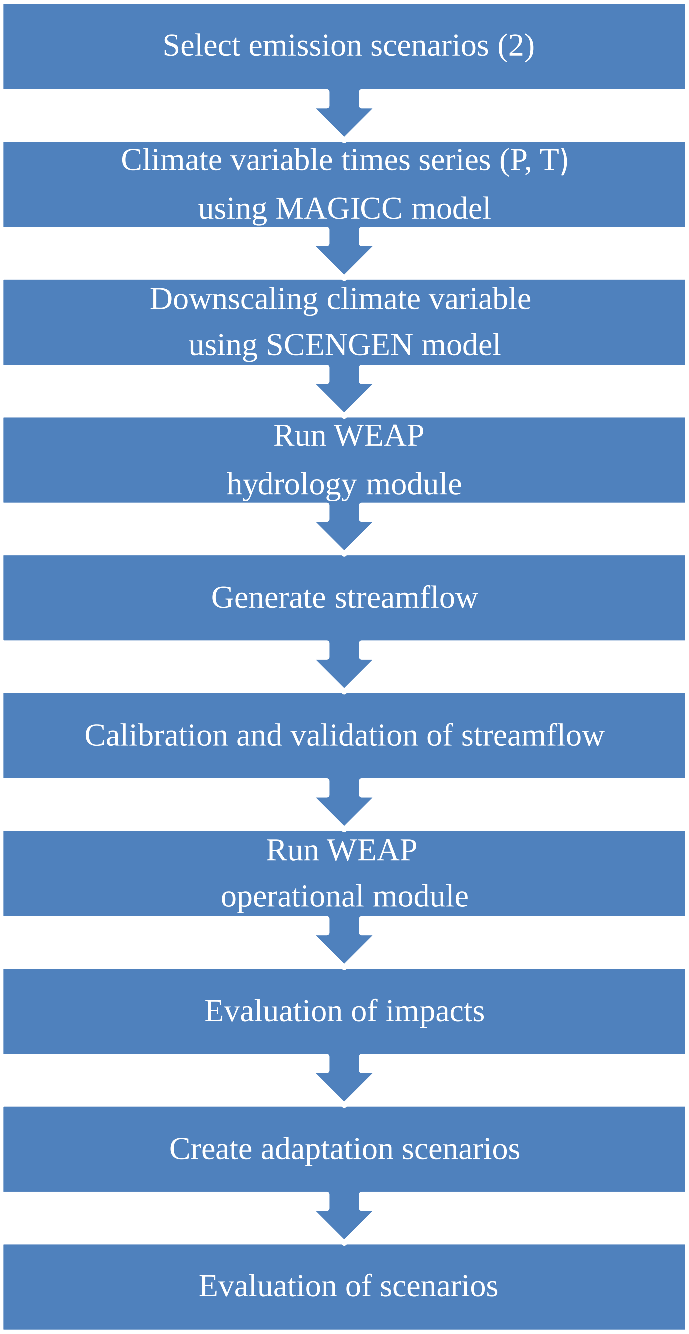
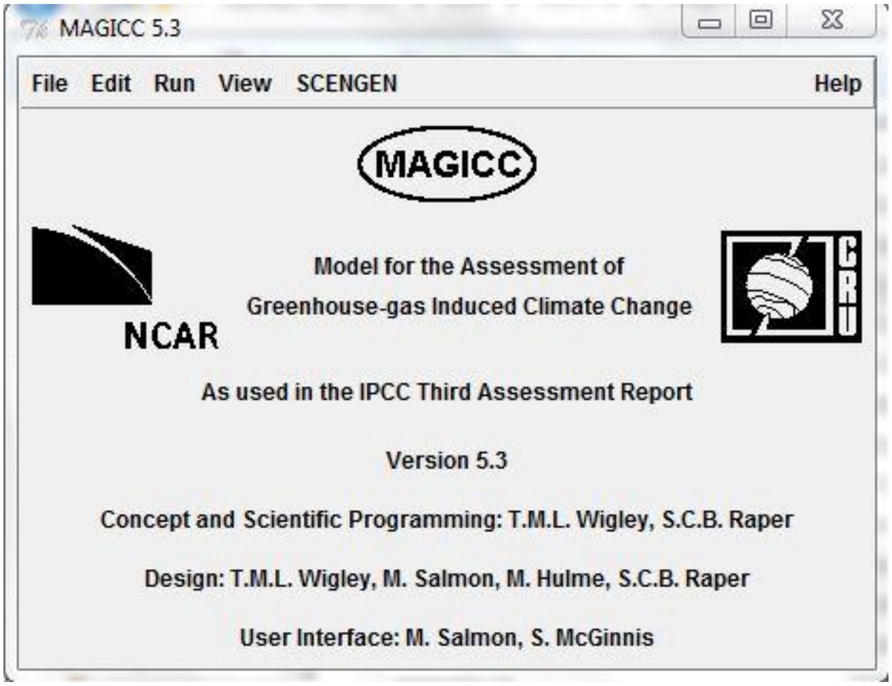


Figure 3. 1: Steps to analyze and evaluate climate change impacts



MAGICC

Model for the Assessment of
Greenhouse-gas Induced Climate Change

As used in the IPCC Third Assessment Report

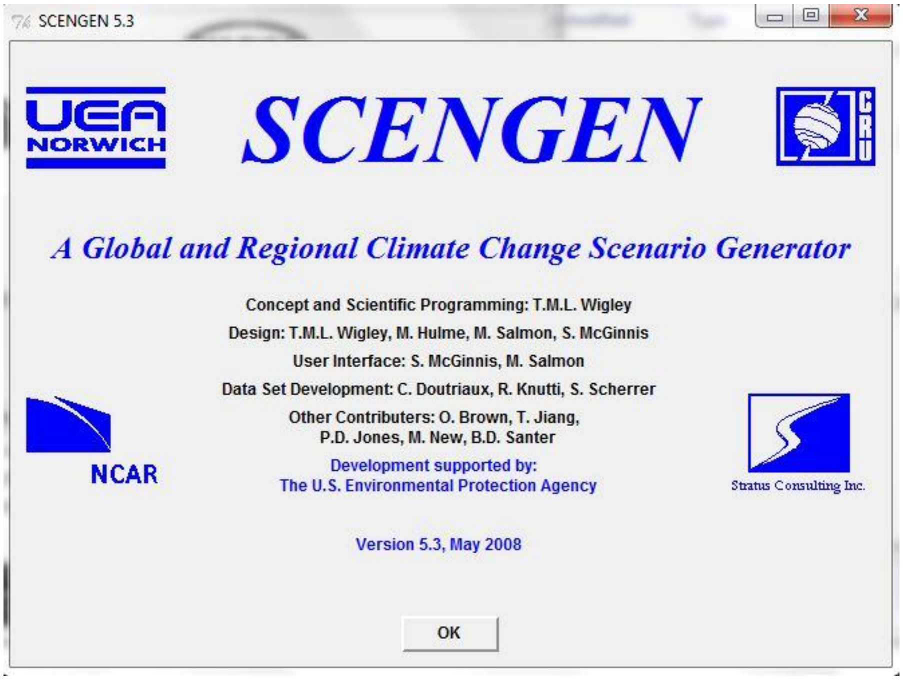
Version 5.3

Concept and Scientific Programming: T.M.L. Wigley, S.C.B. Raper

Design: T.M.L. Wigley, M. Salmon, M. Hulme, S.C.B. Raper

User Interface: M. Salmon, S. McGinnis

Figure 3. 2: MAGICC model 5.3



SCENGEN

A Global and Regional Climate Change Scenario Generator

Concept and Scientific Programming: T.M.L. Wigley
Design: T.M.L. Wigley, M. Hulme, M. Salmon, S. McGinnis
User Interface: S. McGinnis, M. Salmon
Data Set Development: C. Doutriaux, R. Knutti, S. Scherrer
Other Contributers: O. Brown, T. Jiang,
P.D. Jones, M. New, B.D. Santer
Development supported by:
The U.S. Environmental Protection Agency

Version 5.3, May 2008

Figure 3. 3: SCENGEN 5.3 model

The SCENGEN model generates climate change scenarios on a $2.5^o \times 2.5^o$ grid based on the results from the MAGICC model (the global-mean temperature). The method of pattern scaling to generate spatial patterns of change is described in Santer et al. (1990). “The pattern scaling method is based on the separation of the global-mean and spatial-pattern components of future climate change, and the further separation of the latter into greenhouse-gas and aerosol components. Spatial patterns in the data base are normalized and expressed as changes per 1^o C change in global-mean temperature. These normalized greenhouse gas and aerosol components are appropriately weighted, added, and scaled up to the global-mean temperature defined by MAGICC for a given year, emissions scenario and set of climate model parameters” (Wigley, 2007).

The MAGICC/SCENGEN tool provides climate change scenarios monthly which are based on changes in temperature (^{o} C) and precipitation (%). The percent change for each month should be added or subtracted from the value of precipitation for each month of the reference year (1989 in this study). These changes in precipitation were then used to calculate streamflow.

Since population growth in Colorado is moderate to high, two representative greenhouse gas emission scenarios (A2-ASF and B2ASF) among the four available were selected. Based on these two scenarios, the effect of high and low increasing population and economic development on the climate, i.e. temperature and precipitation, and then on the water resources can be projected. Climate change mitigation scenarios are potential actions to reduce emissions of carbon dioxide. Proposed mitigation scenarios range from 350 ppm to 550 ppm policies where the 550 ppm policy is the least conservative meaning it envisions the least reduction in emissions. The policy of 550 ppm, as a mitigation climate change scenario, was also considered to project the temperature and compare it with climate scenarios (A2 and B2) to understand how much temperature might change during this century.

Some research has been done to select the average GCM models for each region in the world since this can help to cancel out, to some extent, the errors in each model (Wigley. T. M.L., 2007). Three GCM models are good for the region of the USA and they are: ECHO, MRI-232A, and UKHADCM (Wigley. T. M.L., 2007).

3.3 WEAP

3.3.1 WEAP Background

Due to increasing population growth, limited fresh water, and climate change, most of the planet is facing water management challenges. Integrated water resources management is a balanced approach to manage water resources (Figure 3.4).

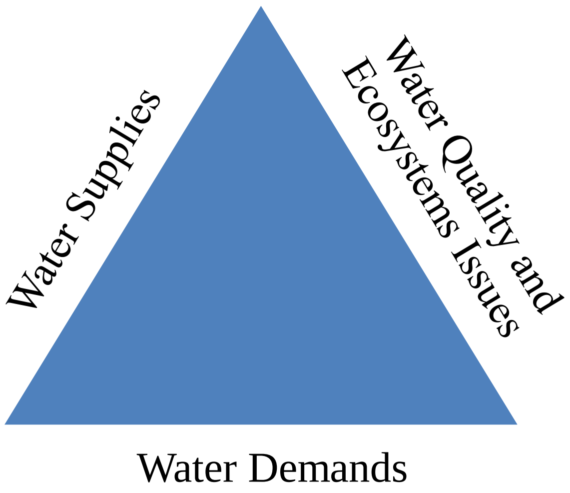


Figure 3. 4: Concept of integrated approach

The Water Evaluation and Planning (WEAP) software, as described comprehensively in the WEAP User Guide, is designed to support integrated water resources management. WEAP is a watershed / river basin simulation model with geo-spatial capabilities that is capable of simulating the allocation on water throughout a river basin based upon a user specified time step. WEAP divides water systems into two sides. One side is the water demands which include municipal and industrial demands, irrigation demands, and hydropower energy demands. The other side is water supply which includes streamflow, groundwater, and reservoir water.

3.3.2 Modeling with WEAP

The WEAP software is a data-driven system that is customized to a specific river basin through a graphical user interface. A set of five different views are located on the left of the main screen along with 6 menus which compose the main user interface of WEAP. The five views are:

1- **Schematic View**: The spatial layout, which is called a schematic, is the starting point for modeling in WEAP. There are fourteen graphical options or interfaces including river, reservoir, and groundwater that one can visualize and simulate the physical features of water systems by dragging and dropping icons to create a node-link schematic diagram (Figure 3.5).

2- **Data View:** In the Data View, there is a hierarchical tree for entering, maintaining and managing data, and specifying assumptions for each scenario and for the current account (the existing condition). The hierarchical tree is composed of six major categories: Key Assumptions, Demand Sites, Hydrology, Supply and Resources, Water Quality, and Other Assumptions (Figure 3.6).

3- **Results View:** The purpose of this view is to report the results of scenario calculations in the form of a graph, table or map.

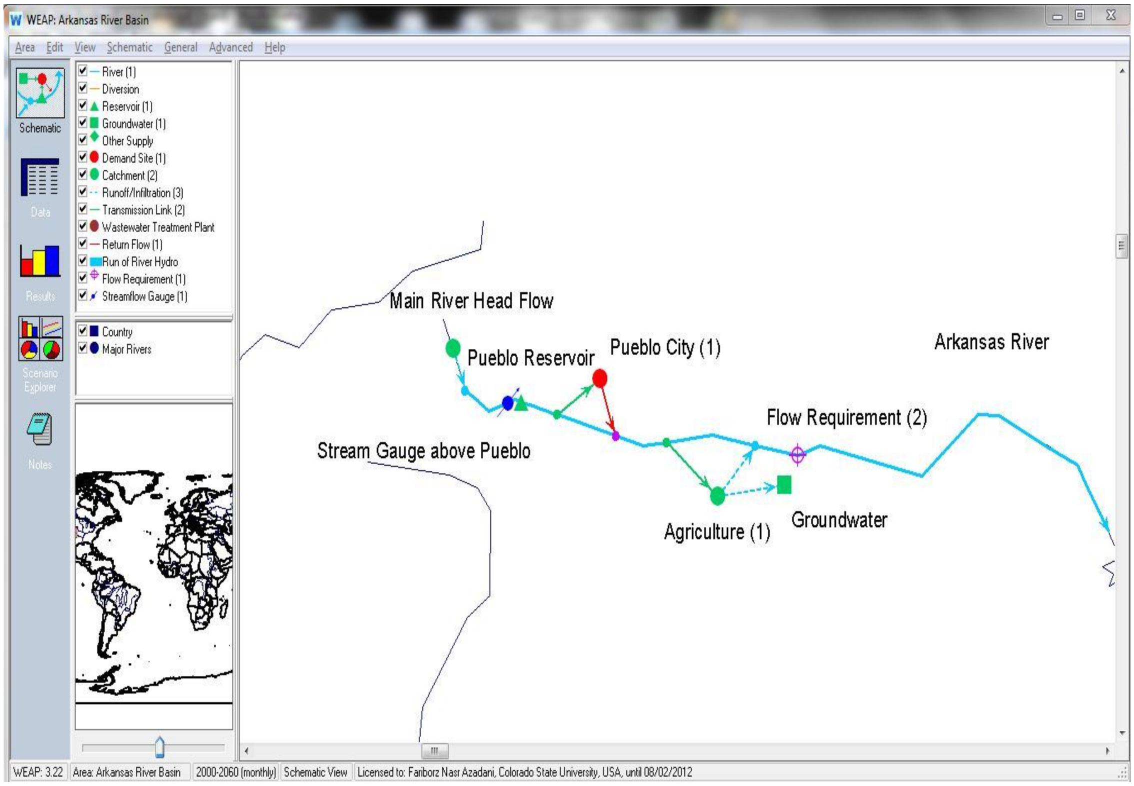
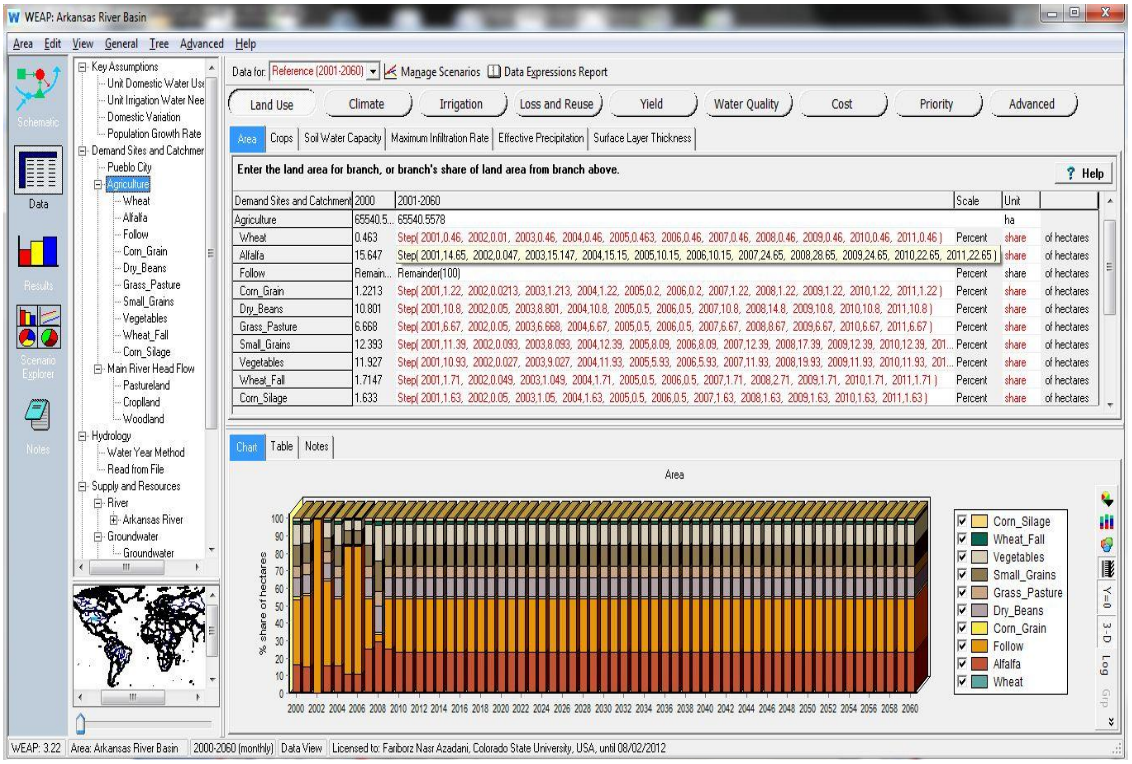


Figure 3. 5: Schematic view of WEAP



Data for: Reference (2001-2060)

Enter the land area for branch, or branch's share of land area from branch above.

Demand Sites and Catchment	2000	2001-2060	Scale	Unit	
Agriculture	65540.5...	65540.5578		ha	
Wheat	0.463	Step(2001,0.46, 2002,0.01, 2003,0.46, 2004,0.46, 2005,0.463, 2006,0.46, 2007,0.46, 2008,0.46, 2009,0.46, 2010,0.46, 2011,0.46)	Percent	share	of hectares
Alfalfa	15.647	Step(2001,14.65, 2002,0.047, 2003,15.147, 2004,15.15, 2005,10.15, 2006,10.15, 2007,24.65, 2008,28.65, 2009,24.65, 2010,22.65, 2011,22.65)		share	of hectares
Follow	Remain...	Remainder(100)	Percent	share	of hectares
Corn_Grain	1.2213	Step(2001,1.22, 2002,0.0213, 2003,1.213, 2004,1.22, 2005,0.2, 2006,0.2, 2007,1.22, 2008,1.22, 2009,1.22, 2010,1.22, 2011,1.22)	Percent	share	of hectares
Dry_Beans	10.801	Step(2001,10.8, 2002,0.05, 2003,8.801, 2004,10.8, 2005,0.5, 2006,0.5, 2007,10.8, 2008,14.8, 2009,10.8, 2010,10.8, 2011,10.8)	Percent	share	of hectares
Grass_Pasture	6.668	Step(2001,6.67, 2002,0.05, 2003,6.668, 2004,6.67, 2005,0.5, 2006,0.5, 2007,6.67, 2008,8.67, 2009,6.67, 2010,6.67, 2011,6.67)	Percent	share	of hectares
Small_Grains	12.393	Step(2001,11.39, 2002,0.093, 2003,8.093, 2004,12.39, 2005,8.09, 2006,8.09, 2007,12.39, 2008,17.39, 2009,12.39, 2010,12.39, 201...	Percent	share	of hectares
Vegetables	11.927	Step(2001,10.93, 2002,0.027, 2003,9.027, 2004,11.93, 2005,5.93, 2006,5.93, 2007,11.93, 2008,19.93, 2009,11.93, 2010,11.93, 201...	Percent	share	of hectares
Wheat_Fall	1.7147	Step(2001,1.71, 2002,0.049, 2003,1.049, 2004,1.71, 2005,0.5, 2006,0.5, 2007,1.71, 2008,2.71, 2009,1.71, 2010,1.71, 2011,1.71)	Percent	share	of hectares
Corn_Silage	1.633	Step(2001,1.63, 2002,0.05, 2003,1.05, 2004,1.63, 2005,0.5, 2006,0.5, 2007,1.63, 2008,1.63, 2009,1.63, 2010,1.63, 2011,1.63)	Percent	share	of hectares

Figure 3. 6: Data view

4- **Scenario Explore View:** This view is for displaying multiple required charts, or/and tables to explore effects of scenarios on the different parts of the water system such as ecosystem needs and water supply (Figure 3.7).

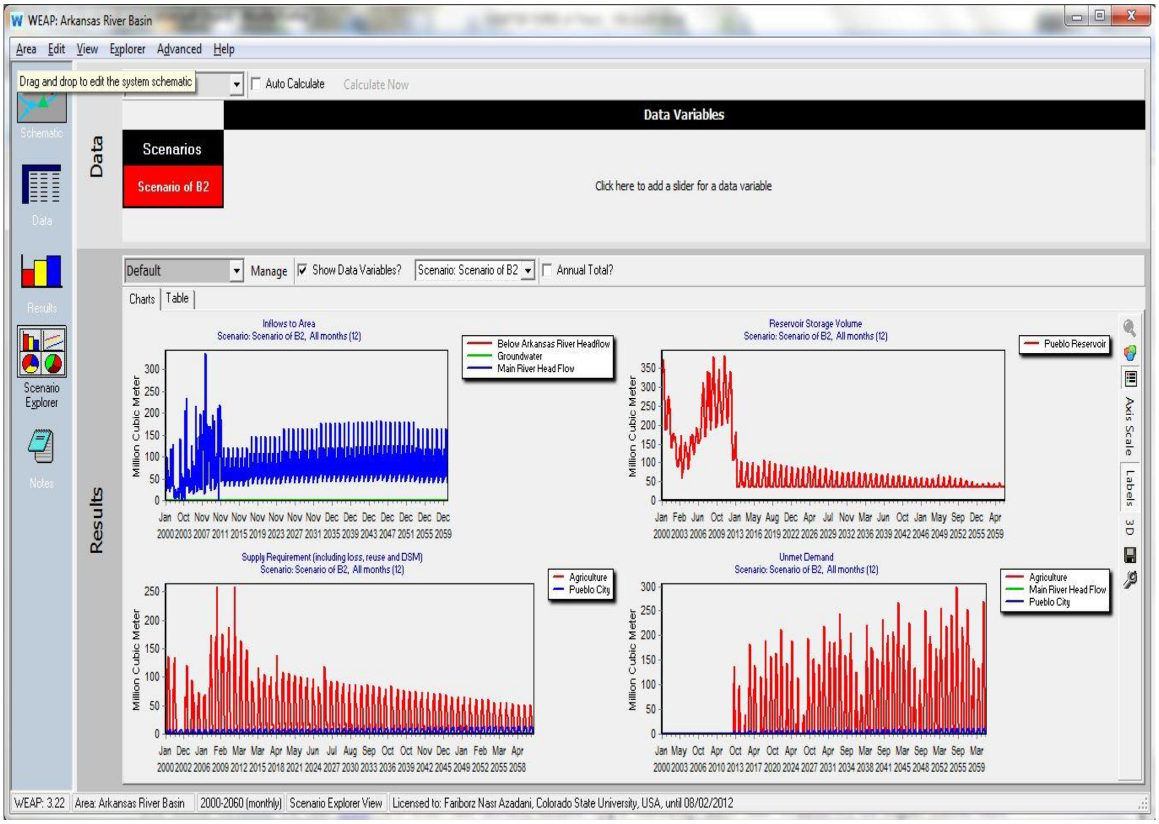


Figure 3. 7: Scenario explore view

5- **Notes View:** This is the place for entering and writing documents for the current account, references, and scenarios.

Modeling a watershed using WEAP is based on the following steps:

- Study area definition by setting up the spatial boundary, system components, and the time frame.

- Current account creation by specifying demands and supplies nodes. Since the current account is the basic description of the system used for modeling and for analyzing scenarios, this is important. The current account is also used for calibration of the existing situation in the water systems being modeled.
- Scenario creation based on policies, ecosystem constraints, etc., is used for addressing a wide ranges of "what if" questions such as: What if climate change alters hydrology? What if more efficient irrigation equipment is used? What if the pattern of agriculture crops changes?
- Scenario evaluation regarding policies, costs, water quantity and quality.

3.3.3 Demand

To model water consumption in the study area WEAP uses a disaggregated, end use approach so that at each node and for each time the demand is calculated from the lower level, e.g., consumption per capita, to the upper level, e.g. consumption for a city. WEAP has flexibility to structure demand data ranging from highly disaggregated to aggregated analyses. In general, a structure can include sectors such as municipal, irrigation, industry, and hydropower and these sectors can in turn be broken down to sub-sectors, depending on kinds of analyses desired and the availability of data.

Based on various measures of economic and social activities and hectares of irrigated farmlands, WEAP calculates water demand. For instance, water use rates of irrigated farmlands are multiplied to activity level (amount of hectares) to find the water requirement for the irrigation sector.

3.3.3.1 Overview of Methods of Demand Calculation

There are two demand calculation options, Monthly Demand and Annual Demand with Monthly Variation, to input and calculate demand.

1. The Monthly Demand option allows the user to input demands values month by month manually or using a ReadFromFile function, monthly demand can be read from a file.
2. The Annual Demand with Monthly Variation option can be used to express demand based on an annual level. Using it, one can enter an activity level (e.g., amounts of hectares) and water use rate (e.g., annual water consumption for each crop) associated with that activity level. Then one can use Monthly Variation to vary demand based on two options, user- defined expression or weight per days for each month.

Since the data which are used in the model are monthly, such as water consumption per capita and monthly demand for agriculture, the Monthly Demand option was used in this research.

Agriculture demands can be calculated either by simulating processes within the catchment like precipitation, infiltration, evapotranspiration, runoff and irrigation requirements or by multiplying activity levels by water use rates, as mentioned above.

3.4 Catchment

WEAP contains four methods (Irrigation Demands Only Method, Rainfall Runoff Method, Soil Moisture Method, and MABIA Method) to simulate catchment processes. These methods range from simple to complex and the choice of method depends upon the purpose of the analysis and the availability of required data. These four methods are (Wigley, 2007):

3.4.1 Irrigation Demands Only Method

The simplest method among the four methods is Irrigation Demands Only that is based on the FAO Crop Requirement approach (Allen, R. G., et al 2000). This method calculates the potential evapotranspiration in the catchment using crop coefficients then determines irrigation requirements in the event that potential evapotranspiration cannot be satisfied by rainfall. This method cannot simulate infiltration, changes of moisture in the soil, or runoff.

3.4.2 Rainfall Runoff Method (based on the FAO Crop Requirement)

This is similar to the Irrigation Demands Only method to calculate evapotranspiration using crop coefficients. The remainder of precipitation that cannot evaporate and transpire by soils and crops is simulated to be runoff to the river.

3.4.3 Rainfall Runoff Method (based on Soil Moisture Method)

The Soil Moisture Method is the most complex method and simulates the catchment with two soil layers along with potential for accumulating snow. Runoff and shallow interflow, moisture change in soils and evapotranspiration can be simulated in the upper soil layer. In the lower layer, the model simulates routing of base flow to the river and changes of soil moisture. Using this method, one can also characterize land use and/or soil types to explore effects on these processes. As a result, this method needs a lot of data to establish parameters to simulate soil and climate processes.

3.4.4 MABIA Method

The MABIA method was developed by Dr. Ali Sahli and Mohamed Jabloun at the Institut

National Agronomique de Tunisie (Sieber. J and D. Purkey, 2011). This method can calculate evaporation, transpiration, amount of water for irrigation and time of irrigation, interval of crop growth along with amount of yields for each crop. One of the interesting abilities of this method, in comparison with CROPWAT, is calculation of evaporation and transpiration separately, based on the dual Kc method.

The dual Kc method, as described in FAO Irrigation and Drainage Paper No. 56, (Allen, R. G. et al. 2000), is separated into a basal crop coefficient, K_{cb}, and evaporation, K_e, from the soil. The basal crop coefficient simulates actual ET situations when there is sufficient moisture in the root zone for transpiration while the surface of soil is dry. Both non-agriculture lands (e.g., woodland and grassland) and agriculture crops can be modeled by this method.

The time step in MABIA is daily and after computing evaporation, transpiration, infiltration, runoff, and irrigation requirement, the results can be aggregated to a monthly step. The MABIA calculation is based on the seven calculation steps which are:

1. Reference Evapotranspiration (ETref)
2. Soil Water Capacity
3. Basal Crop Coefficient (K_{cb})
4. Evaporation Coefficient (K_e)
5. Potential and Actual Crop Evapotranspiration (ET_c)
6. Irrigation
7. Yield

3.5 Supply and Resources

The Supply and Resources section is used to calculate the amount of supply from sources such as rivers, reservoirs, and groundwater. This section of the model simulates monthly river flows and tracks interaction of water surface and groundwater and reservoir storage. Subsections of Supply and Resources are:

- **Transmission Links:** Transmission links, which convey water from supplies (like rivers) to reservoirs, to demand sites are subjected to evapotranspiration, infiltration, capacity of supplies, and other constraints.
- **Rivers and Diversions:** This subsection simulates in-stream flows, reservoir operation, interaction of surface water-groundwater, and streamflow gages.
- **Groundwater:** This subsection simulates groundwater along with storage, natural recharge, and aquifer properties.
- **Local Reservoirs:** This subsection simulates reservoirs which are not located on the mainstream of the river.
- **Other Supplies:** This is used to model other sources of water, like inter-basin transfers, that are not directly modeled in WEAP.
- **Return Flows:** This subsection can simulate routing of wastewater or return flows from demand sites to wastewater treatment plants, groundwater, and/or rivers.

3.5.1 Hydrologic Inflow Simulation

One of the reasons for modeling water systems is to understand how a catchment responds to a variety of hydrologic conditions (e.g., month to month and year to year). WEAP can simulate and project water surface hydrology using four methods: the Water Year Method, Expressions, Catchments Runoff and Infiltration, and the Read FromFile Method. Using these methods, one can model monthly inflows to appropriate surface and ground water locations (or nodes) in the study area.

3.5.1.1 Water Year Method

Using the Water Year Method, one can explore the impacts of hydrologic pattern changes in the future by using historical data as a baseline condition. Future inflows can be modeled by changing inflow data in the Current Account, based on Water Year definitions and sequences. Water years can be defined as Very Dry, Dry, Normal, Wet, and Very Wet by varying inflows (e.g., from +25 % to -25 %) from the Current Account which is generally a normal inflow year.

3.5.1.2 Expressions

“Inflows can be specified with a mathematical expression. Typical expressions include: constants (e.g., groundwater recharge that doesn't vary over time), a specified value for each month (this is usually how the Current Accounts inflow data is specified when you are using the Water Year Method to project future inflows--using the Monthly Time-Series Wizard can be helpful in establishing these data), or some other relationship (e.g., the headflow for an ungaged stream could be modeled as some fraction of the headflow in another river for which good data exists)” (Sieber. J and D. Purkey, 2011).

3.5.1.3 Read From File Method

If monthly sequences of inflow data (historical and future projected) are available, this method allows one read this inflow sequence from a file to be used in the model of the water system.

3.5.1.4 Catchments Runoff and Infiltration

WEAP allows one to simulate catchment runoff using the Soil Moisture Method or using the Rainfall Runoff Method runoff. The simulated runoff is then directed to rivers and groundwater nodes using a Runoff/Infiltration link. This was the method used in this study.

3.6 Calculation Algorithms

The calculation process, as comprehensively described in the WEAP User Guide, is based on mass balance of water for every node and link and is subject to demand priorities, supply preferences, and water requirements. Calculation starts from the first month of the Current Account year to the last month of the last scenario. For non-storage nodes, such as points on a river, the currently month's calculation is independent from the previous month's calculation. For storage nodes, such as reservoirs, soil moisture, or aquifer storage, the storage for the current month depends upon the previous month's value. Whatever water enters the system during a month, it will either be stored in a reservoir, aquifer, or catchment soils, or leave the system by demand site consumption or evapotranspiration.

3.6.1 Demand Calculation

Annual Demand for each node is calculated by summing of the demands for the entire demand site's bottom-level branch (Br). "A bottom-level branch is one that has no branches below it." (Sieber. J and D. Purkey, 2011). For example, in a single family home the bottom-level branches would include showers and toilets.

The following equations are taken from the WEAP user manual:

$$AnnualDemand \ = \sum_{Br}(TotalActivityLevel * \ WaterUseRates)$$

“The total activity level for a bottom-level branch is the product of the activity levels in all branches from the bottom branch back up to the demand site branch (where Br is the bottom-level branch, Br' is the parent of Br, Br" is the grandparent of Br, etc.).”

$$TotalActivityLevel_{Br} = ActivityLevel_{Br'} * ActivityLevel_{Br''} * ActivityLevel_{Br'''}$$

For example,

$$\mathrm{TotalActivityLevel}_{\mathrm{Showers}} = \mathrm{ActivityLevel}_{\mathrm{Showers}} \text{ x } \mathrm{ActivityLevel}_{\mathrm{SingleFamily}} \text{ x } \mathrm{ActivityLevel}_{\mathrm{City}}$$

which calculates the percent of people in single family homes who have showers * percent of people who live in single family homes * number of people in the city. (Sieber. J and D. Purkey, 2011).

3.6.1.1 Monthly Demand

The monthly demand fraction for each month is multiplied by the adjusted annual demand to give the demand (m) for that month which is taken from the WEAP user manual. (Sieber. J and D. Purkey, 2011).

$$MonthlyDemand_{DS,m} = MonthlyVariationFraction_{DS,m} \, x \, AdjustedAnnualDemand_{DS} \qquad \text{Eqn. 3.1}$$

3.6.2 Catchment Calculation

The snowpack in the mountains at the western border of study region constitutes the major runoff in the Arkansas Basin. The Soil Moisture Method is the only method that can represent a catchment with two soil layers and the potential for snow accumulation. Therefore the Soil Moisture Method was selected to simulate Arkansas River for this research.

3.6.2.1 Soil Moisture Method Calculation

This method is one dimensional using the concept of two control volumes, called buckets, for soil moisture that include terms for evapotranspiration, deep percolation, surface runoff, and interflow for a catchment unit (Figure 3.8).

Deep percolation can be conducted to surface water (e.g., baseflow) or to groundwater if the appropriate link exists between groundwater and catchment unit nodes. In this method, the catchment unit can be separated to N sub-catchments to signify land uses/soil types and then water equilibrium is calculated for each sub-catchment, j of N, assuming climate is constant within each sub-catchment. The equation of the water balance along with the other equations which are taken from WEAP user manual are specified below (Sieber. J and D. Purkey, 2011).

$$\mathrm{Rd_j}\,\frac{\mathrm{dz_{1,j}}}{\mathrm{dt}} = \mathrm{P_e(t)} - \mathrm{PET(t)k_{c,j}(t)}\left(\frac{5\mathrm{z_{1,j}} - 2\mathrm{z_{1,j}^2}}{3}\right) - \mathrm{P_e(t)z_{1,j}^{RRF_j}} - \mathrm{f_j k_{s,j}\, z_{1,j}^2} - \left(1 - \mathrm{f_j}\right)\mathrm{k_{s,j} z_{1,j}^2} \qquad \text{Eqn. 3.2}$$

Where $\mathrm{Rd_j}$ (mm) is the land cover fraction, $z_{1,j}$ is relative storage [0, 1], based on the total effective storage of the root zone, and P_e is the effective precipitation based on the precipitation and snow melt from accumulated snowpack within each sub-watershed, where m_c is melt coefficient. The PET term is the Penman-Monteith reference crop potential evapotranspiration so that the crop/plant coefficient is defined by $k_{c,j}$ for each fractional land cover. The term $k_{s,j}$ is the root zone saturated conductivity (mm/time) estimate and f_j is the partitioning factor to partition water horizontally and vertically, based on the soil, type of land cover, and topography.

P_e can be defined by a melt coefficient, snow accumulation, and melt rate (equation 3.3, 3.4, 3.5 and 3.6). The melt coefficient (m_c) computation is:

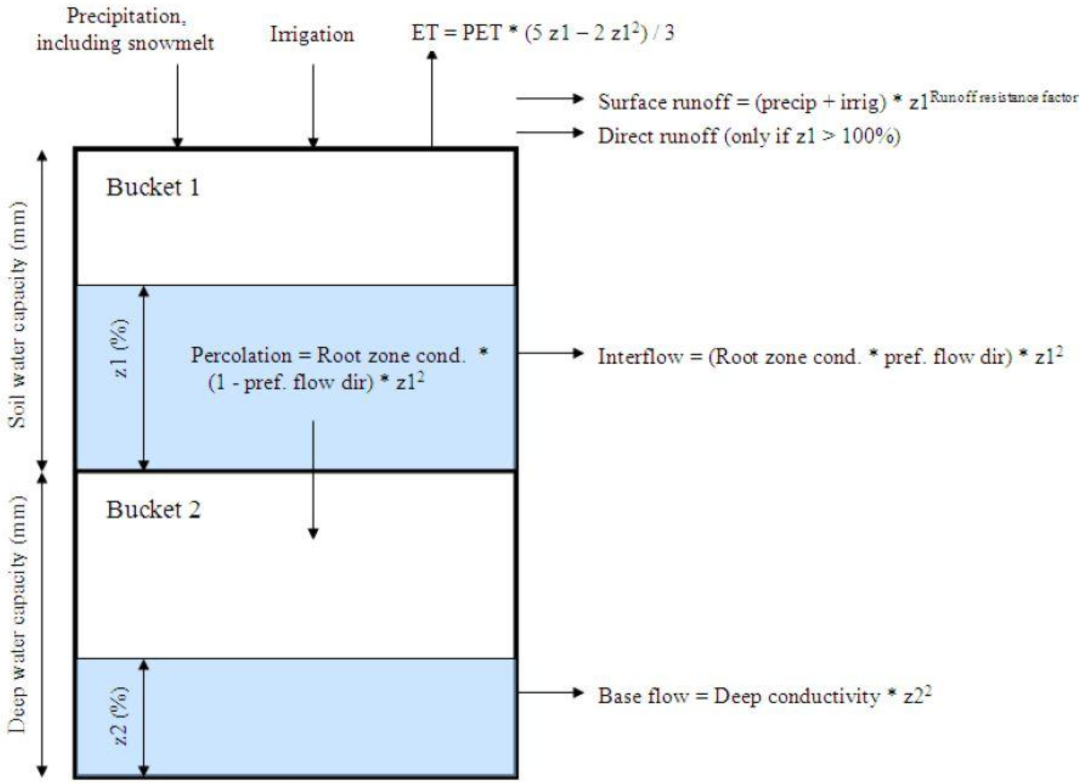


Figure 3. 8: Concept of soil moisture and equations (source: WEAP User Manual)

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 \quad \text{if} & T_i > T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & T_s \le T_i \le T_l \end{cases}$$ Eqn. 3.3

where T_s are temperature thresholds of melting and freezing while T_i is the measured temperature for month i.

The snow accumulation Ac_i computation is:

$Ac_i = Ac_{i-1} + (1 - m_c) P_i$ Eqn. 3.4

where P_i is the total measured precipitation for month i.

The melt rate m_r computation is:

$m_r = Ac_i \, m_c$ Eqn. 3.5

Then P_e is can be computed as

$P_e = P_i \, m_c + m_r$ Eqn. 3.6

In equation 3.2, the PET term is the Penman-Monteith reference crop potential evapotranspiration so that the crop/plant coefficient is defined by $k_{c,j}$ for each fractional land cover. The term of RRF_j is the Runoff Resistance Factor of the land cover. Low and high values of RRF_j may cause more or less surface runoff.

Interflow and deep percolation are defined by the fourth and fifth terms so that $k_{s,j}$ is the root zone saturated conductivity (mm/time) estimate and f_j is the partitioning factor to partition water horizontally and vertically, based on the soil, type of land cover, and topography.

Total surface and interflow runoff at time t for each sub-watershed, RT, can be computed as:

$$RT(t) = \sum_{j=1}^{N} A_j \left(P_e \, (t) \, Z_{1,j}^{RRF_j} + f_j k_{s,j} \, Z_{1,j}^2 \right) \qquad \text{Eqn. 3.7}$$

For the situation where there is no link from the catchment to the groundwater node, computation for emerging baseflow from the second bucket is:

$$S_{max} \, \frac{dz_2}{dt} = \left(\sum_{j=1}^{N} (1 - f_j) k_{s,j} z_{1,j}^2 \right) - \, k_{s2} z_2^2 \qquad \text{Eqn. 3.8}$$

Where the term of S_{max} is deep percolation from the first bucket, calculated in Eqn. 3.2, and K_{s2} is the saturated conductivity of the second bucket (mm/time).

If there is a link between the catchment and the groundwater node, then Eqn. 3.8 is ignored and aquifer recharge, R (volume/time) is calculated as:

$$R = \sum_{j=1}^{N} A_j (1 - f_j) k_{s,j} z_{1,j}^2 \qquad \text{Eqn. 3.9}$$

where A_j is area for sub-catchment j.

3.6.1.2 Reservoir Calculation

In general, the main purpose of the reservoir is to provide a source of water for demand sites during dry periods. WEAP can simulate a reservoir taking account the reservoir's operating rules, downstream requirement priorities, net evaporation on the reservoir, and hydropower generation.

Reservoirs can use a zone-based operation and reservoir storage is separated into four zones (Figure 3.9):

1- Flood-control zone (S_f) that can hold water temporarily therefore release can be controlled

2- Conservation zone (S_c) which is available storage for downstream demands

3- Buffer zone (S_b) that can be used to control and regulate water demands during dry periods

4- Inactive zone (S_i) which is dead storage.

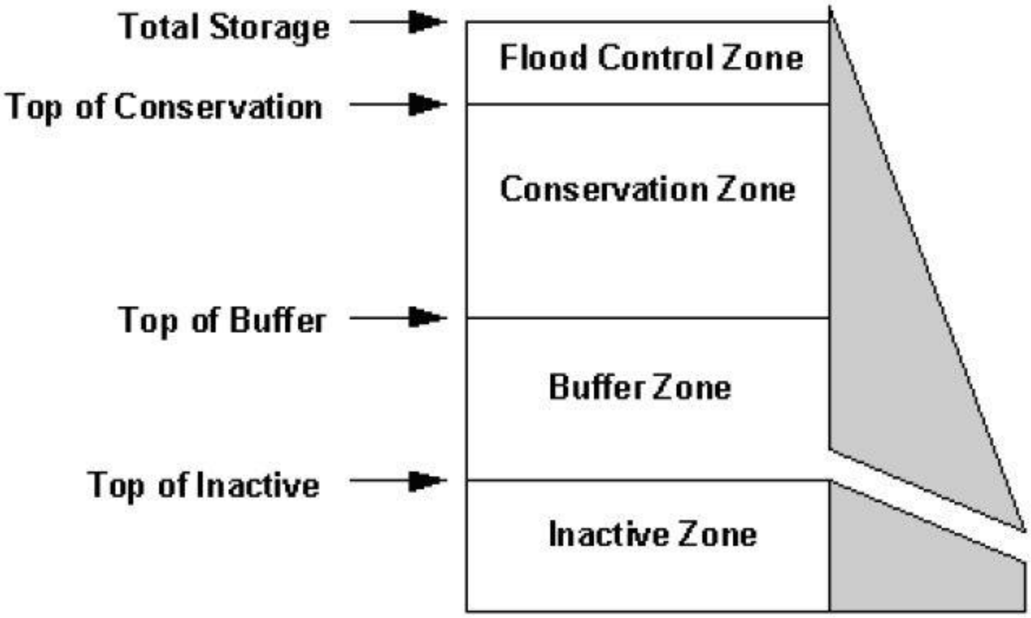


Figure 3. 9: Reservoir storage zones (source: WEAP User Manual)

The total amount of available water for release from a reservoir is the summation of the storage in the flood control zone, the conservation zone, and a fraction (given by b_c) of the storage in the buffer zone.

$$S_r = S_f + S_c + (b_c * S_b) \qquad \text{Eqn. 3.10}$$

Where S_r is total available water that can be released from the reservoir, S_f is storage of flood control, S_c is storage of conservation, and b_c is the buffer coefficient.

3.7 Arkansas River Basin Simulation

The WEAP software was used in this research to simulate the case study area in the Arkansas River Basin in Colorado. The design of the WEAP software made it ideal to use to simulate various climate change and adaptation scenarios. The components simulated are the Arkansas River, Pueblo Reservoir, the City of Pueblo (as the biggest urban demand), aggregated agriculture demands, and groundwater.

3.7.1 Arkansas River

The Soil Moisture Method was used to simulate the Arkansas River. The required data to use this method are:

1. Land use (Area, Kc, Soil Water Capacity, Deep Water Capacity, Runoff Resistance Factor, Root Zone Conductivity, Initial Z1, and Initial Z2)
2. Climate (Precipitation, Temperature, Humidity, Wind, Latitude, Initial Snow, Melting Point, Freezing Point)

Data from the SNOTEL Rough and Tumble Station, located in Park County, Colorado, was used to represent the climatic data, i.e., precipitation, temperature and snow depth. SNOTEL is operated by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture. The range of data is between 1998 to the present and monthly precipitation data was obtained from 2000 to 2011.

The U. S. Bureau of Reclamation website was used to obtain measured river flow data (http://www.usbr.gov/gp-bin/arcweb_puer.pl). The measured flow data were used to calibrate and validate the model.

3.7.2 Pueblo Reservoir

Pueblo Reservoir, part of the Frying Pan-Arkansas Project, serves about 650,000 people and irrigates around 281,000 acres. This includes the downstream communities of Colorado Springs in El Paso County all the way out to Lamar in Bent County on the Kansas border.

The required data for simulating the reservoir are:

1. Storage Capacity
2. Initial Storage
3. Volume Elevation Curve
4. Net Evaporation
5. Observed Volume (for calibration)

The storage capacity of Pueblo reservoir is 593.9 million cubic meters (MCM) and initial storage was set as 311.7 MCM, initial storage which was recorded for the first day of January of 2000, in the first month of the Current Account. The required data and volume elevation curve (Figure 3.10) were obtained from the U. S. Bureau of Reclamation, http://www.usbr.gov/gp-bin/arcweb_puer.pl.

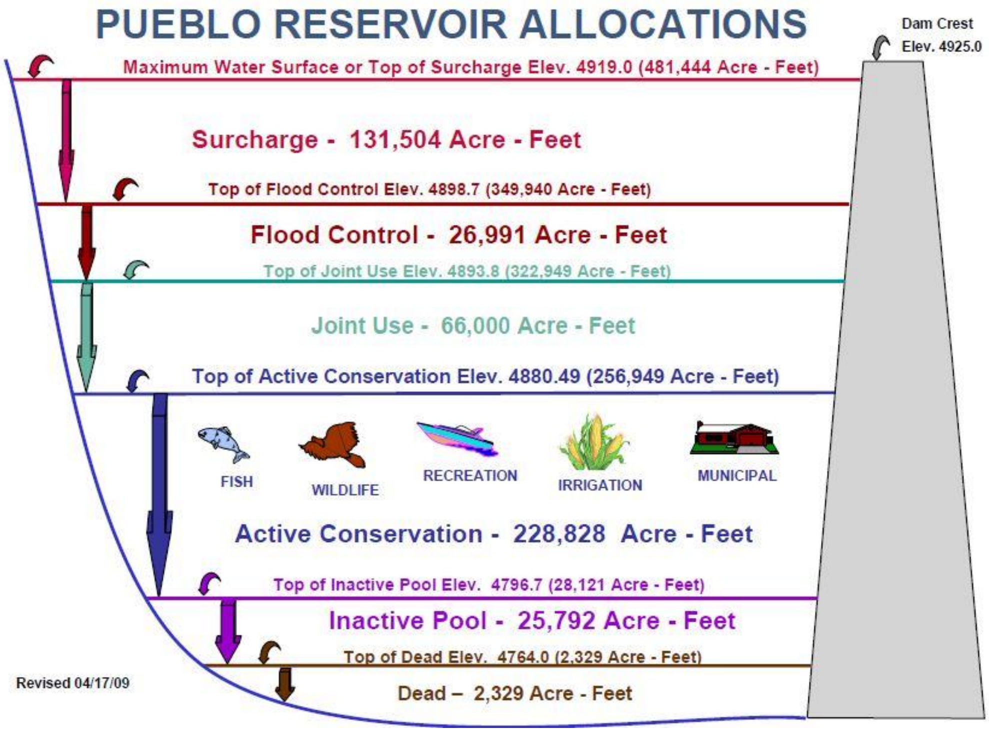


Figure 3. 10: Pueblo reservoir allocation (Sources: U. S. Bureau of Reclamation)

3.7.3 The City of Pueblo

The population of Pueblo in the year 2000 was about 142,000 and population growth is increasing at a rate of 1.1% per year. The annual water use rate is 261 m^3 per capita. In June, July, and August, the rate of water use as well as the rate of consumptive use is the highest. In December, January, and February, the rate of water use and rate of consumptive use is the lowest.

3.7.4 Agriculture Lands

The MABIA method can calculate evaporation, transpiration, amount of water for irrigation and time of irrigation, interval of crop growth along with amount of yields for each crop. This method was used to simulate water use on agriculture lands in the Arkansas River basin. Using this method, the type of crops and irrigation schedule can be defined which are very important to define amount and time of water requirement for agriculture sector. The required data are as following:

1- Land Use (area, crops, soil water capacity, effective precipitation)
2- Climate (precipitation, ET reference, latitude, wind)
3- Irrigation (irrigation schedule, irrigation efficiency, loss to runoff)

The agriculture area is 65541 ha and wheat, alfalfa, corn grain and silage, dry beans, vegetable, and small grains are common crops. The monthly measured precipitation and ET reference data were obtained from the Avendelon station, on the CoAgMt, http://climate.colostate.edu/~coagmet/index.php. Effective precipitation is 95 percent, in general. The amount and time of irrigation is determined using a percentage of depletion, and Readily Available Water (RAW). Crops are irrigated when soil moisture depletion is greater than or equal to a specified percentage of RAW. To prevent crop water stress, depletion should never exceed RAW.

3.8 Model Calibration and Validation

The calibration of an integrated river basin model, such as WEAP, is a challenging process. The calibration is described in detail in the next chapter. In general, calibration is process of adjusting the parameters of the models to appropriately simulate historical observations. For this research, the monthly observed streamflow data from 2000 to 2011 into Pueblo Reservoir were used to calibrate and validate the WEAP model. To calibrate the model the data from 2000 to 2006 were used to estimate the model parameters. The stability of these parameters was tested in the validation period of 2007 to 2011.

3.9 Scenario Creation

Scenarios explore how a water system will respond to different conditions (e.g., new policies, population change, climate change, new technologies). The simulated results from the scenarios are compared against a reference scenario to assess their impacts on the water system. All scenarios are based on the Current Account year reference period.

Three adaptation scenarios were created to assess their potential to mitigate of the impacts of climate change on the Arkansas River Basin. Since climate change and increasing population will increase the demand for water, and agricultural demand is the largest use, the scenarios explore potential options to reduce agricultural demands. All scenarios were built and analyzed for the period 2012 to 2040. The three adaptation scenarios are following as:

1. New irrigation technology scenario, which is the introduction and use of new irrigation technologies, such as drip and sprinkler irrigation, which can minimize the volume of water use for the irrigation sector.

2. New irrigation technology along with crop change scenario, which is introduction of new irrigation technologies along with change of crops that require less water such as soybeans and safflower.
3. New irrigation technology along with reducing crop area scenario, which is introduction of new irrigation technologies along with decreasing the amount of irrigated farmland area. (The crops are the same as in scenario 1).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

The results of climate change impacts and analysis of scenarios in the Arkansas River basin using MAGICC/SCENGEN and WEAP are presented in this chapter. Previously the four scenarios for climate change defined by the IPCC (2007) were described. For this study, two climate change scenarios were analyzed and for each climate change scenarios, three adaptation scenarios were analyzed that are based on the reference scenario. Since increasing population growth is between moderate and high, the two climate change scenarios analyzed are A2-ASF and B2 ASF and these scenarios are used to project future precipitation and temperature to 2040. The 550 ppm policy was also analyzed since it represents less severe climate change impacts. The effects of these climate scenarios and the 550 ppm policy on the water resources of the Arkansas basin were analyzed using the WEAP model. The three adaptation scenarios were analyzed to consider the impacts of adaptation scenarios on the water resources of the basin.

4.2 Streamflow and Reservoir Calibration Results

Calibration and validation of streamflow and reservoir are necessary to make sure the WEAP model is correctly representing the current situation in the study area. Therefore WEAP was calibrated and validated before analyzing the scenarios. The period of 2000 to 2011 of the streamflow data were used for calibration and validation of the model (Figure 4.1). Note that Figure 4.1 displays both the calibration and validation periods. In additional to visual comparison of the predicted and observed values, the performance of model was also assessed by statistical measures of calibration; Root Mean Square error (RMSE), correlation (R^2) which are explained in the following equations (Anderson, D.R. et al. 1994).

$$E_{t,i} = error = Q_{t,i\,measured} - Q_{t,i\,simulated} \tag{4.1}$$

$$Total\ Squared\ error = \sum_{t=1}^{T} \sum_{i=1}^{m} E_{t,i}^2 \tag{4.2}$$

$$Root\ Mean\ Squared\ error\ = \sqrt{\frac{1}{T}\sum_{t=1}^{T} \frac{1}{m}\sum_{i=1}^{m} E_{t,i}^2} \tag{4.3}$$

$$Root\ Mean\ Squared\ error\ percentage = \frac{\sqrt{\frac{1}{T}\sum_{t=1}^{T} \frac{1}{m}\sum_{i=1}^{m} E_{t,i}^2}}{Q_{t,i\,measured}} \times 100 \tag{4.4}$$

$$Correlation\ , R^2 = \left\lfloor 1 - \frac{SSE}{SST} \right\rfloor \tag{4.5}$$

$$SST = \sum_{t=1}^{T} (Q_{t,measured} - \overline{Q}_m)^2 \tag{4.6}$$

Where *i* is number of the point data and *t* is time.

The Root Mean Squared Error (RMSE) incorporates both the variance of the estimator and its bias (Lehmann, E. L., Casella, G. 1998). R^2 is a statistical measure of how well a regression model matches observed data points. If R^2 equals to one that means there is a perfect fit between observed data and predicted values with the model.

The analysis showed RMSEs and RMSE% are 22.32 and 29.35 (MCM/mo) for stream-flow and reservoir storage and 0.046% and 0.048% for streamflow and reservoir storage respectively as well as R^2 are 0.79 and 0.86 for streamflow and reservoir storage respectively. Evaluation of the graphs and the statistical analysis indicates that the model is reproducing the observed data reasonably well.

For calibration of streamflow, the land use factors which are area of each type of land-use (pastureland, woodland, and cropland), crop coefficient (Kc) related to each crop, and soil properties (root zone conductivity and deep zone conductivity) were spatially aggregated and modified. The calibration was started with an initial area of each type of land-use in the watershed and an estimate of the soils in the watershed, based on the data which have been obtained from Colorado Division of Water Resources, http://water.state.co.us/Home/Pages/default.aspx, and US Department of Agriculture, http://www.usda.gov/wps/portal/usda/ us-dahome. It is recognized that there is imprecision in this data. The soil distribution is not uniform but is highly variable throughout the watershed and the area of each type of land-use is an estimate.

The goal of calibrating the watershed rainfall runoff model in WEAP was not to exactly represent the true runoff properties of the existing watershed but rather to develop a good representation of the existing streamflow that could serve as a base condition for the climate change analysis. By adjusting the parameters of area and Kc for each crop type along with soil properties, the model was able to get reasonably good match to observed samples. For assessing the climate change impact, it is assumed that the basic characteristics of the watershed, that is the areas in each type of land-use and the soil properties, will not change for the projected period of analysis to 2040. Once a set of characteristics for the watershed have been selected, there is a further assumption that the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions. While the changing temperature and precipitation conditions will impact the runoff simulation through increased evapotranspiration for example and reduction of baseflow, it is assumed that the watershed runoff characteristics will not substantially change as a result of climate change.

Figure 4.1 shows the observed and simulated time series of streamflow for the reference scenario. The trend of simulated flow is reasonably close to the trend of observed streamflow and both the calibration and validation periods show a similar fit to the data. However, there are some differences in the observed and simulated values. The reason for these deviations might be errors in the amount and distribution of precipitation over the watershed, errors in evapotranspiration estimates, or errors due to other factors that the model did not account for.

Water is being released from Pueblo reservoir to satisfy demands for water for Pueblo city, agriculture land uses between Pueblo and John Martin reservoirs, and in-stream flow for ecosystem and downstream purposes. The water requirement data of the city of Pueblo was obtained from the Board of Water Works of Pueblo. The consumption use per capita was determined for each month for years 2001-2007. Agricultural land uses were obtained from the Colorado Water Division of Water Resources. Based on these data, the area of agriculture lands, between Pueblo and John Martin reservoirs, is about 65540 ha. The common crops are alfalfa, small grains, vegetables, dry beans, grass and pasture, wheat, corn silage, and corn grain. The water requirement for each crop was determined by the MABIA Method which was explained previously.

For calibration of the reservoir storage, the least precise input data are the estimate of demands and the inherent assumption about how the reservoir will be operated using the zones. The operating zones were based on the information provided by the USBR and it is assumed that these zones will not change over the projected period up to 2040. Estimated demands were based upon urban population, agricultural area, and a distribution of crops within the agricultural area. It is important to understand that there is imprecision in the estimate of the demands and also important to realize that reservoir operators use the zones as operational guidelines, not

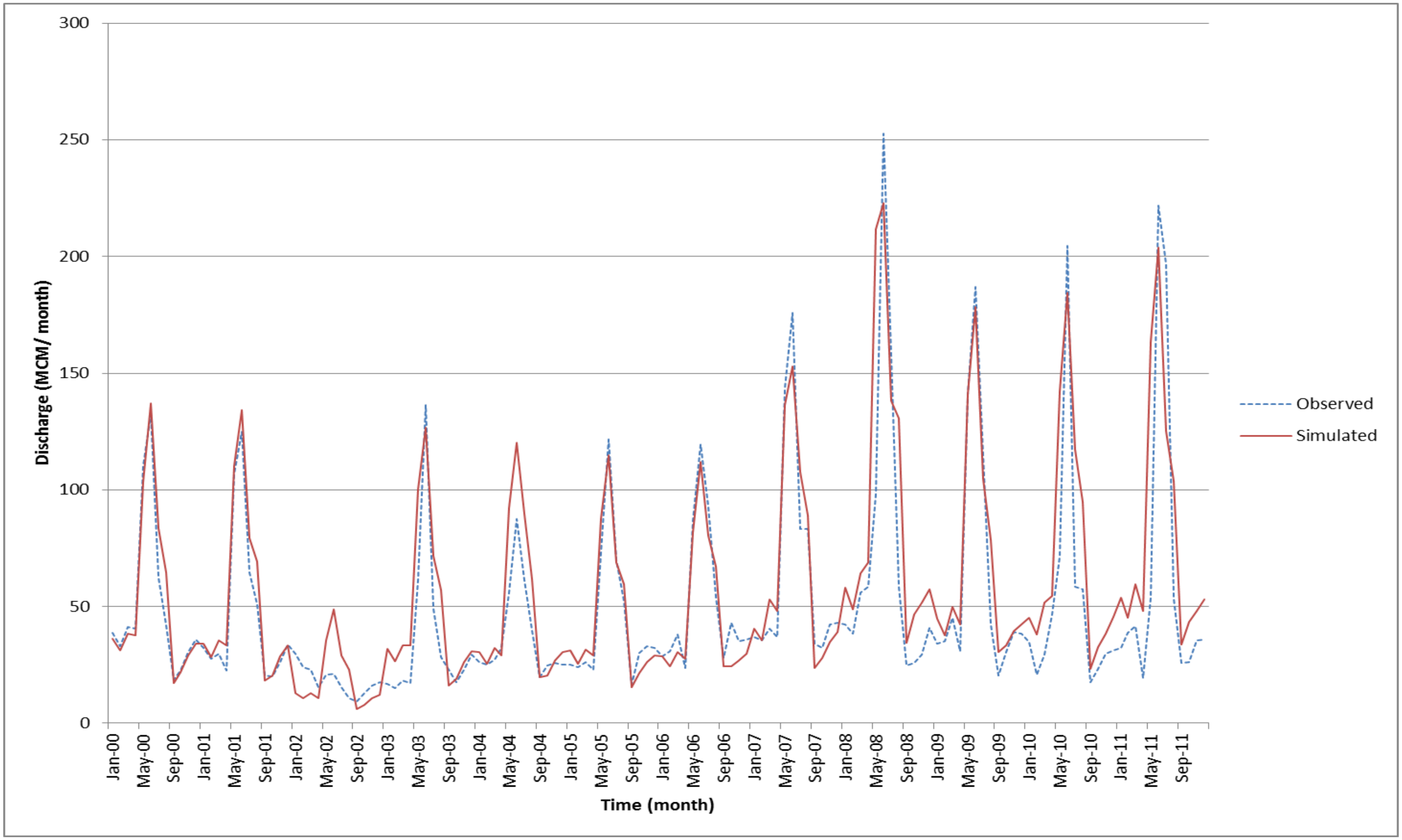


Figure 4. 1: Calibration and validation of streamflow

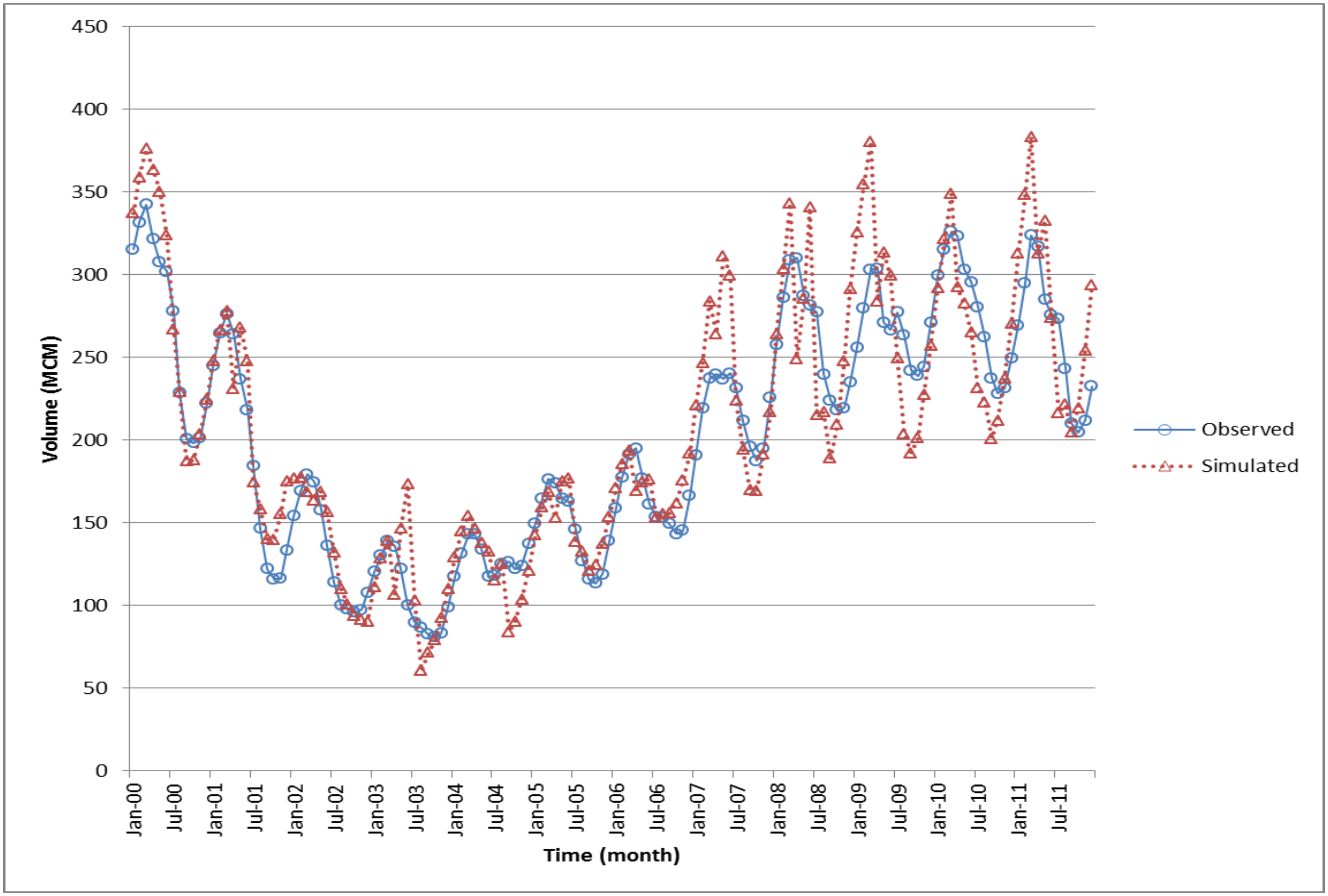


Figure 4. 2: Calibration and validation of Reservoir

necessarily firm rules.

Figure 4.2 shows the simulated volume trend follows the observed volume trend reasonably well however there are some differences. The simulation of storage levels is much better in the early part of the record as opposed to the ending part of the record. The latter part of the period is the validation and a worst fit might indicate that the data and parameters used in the calibration period are not stable over time. There are many reasons that might cause this, the two most obvious ones being that the demand estimates or perhaps the type of crops grown changed during this latter period, or that the reservoir operators were not strictly following the zone information obtained from the USBR. To make the projections of the impact of climate change to the year 2040, it was assumed that the pattern of the demands, that is urban consumption and the amount of agricultural area along with the type of crops allocated within that area, would not change. While this assumption will not strictly be true, what the study is attempting to analyze is the potential impacts of climate change if the exact agricultural demands continue to be used in the future. In other words the study attempts to create a representative snapshot of what the current operation is and then to estimate how that snapshot would respond to different kinds of future conditions in terms of temperature and precipitation. It's important to stress, that the study is not predicting the future but rather assessing how our current conditions would be impacted in a future with changes in temperature and precipitation. While the poorer fit to the data at the end of the storage period in our calibration indicated something may be changing with time, there was no systematic way to estimate what data or parameters or operational policies might be changing and further to predict the nature of the change. Overall the calibration of the existing situation in terms of streamflow and storage levels is reasonable and therefore it was assumed that for the purpose of this study , the reservoir operators would follow these operational zones and that the zones would not change over the projected scenario to the year 2040.

4.3 Changes in Climate

As mentioned previously, three GCM models were used to assess impacts of climate change under two climate scenarios (A2 and B2).

4.2.1 Scenario A2

The scenario A2 is based on the high population growth with regional economic development. The impact of high population growth along with regionally economic development was modeled by the MAGICC tool (Figures 4.3 and 4.4). Figure 4.3 shows the emission of carbon dioxide which is anticipated to gradually increase until 2100 based on the A2 scenario. Based on the 550 ppm policy scenario, it is expected the emission of carbon dioxide will increase until about 2035 and then decrease until the year 2100.

Figure 4.4 presents the change of temperature based upon the three combined climate models. The projection shows that temperature is anticipated to be increased by 3.8^{o} C globally based on the A2 scenario.

The A2 scenario was regionalized to the Arkansas River Basin using the SCENGEN tool. The SCENGEN tool was run 672 times ($12\ {}^{month}/_{year} \times 28\ years\ \times\ 2$ characteristics (*precipitation and temperature*) = 672 *runs*) to project precipitation and temperature for each month between 2012 and 2040 (Figures 4.5 and 4.6).

The changes in precipitation are provided on a monthly basis and these changes must be applied on a monthly basis. These changes were added or subtracted from the each month of the

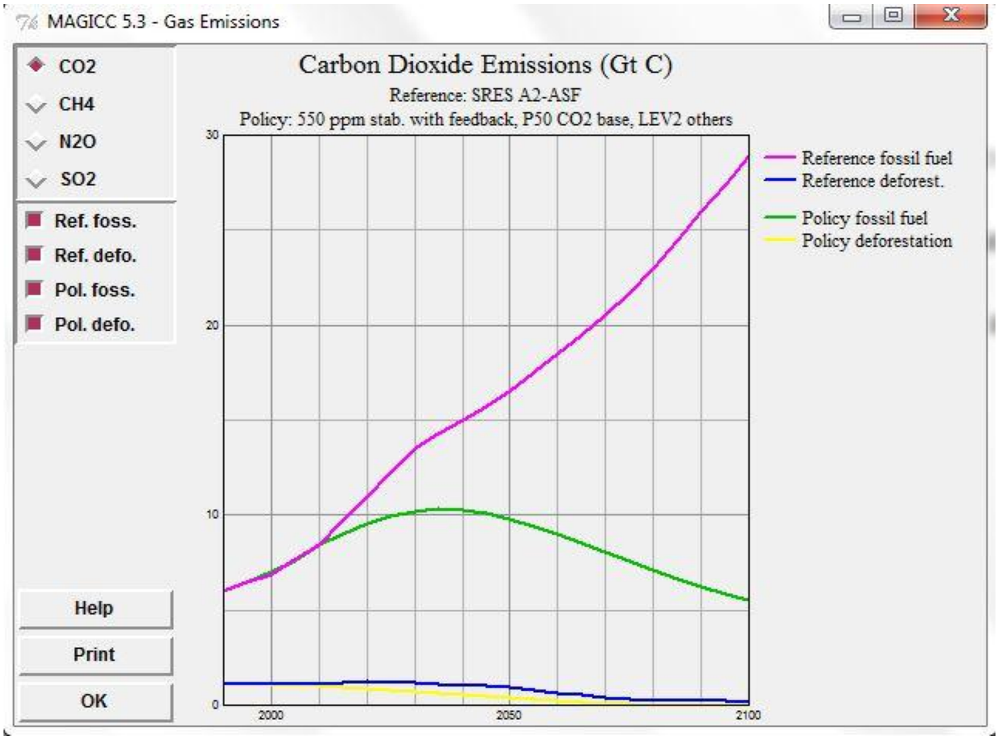


Figure 4. 3: Emission of carbon dioxide based on the A2 and 550 ppm policy scenarios

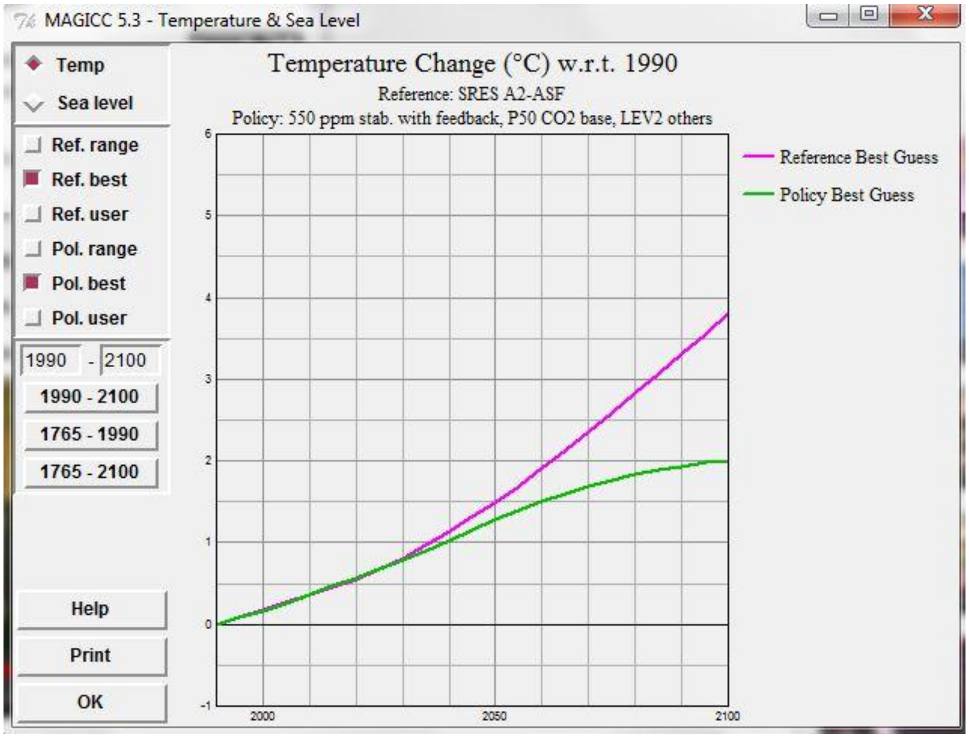


Figure 4. 4: Change of temperature based on the A2 and 550 ppm policy scenarios

reference year. For defining the reference year, the period of 1960 to 1990 was used to calculate average precipitation and the reference year was selected as the closest year to the average precipitation which is 1989. The long-term demands on the river system are practically limited to a fraction of the mean annual flow. Choosing an average year would be the most reasonable in assessing the long-term ability to meet demands on average. Essentially then what is assumed for the projected period is that the average year or the reference year occurs every year of the projected period. In other words this completely eliminates the year-to-year variability in the record. Again the interest of this climate study is not to look at how the situation will vary year-to-year but instead to look at what will happen to the longer-term ability to meet demands as climate change continues to reduce precipitation. Based on the annually projected precipitation, the amount of precipitation will be decreased until 2040 and then will be increased gradually until 2100 so the period of 2012 to 2040 is the more critical period.

Figure 4.5 shows the projection of monthly temperature in the Arkansas River Basin in Colorado. The projection shows that warmer climate is anticipated for the region so that the change of temperature is between 0.5 C^o and 5 C^o for the winter and summer seasons.

Figure 4.6 shows the projection of precipitation for the region. Based on this projection, the precipitation is anticipated to increase for the months of January, March, and August between 1% and 20% and to decrease for the other months between -1% and -20%. The reason that pattern is so similar over time is that the monthly projected precipitation was based on changes in percentage, which were added or subtracted from each month in the reference year (1989). For example, the projected change in precipitation for the month of June in 2017 is -8.9% and amount of precipitation in June of the reference year of 1989 is 28.78 mm.

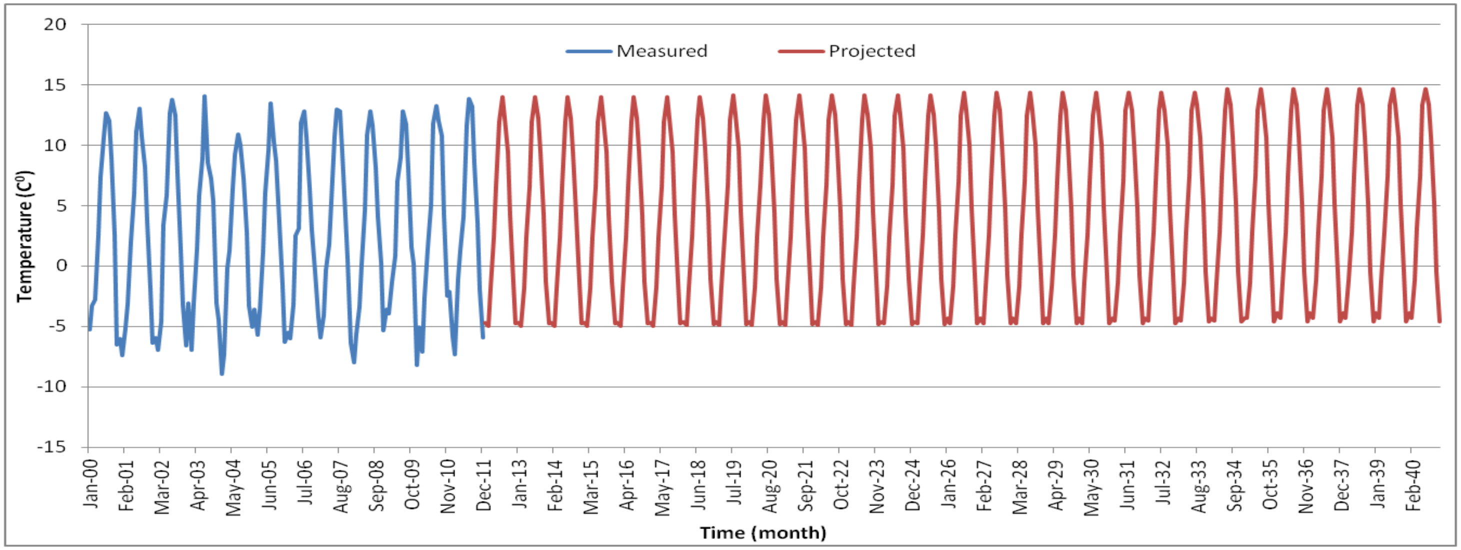


Figure 4. 5: Projected temperature based on the A2 scenario

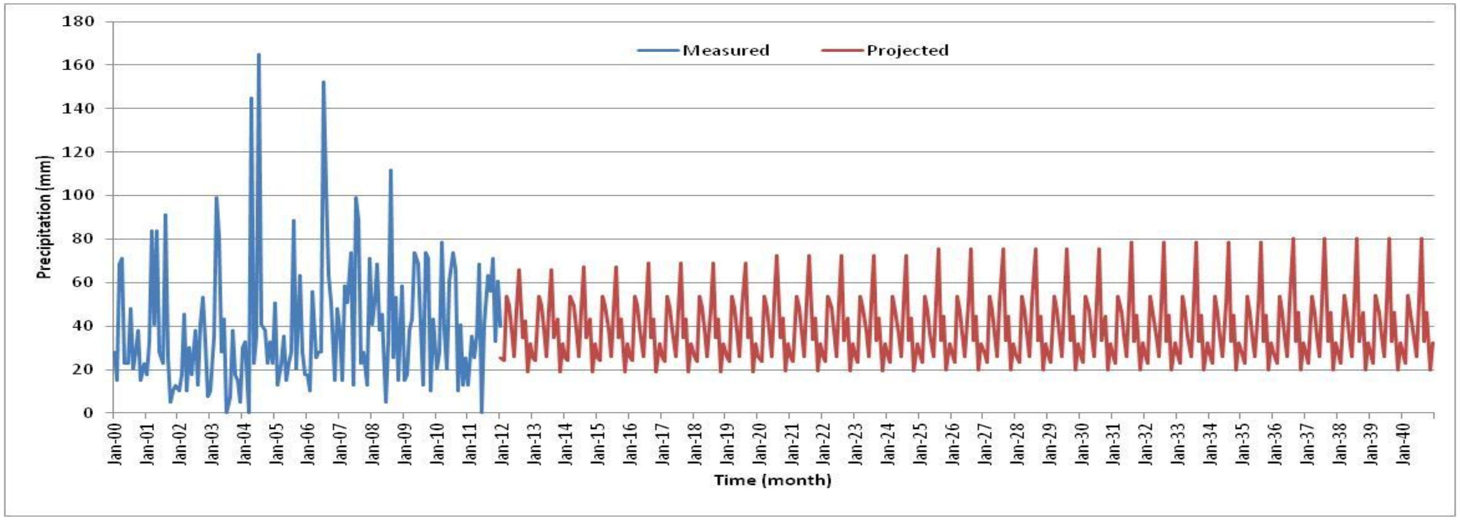


Figure 4. 6: Projected precipitation based on the A2 scenario

Therefore, the amount of projected precipitation for the month of June equals 26.22 mm ($28.78\,mm - 28.78 * 8.9\% = 26.22\,mm$). Since the percentage change pattern is similar from year to year, even though the amount of the percentage is changing, the projected precipitation pattern is similar.

4.2.2 Scenario B2

The B2 scenario represents a world with moderate population growth along with an intermediate level of economic development. The impact of moderate population growth along with an intermediate level of economic development was modeled by the MAGICC tool (Figures 4.7 and 4.8).

Figure 4.7 shows the emission of carbon dioxide which is anticipated to increase rapidly until 2030 and then increase gradually until 2100. Based on the 550 ppm policy scenario, it is expected the emission of carbon dioxide will increase until about 2035 and then decrease until the year 2100.

Figure 4.8 presents the change of temperature. The projection shows that temperature is anticipated to be increased by 3.4^{o} C globally based on the B2 scenario.

The SCENGEN tool was run to regionalize precipitation and temperature based on the B2 scenario on the Arkansas River Basin. The precipitation and temperature was projected for each month between 2012 and 2040 (Figures 4.9 and 4.10).

Figure 4.9 shows the projection of temperature for the region. The region is anticipated to be warmer. The change of temperature is expected to be between 0 C^{o} and 5 C^{o} for the winter and summer seasons.

Figure 4.10 shows the projection of monthly precipitation in the study area. Based on this scenario the amount of increasing precipitation for three months of January, March, and August is lower in compassion with the A2 scenario while the decreasing amount of precipitation for the other months is more than the A2 scenario although the differences are between 1% and 10%.

4.4 Scenario Analysis

Scenario analysis allows decision makers and water managers to answer "what if" questions related to water systems. The reference scenario, based on the Current Account, is the base scenario and the other scenarios are based on the reference scenario by varying the supply and/or demands. Demands were projected for urban use by multiplying the population times a per capita use rate. The population was projected to the year 2040 by using an annual growth rate of 1.1% and a base population of 142,000 in the year 2000. Therefore the urban demand increases throughout the analysis period. It was assumed that the area of the agricultural lands (65541 ha) and the types of crop would stay the same for the purposes of the baseline scenario. Therefore the agricultural demand is constant over time. The projected demands are illustrated in Figure 4.11. It is important to note that the projected demands and model results are shown beginning in 2014. The simulations were actually made beginning in 2012; however, the first two years of the simulations were used for model warm-up and are not shown in the model results.

4.4.1 Scenario one: Impact of the A2 Scenario

Scenario A2 is based on high population growth with regional economic development. The impact of scenario A2 was modeled in the study area and the results are compared to streamflows and storage levels in Pueblo Reservoir (Figures 4.12, 4.13 and 4.14). Figure 4.12 shows that streamflow will decrease in the future. There are various reasons why decreasing

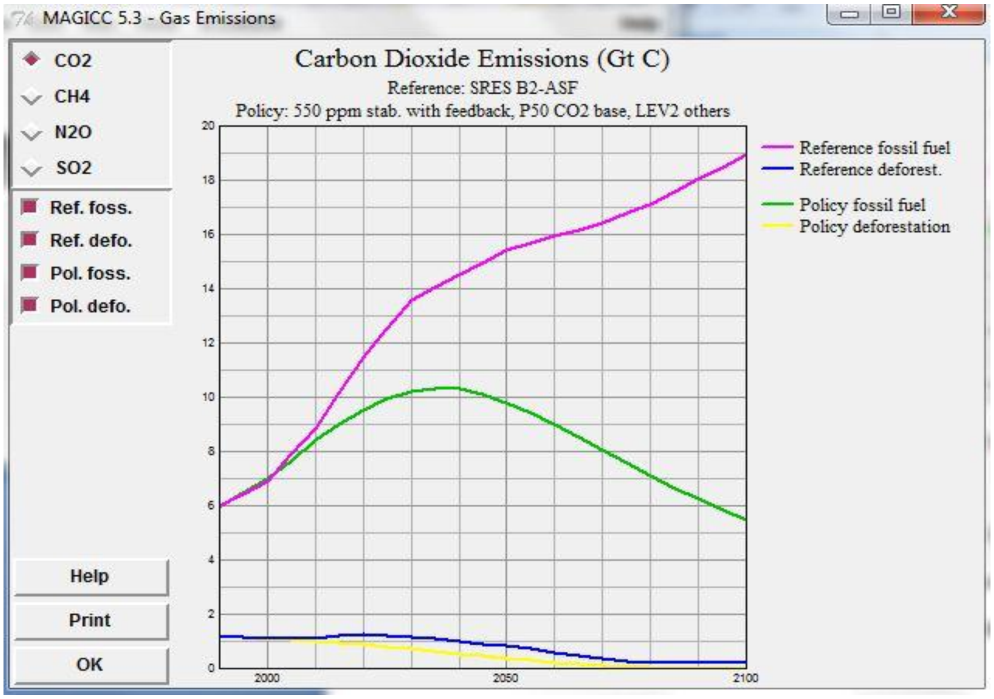


Figure 4. 7: Emissions of carbon dioxide based on the B2 and 550 ppm policy scenarios

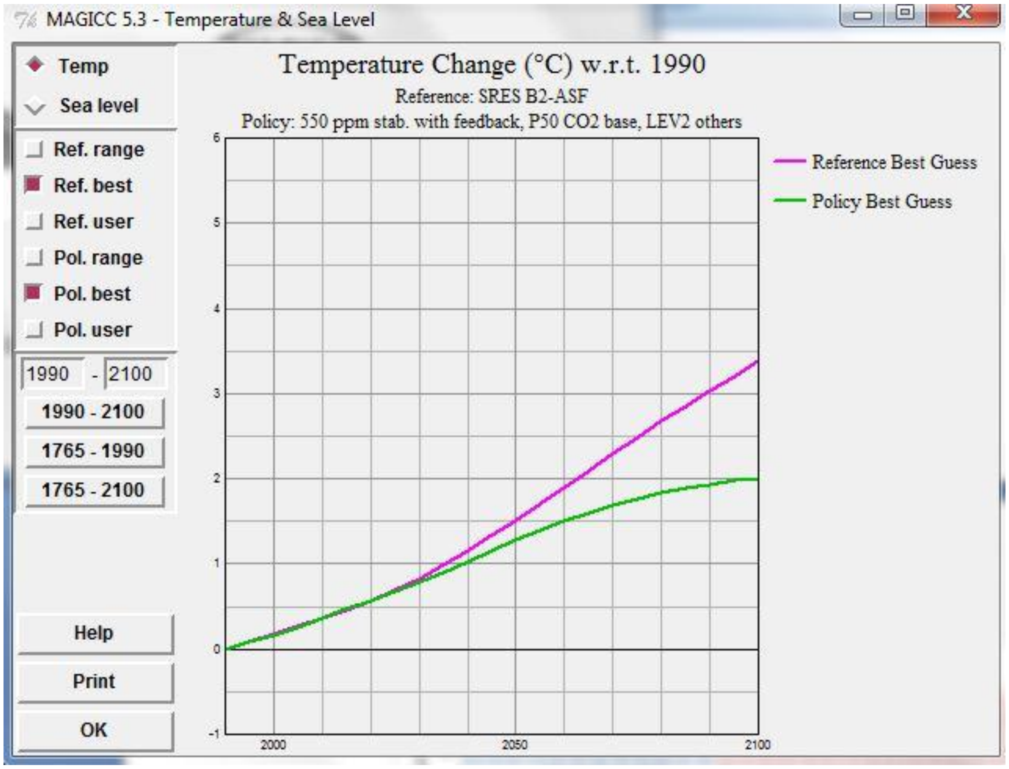


Figure 4. 8: Change of temperature based on the A2 and 550 ppm policy scenarios

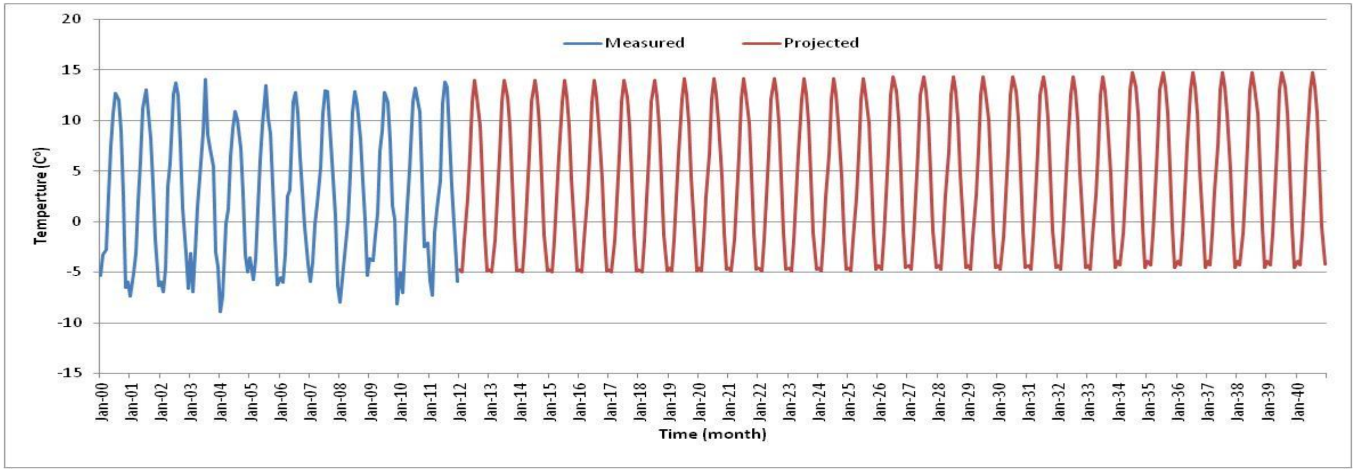


Figure 4. 9: projected temperature based on the B2 scenario

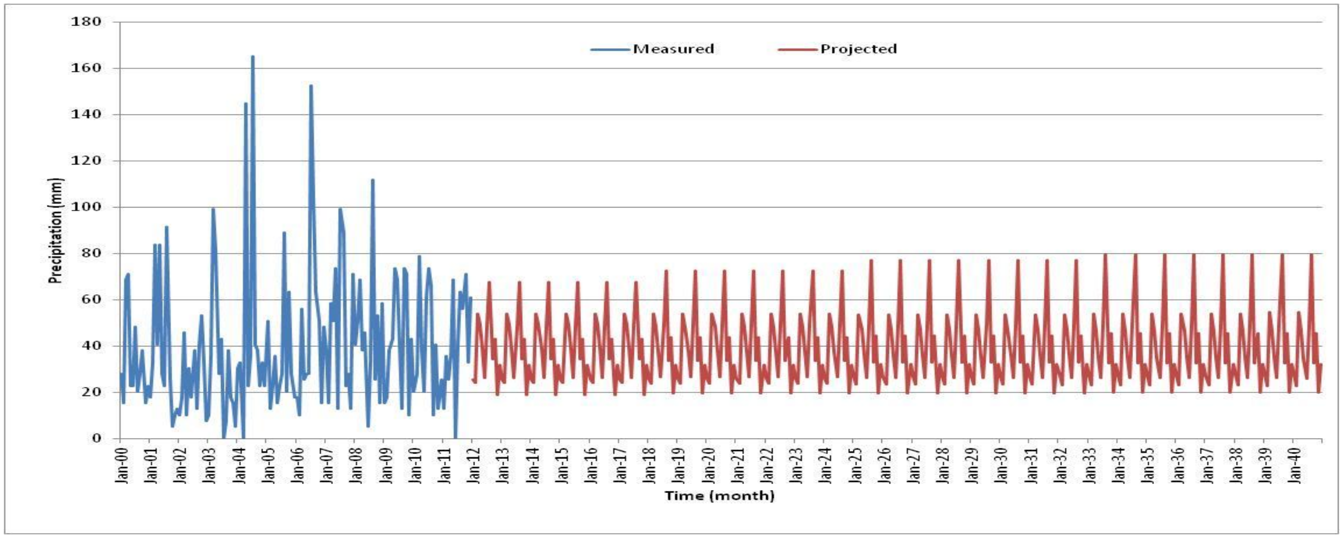


Figure 4. 10: Projected precipitation based on the B2 scenario

streamflow would be expected. The first reason is that temperature is increasing resulting in increasing evapotranspiration by crops, and therefore the soil will be dried more and sooner. In this situation plant roots would try to uptake water from deeper layers. Also due to a more negative potential suction, capillary force will uptake more water from deeper layers. As a result the groundwater table will likely decrease and therefor the amount of base flow which is contributed to streamflow will be decreased. Another reason is that the amount of precipitation is being decreased due to increasing temperature. In this situation much of the precipitation will be infiltrated into the soil, which is drier due to high temperature and evapotranspiration. Therefore the combination of all these processes can be lead to less available runoff.

Figure 4.13 shows that the reservoir storage will decrease significantly. This is because of increasing population, increasing temperature and decreasing precipitation. In this situation most of the agricultural lands will be more dependent on reservoir releases. Unfortunately the amount of inflow to the reservoir is decreasing and the net evaporation from the reservoir would increase due to the increasing temperature. Figure 4.14 illustrates the amount of unmet demands, or shortages, due to climate change impacts. Some of these unmet demands are large and have an order of magnitude approaching 40 – 50% of the demand. The unmet demands are the total shortage of the urban and agricultural shortages. The simulations assumed an equal priority to both urban and agricultural demands, and therefore both demands will have shortages.

4.4.2 Scenario Two: Impact of the B2 Scenario

The B2 scenario represents a world with moderate population growth along with an intermediate level of economic development. Figures 4.15, 4.16 and 4.17 show the impacts of the B2 scenario on the upper Arkansas River basin, Pueblo Reservoir and the ability to satisfy demands. In this

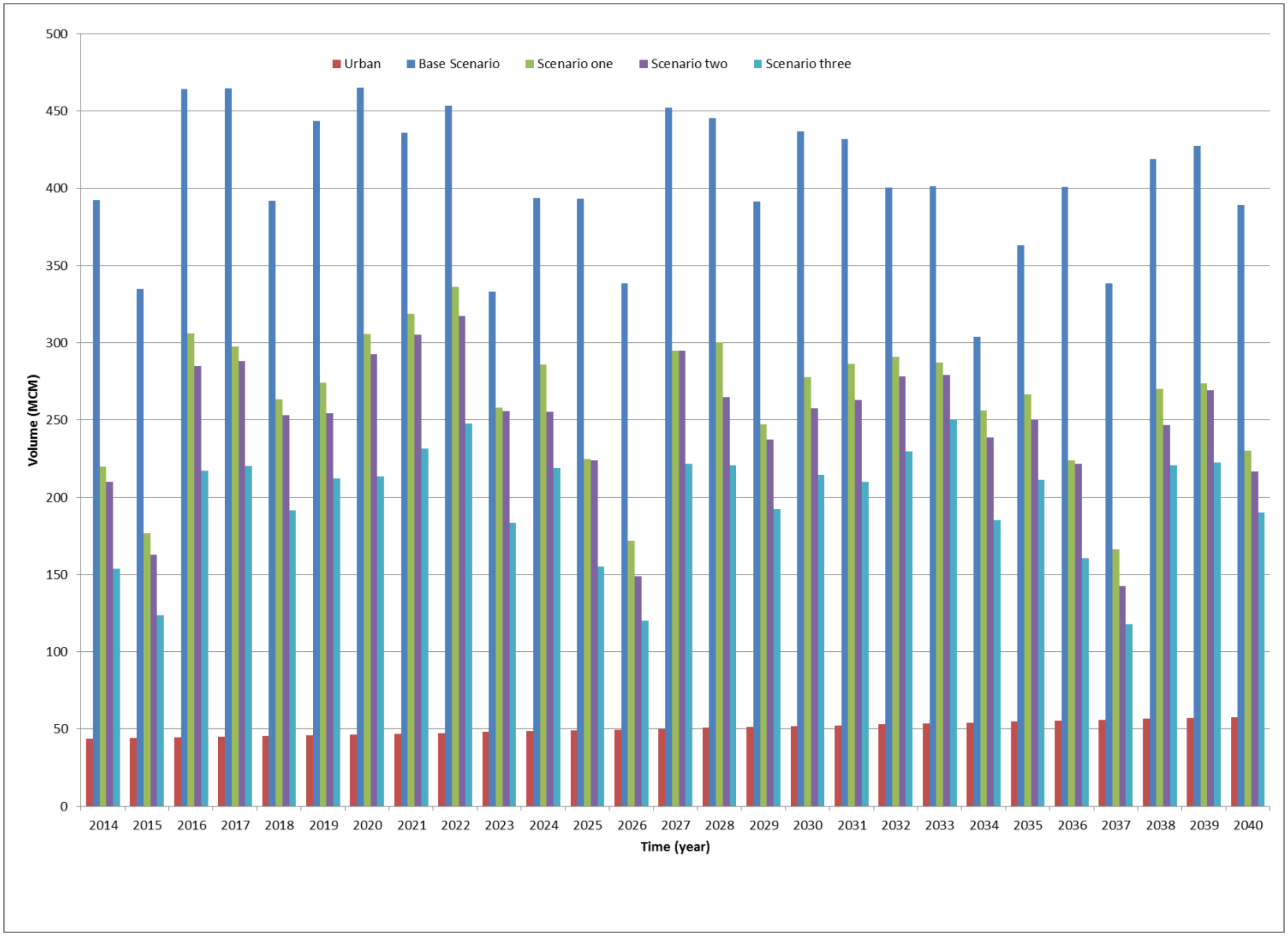


Figure 4. 11: Projected demands

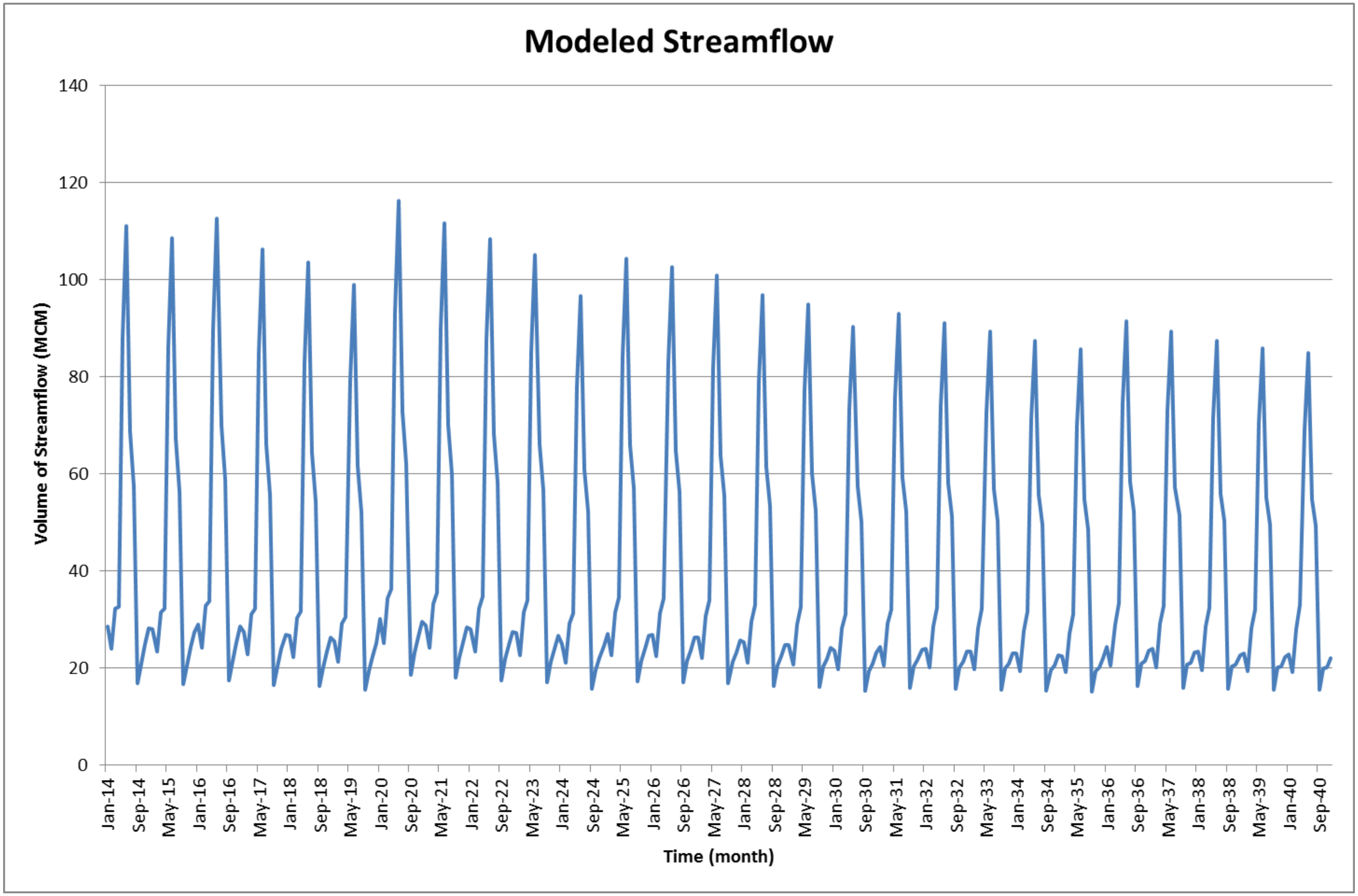


Figure 4. 12: Modeled streamflow based on the A2 scenario

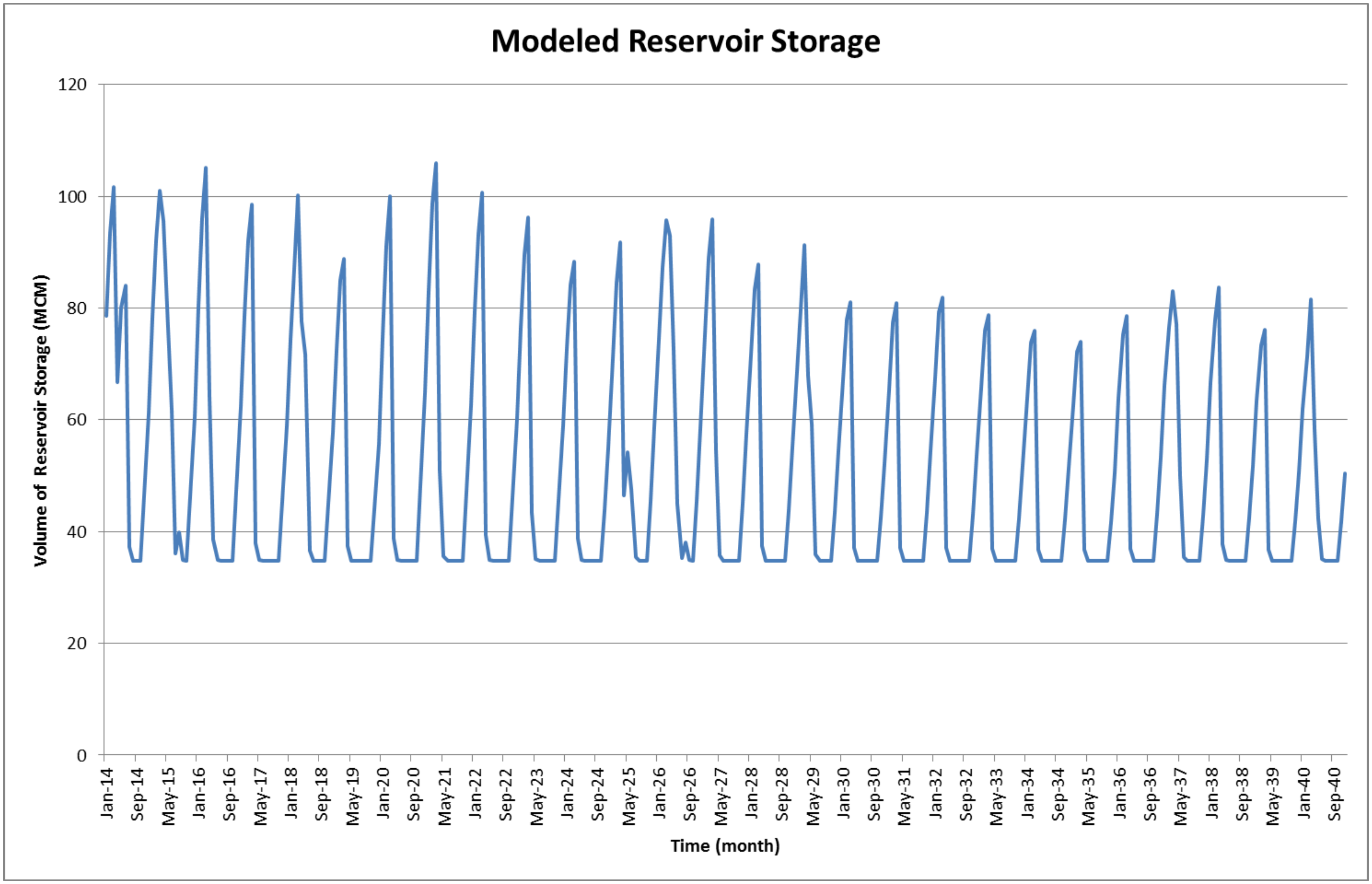


Figure 4. 13: Modeled reservoir storage based on the A2 scenario

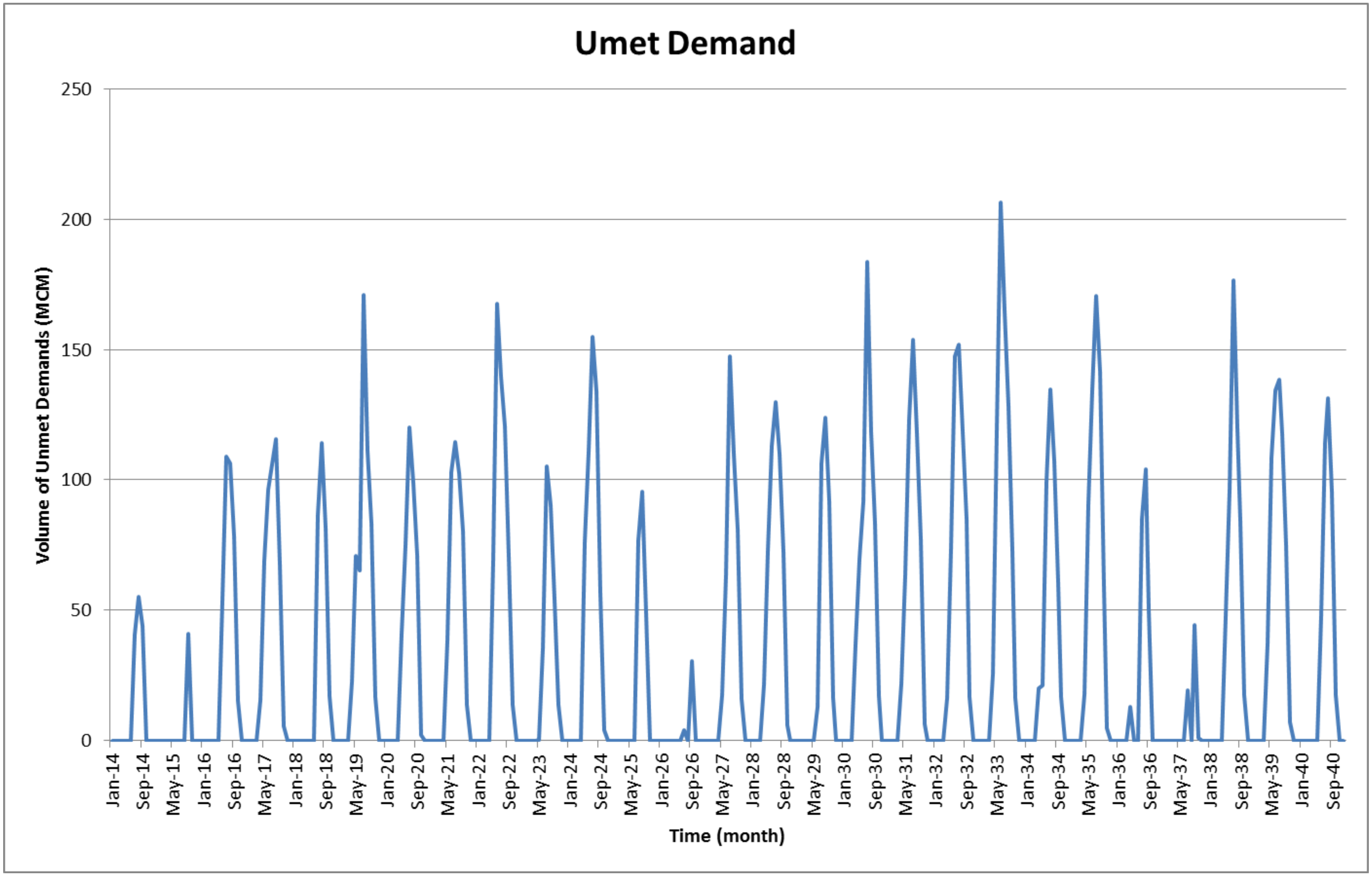


Figure 4. 14: Total unmet demand Based on the A2 Scenario

scenario the amount of precipitation is lower in comparison with the A2 scenario so the trend of decreasing streamflow is greater than the A2 scenario. Also since the inflow into the reservoir is being decreased, due to decreased streamflow, and demand consumption is being increased similar to the A2 scenario the trend of decreasing reservoir storage is greater than the A2 scenario. Comparison of the unmet demands shows that the magnitude of unmet demands or shortages is larger in magnitude for the B2 scenario.

4.5 Adaptation Scenarios

The analysis of potential climate change scenarios has demonstrated the possibility for less streamflow to be available to meet increasing demands. The simulations show that the projected demands are not being met and the shortages can be large. The range of reservoir storage is limited due to lower inflows and higher demands. In order to prevent large failures in the water resources system, decision makers and water managers will need to explore adaptation of their current water management practices to mitigate the negative effects of less available water resources. In this research study three potential irrigation water management adaptation scenarios were defined. They were then tested using the climate scenarios, A2 and B2, to determine their effects on the Pueblo Reservoir. The three adaptation scenarios were described previously.

4.5.1 New Irrigation Technology Scenario:

The new irrigation technology scenario was modeled using WEAP for both climate scenarios, A2 and B2 (Figures 4.18, 4.19, 4.20 and 4.21). This scenario was modeled by improving irrigation efficiency from 50% to 80% to simulate efficiencies that can be attained by sprinkler and drip irrigation methods. The scenario is assumed to be implemented immediately. While

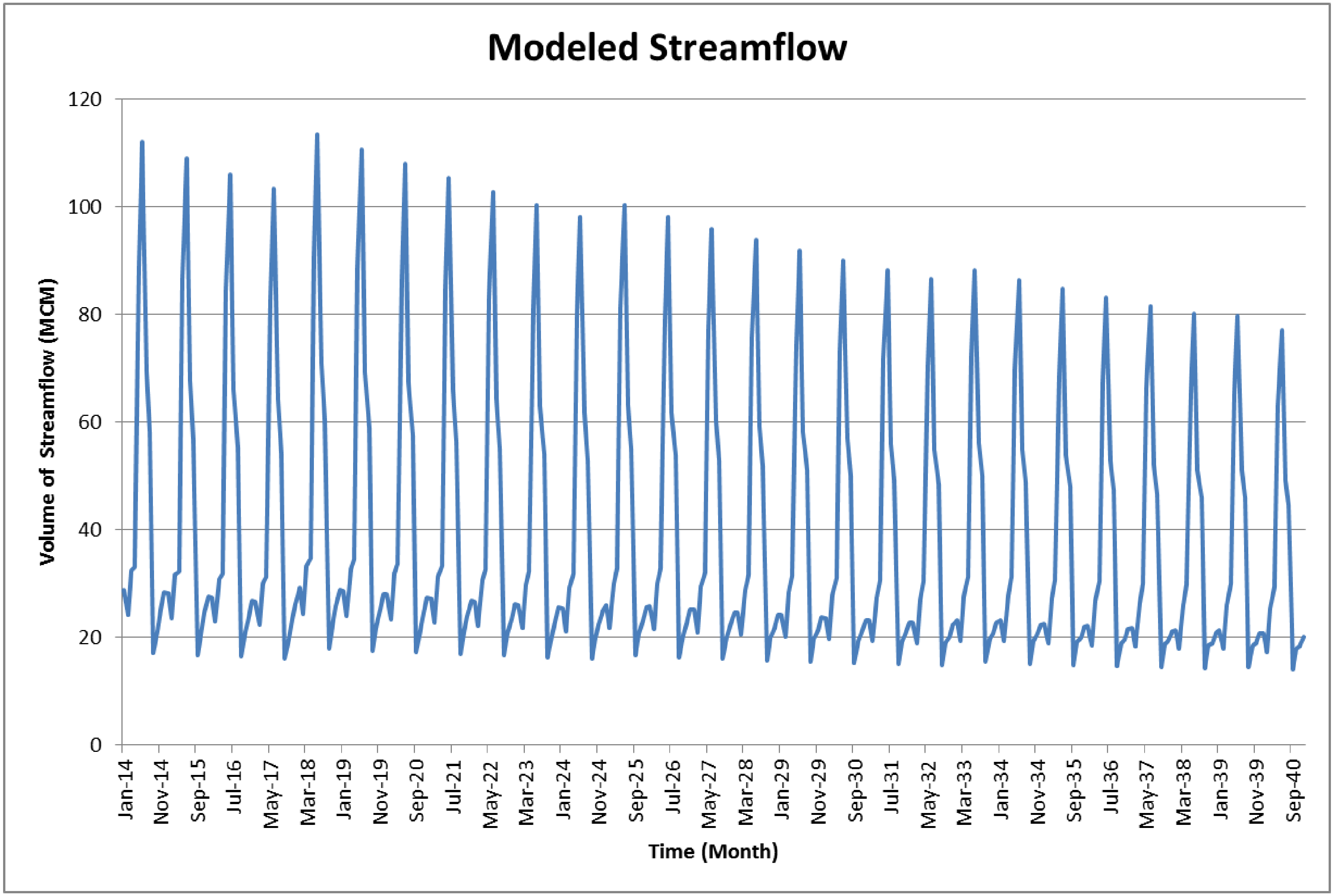


Figure 4. 15: Modeled streamflow based on the B2 scenario

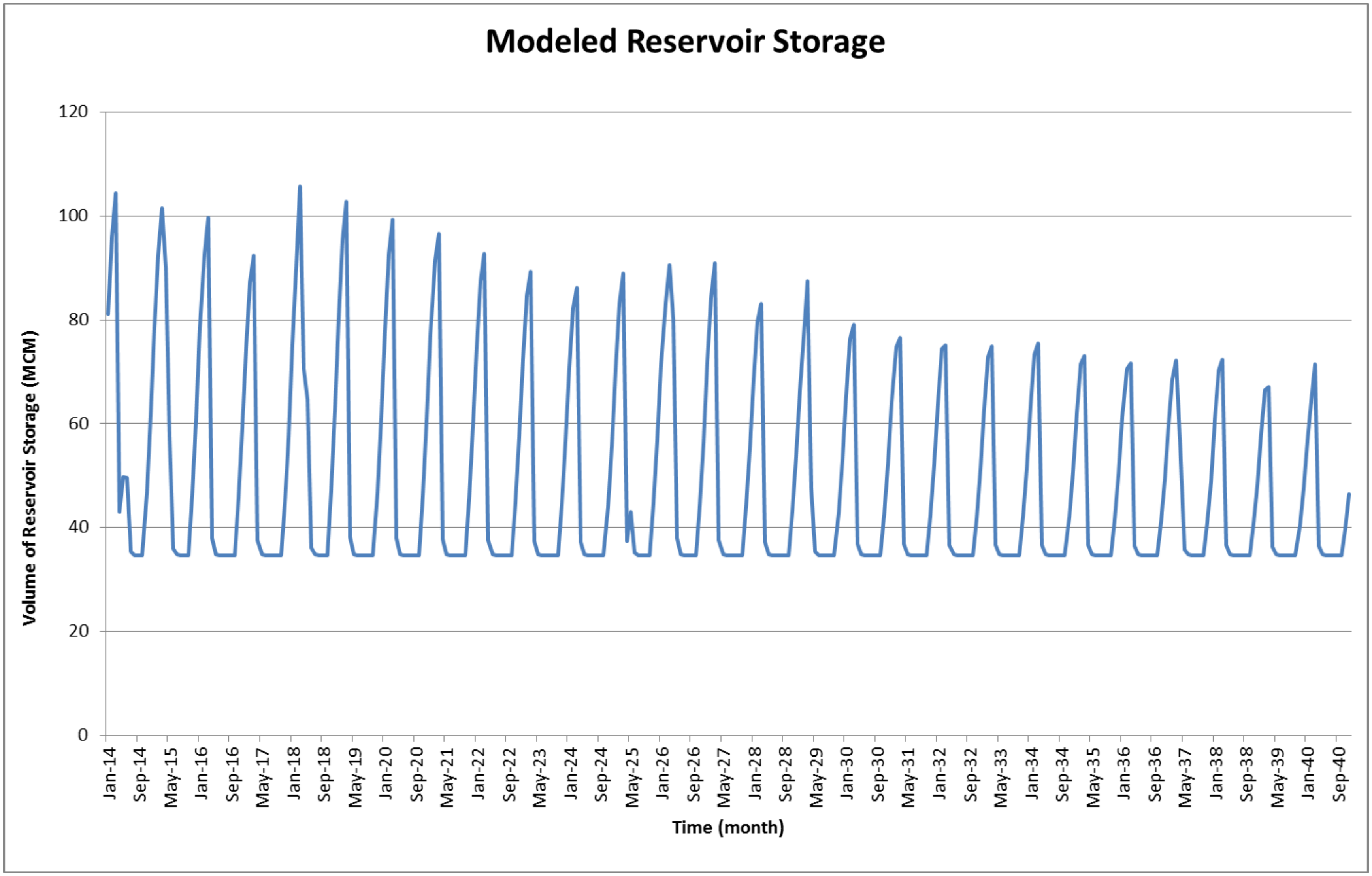


Figure 4. 16: Modeled reservoir storage based on the B2 scenario

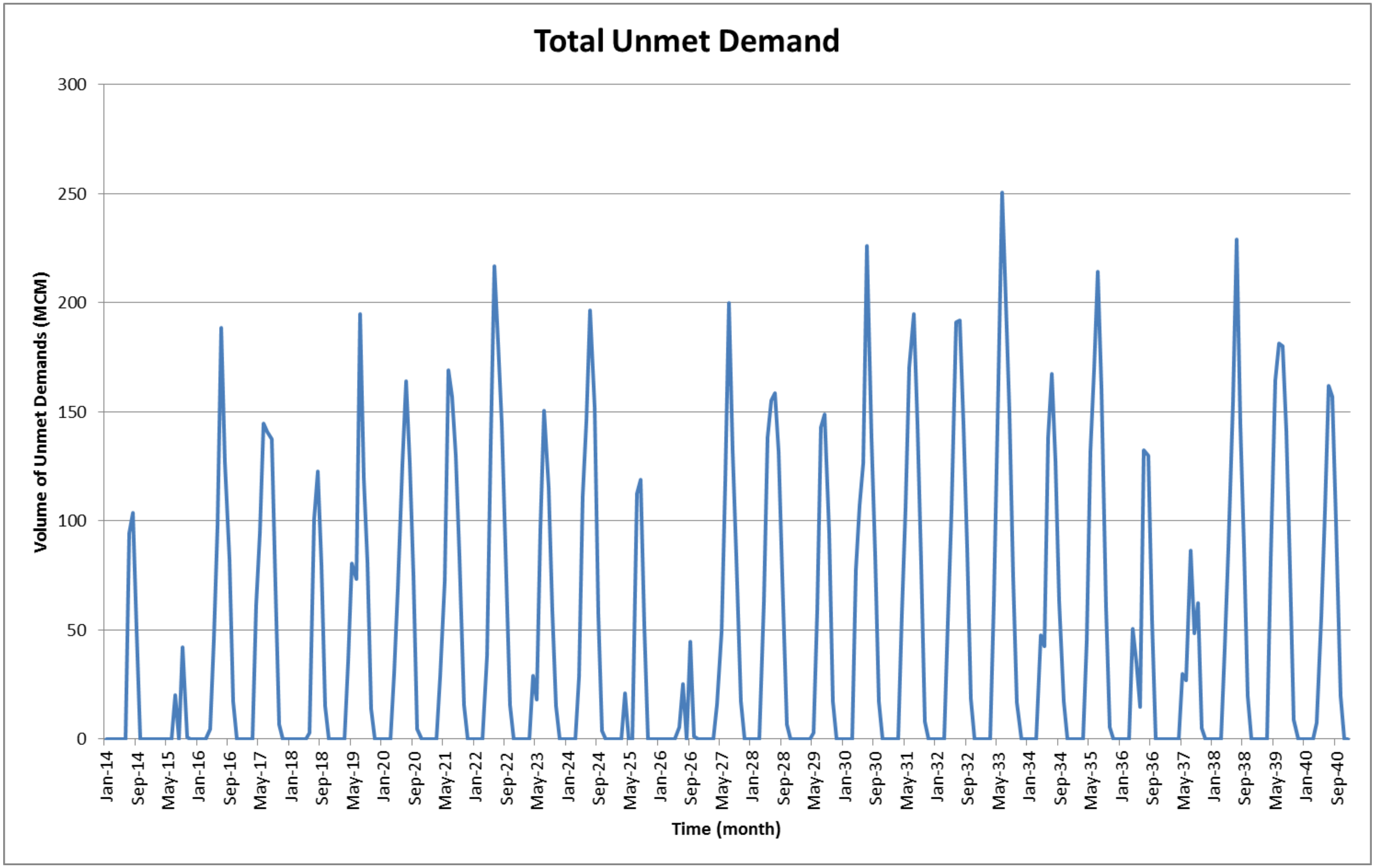


Figure 4. 17: Total unmet demand based on the B2 Scenario

such a scenario would actually take time to implement throughout the agricultural sector, assuming it is immediately implemented provides a “best case” for mitigating the impact. The agricultural demand will decrease as illustrated in Figure 4.11 while the urban demand will stay the same. The results of the simulation for this scenario indicate that improving irrigation efficiency show lower values of unmet demand indicating a reduction in water stress in the other sectors and Pueblo Reservoir during a short time until 2014 for the B2 scenario and until 2016 for the A2 scenario. It should be noted that this mitigation scenario will last less than 5 years (under the best case for implementation) and might be considered to be insignificant.

4.5.2 New Irrigation Technology plus Crop Change Scenario:

This scenario is based on the improving irrigation efficiency from 50% to 80% along with substituting alfalfa with sorghum (Figures 4.22, 4.23, 4.24 and 4.25). The amount of water consumption by sorghum is much less in comparison with alfalfa. The agricultural demand will decrease even more as illustrated in Figure 4.11 while the urban demand will stay the same. The unmet demands were improved in comparison with the base scenarios (A2 and B2 scenarios).

The results of the simulation for this scenario show that improving irrigation efficiency plus substituting alfalfa with sorghum will reduce water stress and impact Pueblo Reservoir during a short time period until 2018 for the B2 scenario and until 2020 for the A2 scenario.

This scenario indicates that changing only one crop can significantly reduce water requirements for agriculture demand along with water stress in the other water demands. So by changing the type and area of the other crops that consume a lot of water with crops that require less water, it is possible to allocate more water for urban and industrial uses or to store it for dry periods.

4.5.3 New Irrigation Technology plus Reducing Area Scenario:

This scenario can give a perspective to decision makers and water managers that by reducing 30% of irrigated farmlands along with improving irrigation efficiency from 50% to 80%, the water stress can be reduced on Pueblo Reservoir and the other water sectors (Figures 4.26, 4.27, 4.28, and 4.29). The agricultural demand will decrease the most as illustrated in Figure 4.11 while the urban demand will stay the same.

Based on this scenario, Pueblo reservoir storage levels and unmet shortage will not experience large impacts until approximately 2028 and 2020 based on the A2 and B2 projections, respectively. Again it is important to note that the scenario was assumed to be implemented immediately and under the “best case” situation, the reduction in demand only helped the system for less than about 20 years. Further, this scenario could have a negative impact in terms of socio-economic problems that could happen due to reducing employment opportunities in the agriculture section. This negative effect might be mitigated by creating jobs in the high technology sector that require less water in comparison with the agriculture sector.

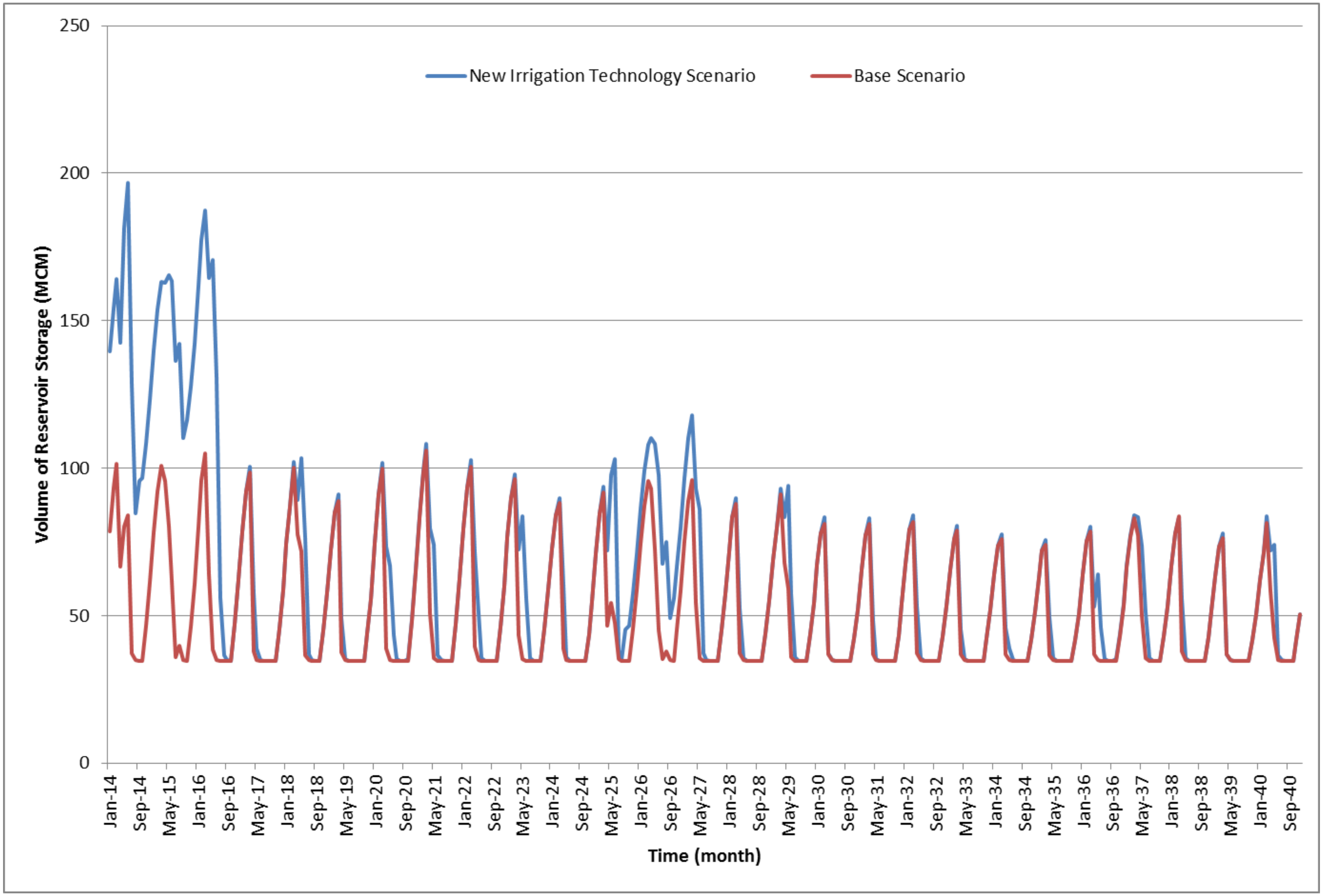


Figure 4. 18: New irrigation technology scenario based on the A2 scenario

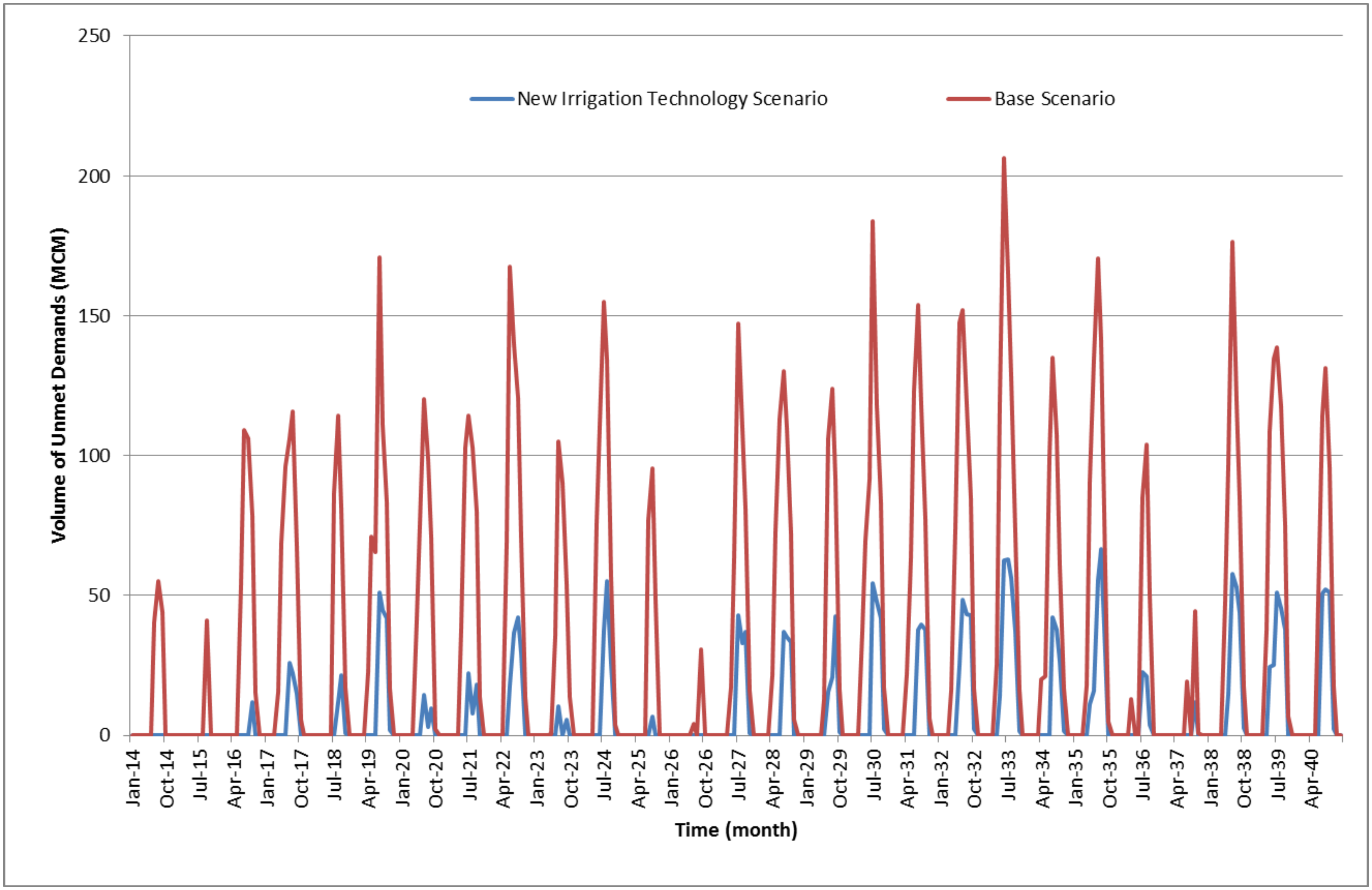


Figure 4. 19: Total unmet demand based on new irrigation technology scenario under the A2 scenario

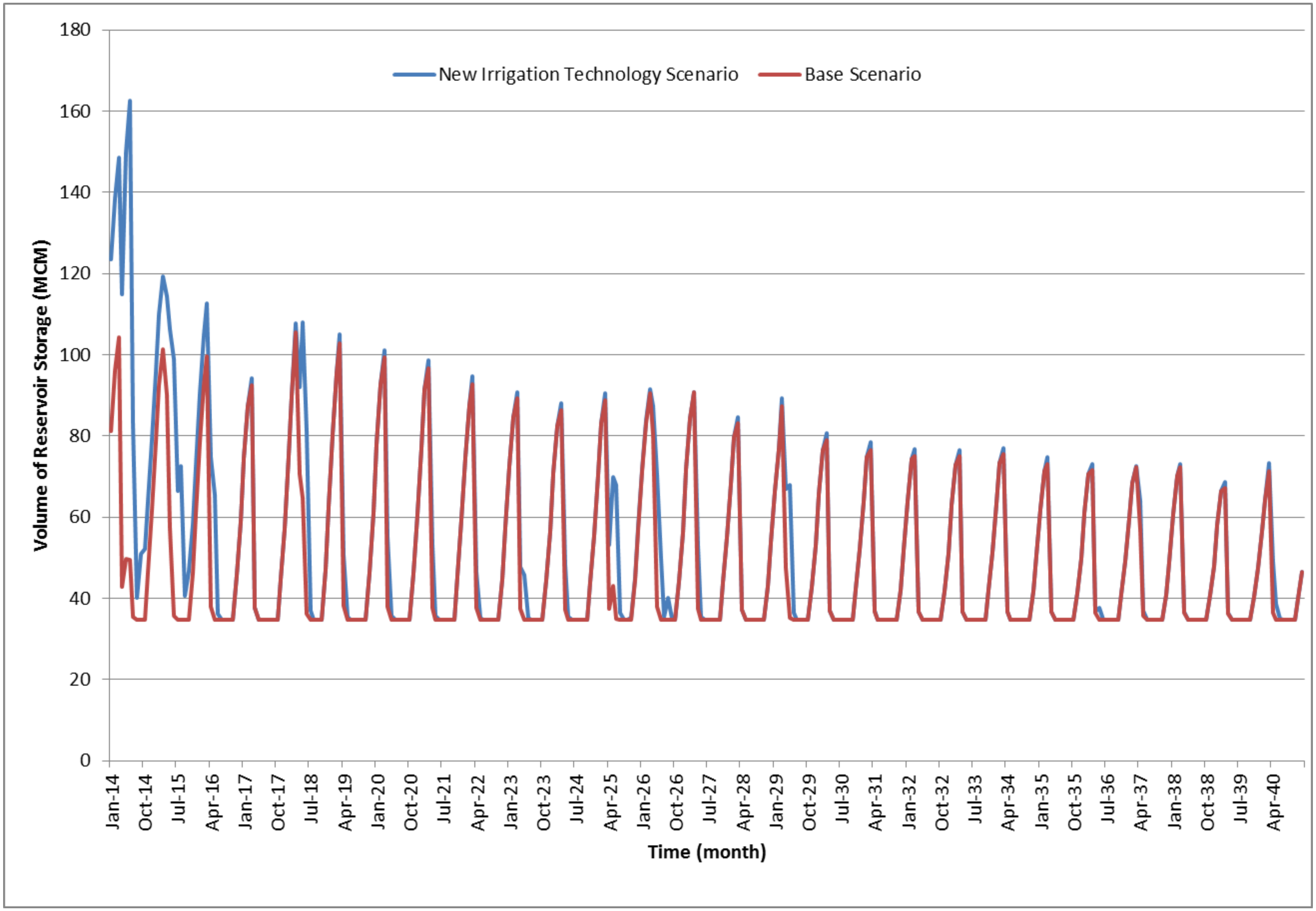


Figure 4. 20: New irrigation technology scenario based on the B2 scenario

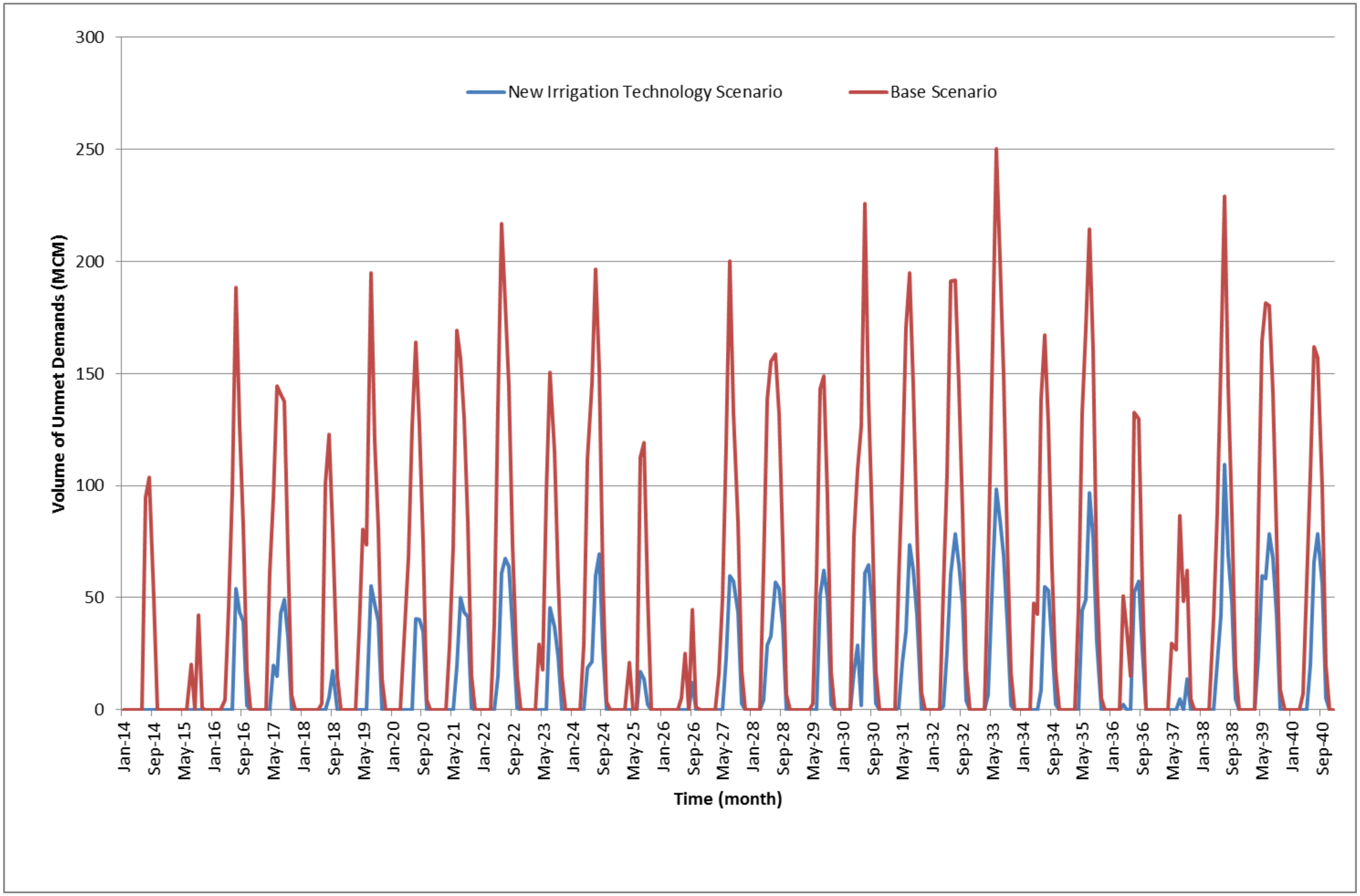


Figure 4. 21: Total unmet demand based on new irrigation technology scenario under the B2 scenario

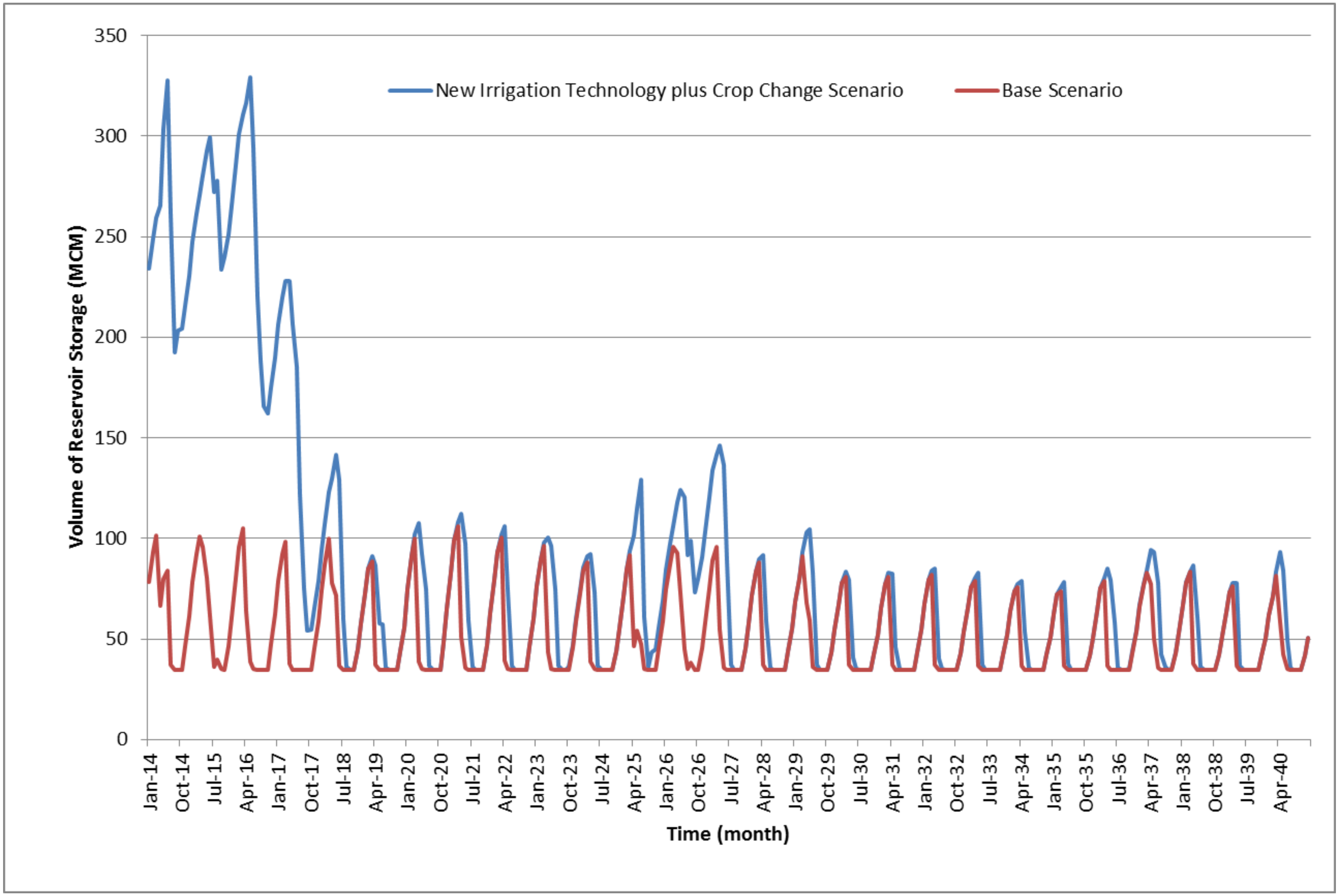


Figure 4. 22: New irrigation technology plus crop change scenario based on the A2 scenario

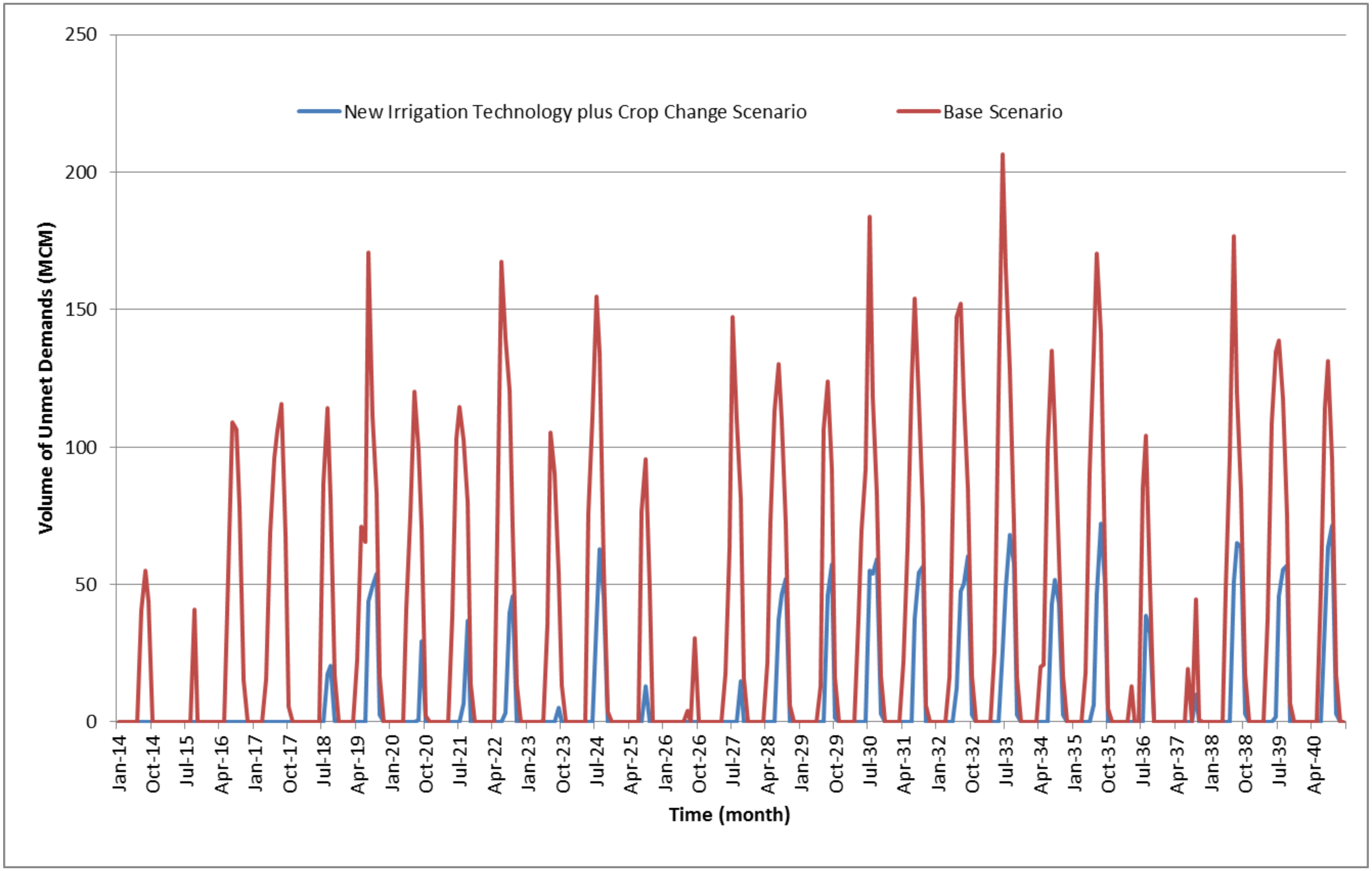


Figure 4. 23: Total unmet demand based on new irrigation technology plus changing crop scenario under the A2 scenario

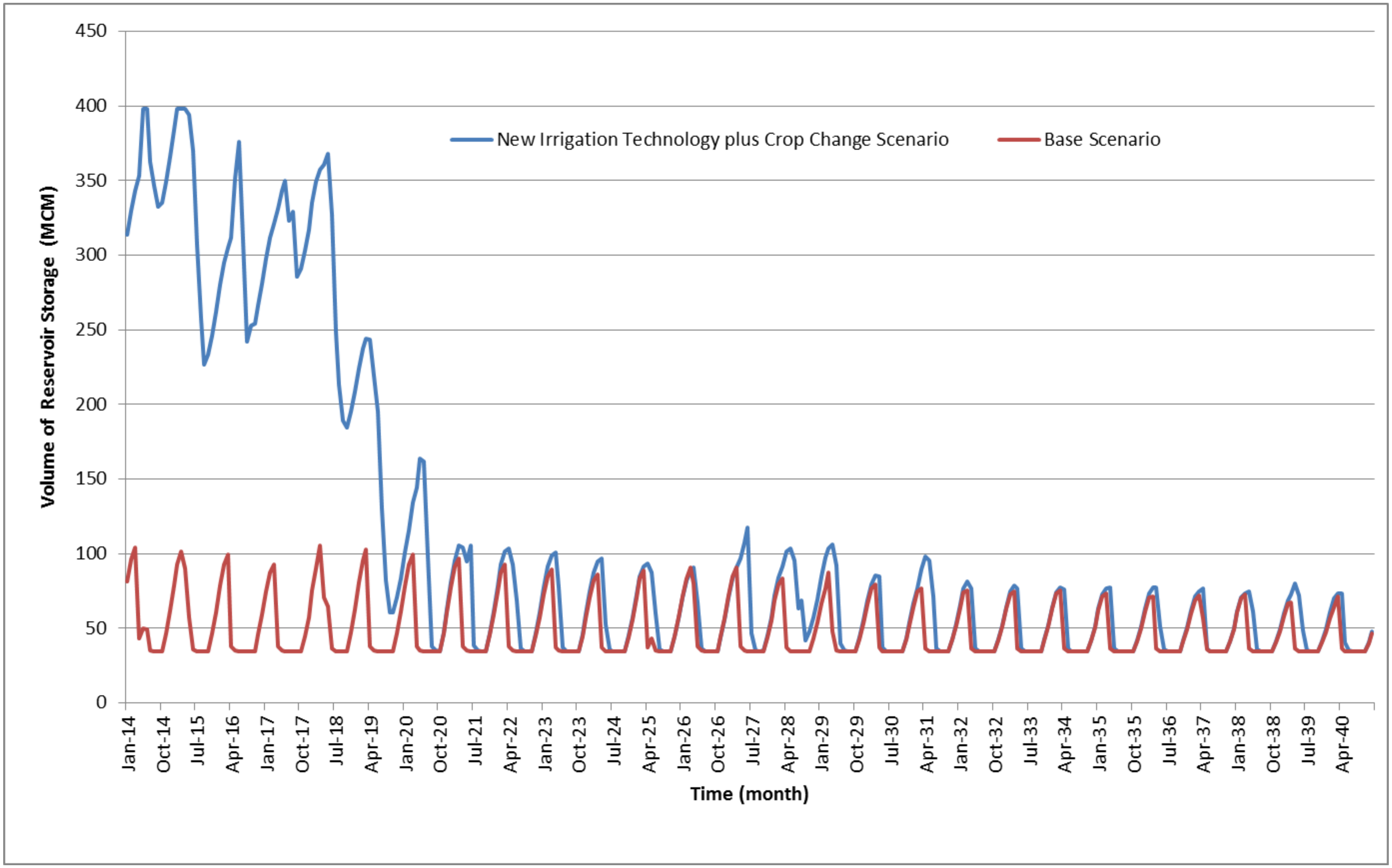


Figure 4. 24: New irrigation technology plus crop change scenario based on the B2 scenario

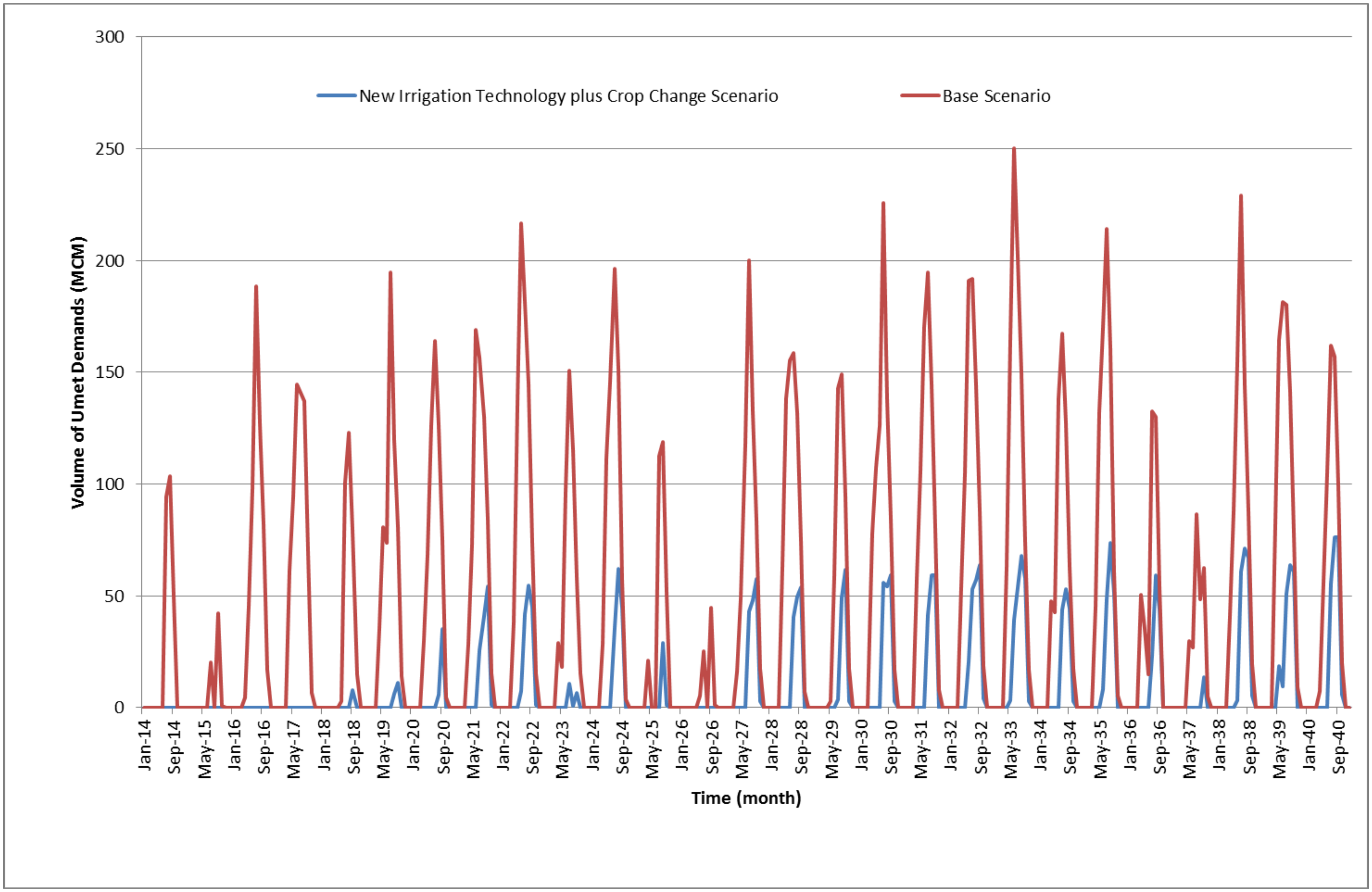


Figure 4. 25: Total unmet demand based on new irrigation technology plus changing crop scenario under the B2 scenario

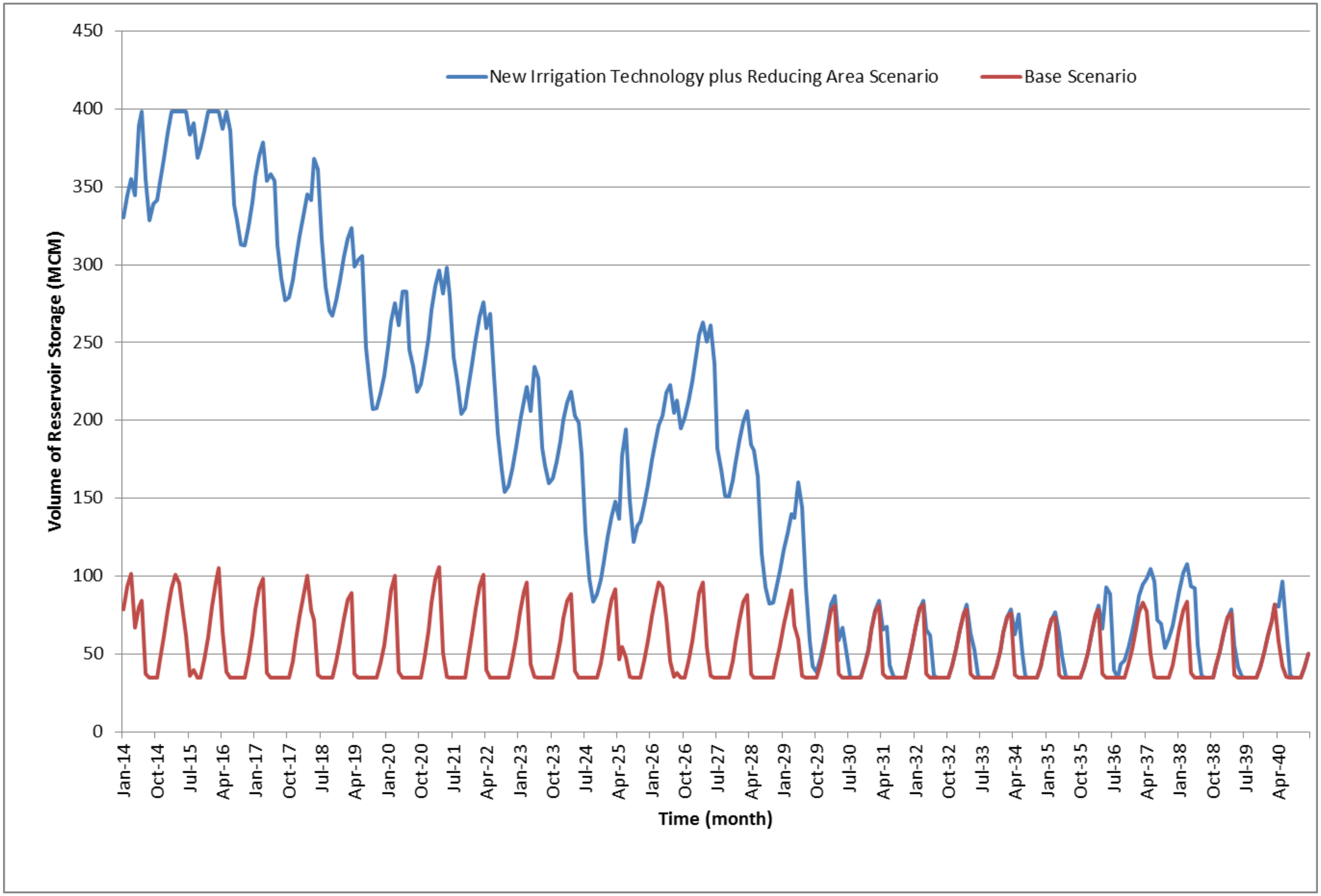


Figure 4. 26: New irrigation technology plus reducing area scenario based on the A2 scenario

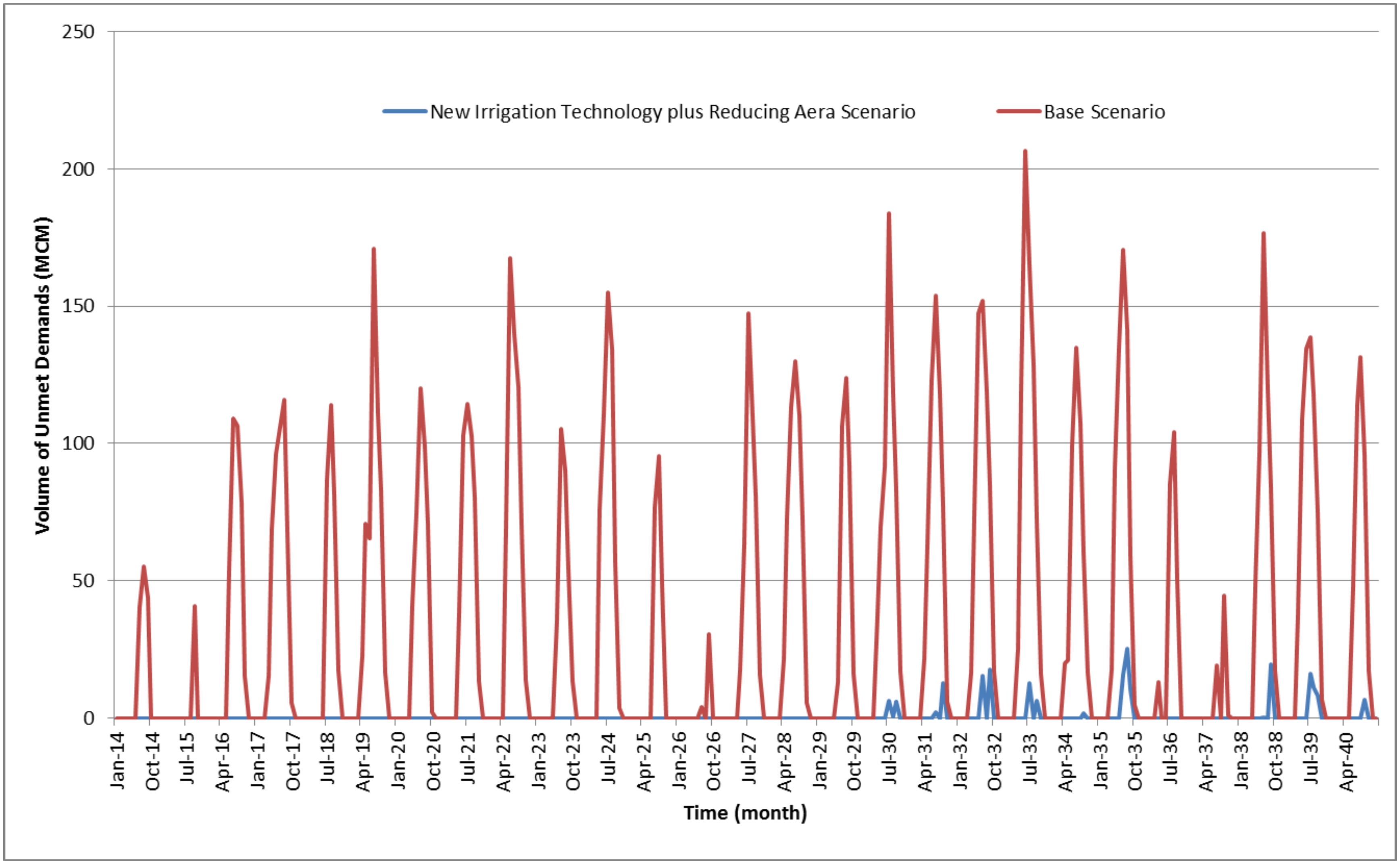


Figure 4. 27: Total unmet demand based on new irrigation technology plus reducing area scenario under the A2 scenario

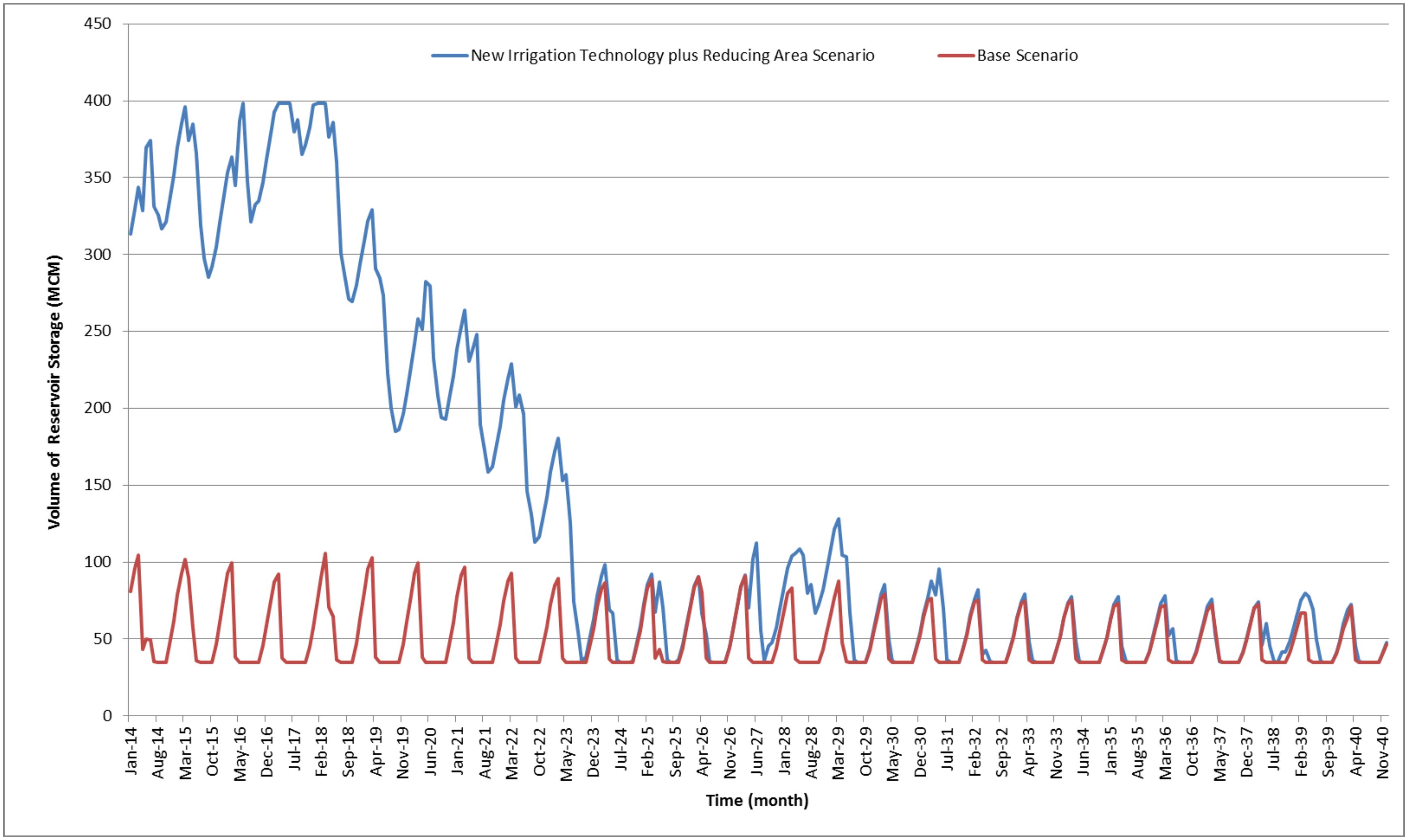


Figure 4. 28: New irrigation technology plus reducing area scenario based on the B2 scenario

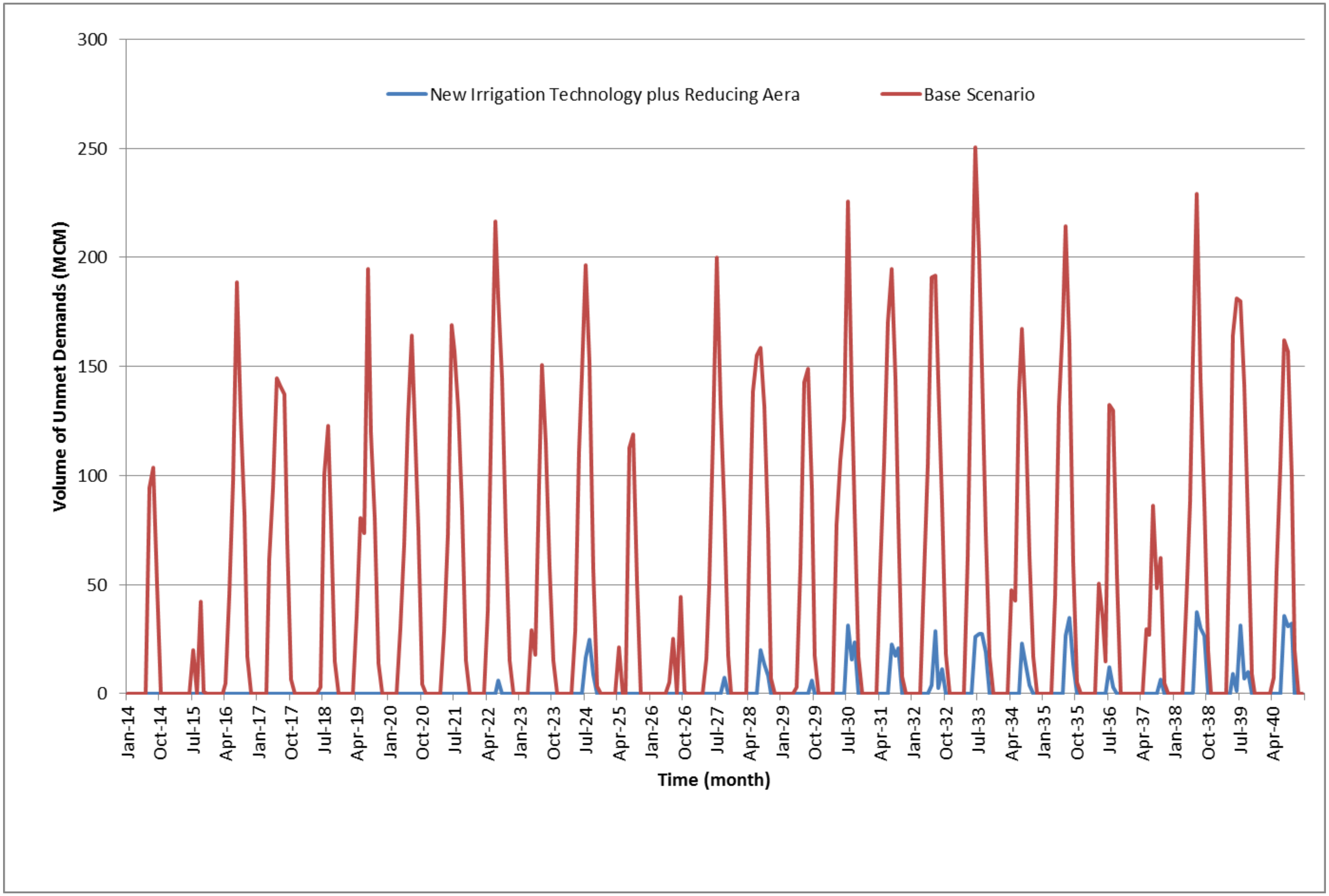


Figure 4. 29: Total unmet demand based on new irrigation technology plus reducing area scenario under B2 scenario

CHAPTER FIVE: CONCLUSIONS

In this research, three models (MAGICC, SCENGEN, and WEAP) were used to explore the potential impacts of climate change on the water resources in the portion of the Arkansas River Basin in Colorado. The first model MAGICC generates outputs of global and hemispheric-mean temperatures. The second model SCENGEN down-scales climate change scenarios on a $2.5^o \times 2.5^o$ grid based on the results from the MAGICC model (the global-mean temperature). The combination of these two models provides monthly projected changes in temperature and precipitation. These changes were used to calculate streamflow using the WEAP model. The WEAP model was calibrated to an existing data set for the Arkansas River Basin and then used to explore the impact of climate change on basin. Finally three potential irrigation adaptation scenarios were simulated to determine their potential to mitigate the impacts of climate change.

Two climate scenarios (A2 and B2) and a 550 ppm policy were used to project future temperature and precipitation in the Arkansas River Basin for the period of 2012 to 2040. Based on the results from the two climate scenarios, the trends of impact of climate change are similar. A warmer climate is anticipated for the region with a projected change of temperature between 0.5 C^o and 5 C^o for the winter and summer seasons.

Precipitation projected using these two climate scenarios decreased precipitation for the region. Based on A2 scenario, the precipitation is anticipated to increase for the months of January, March, and August between 1% and 20% and to decrease for the other months between -1% and -20%. The B2 scenario, as compared to the A2 scenario, showed less increases of precipitation for January, March, and August and a greater decrease in precipitation for the other months. The effects of these climate scenarios on the water resources of the Arkansas basin were analyzed using the WEAP model.

The WEAP model was calibrated using streamflow and reservoir levels for the period of 2000 to 2011. The results of calibration and validation indicated the streamflow and reservoir levels were simulated reasonably well although there are indications that the system might be changing for the latter part of this period. The calibrated model was then used to simulate the impacts of the climate change scenarios on the streamflow and reservoir levels. Urban and agricultural demands were projected to increase to the year 2040. The reservoir was operated to release water to attempt to meet the demands.

For assessing the climate change impact on watershed, the simulation model assumed that the basic characteristics of the watershed will not change for the projected period of analysis and that the rainfall-runoff processes will stay reasonably constant under changing precipitation and temperature conditions. Further the study assumed that the pattern of demand, that is the amount of agricultural area and the type of crops allocated within that area, would not change.

These assumptions may not be strictly true; however, they allow the separation of the impacts of climate change, from other potential changes in the system. A final assumption of immediate implementation of mitigation scenarios was made to represent a "best-case" mitigation of climate impacts.

The results of these projections using the modeling framework indicates that the projected demands will not fully be met, that reservoir levels may have a smaller range as compared to current conditions, and that the reservoir will not refill fully. Due to increasing demand, the trend in reservoir levels will be lower over time. This indicates that the reservoir is less able to respond to variations in inflow conditions, such as droughts. The results show that the projected demands are unsustainable.

The adaptation scenarios were evaluated to reduce the demand for water from the agricultural sector. The scenarios ranged from increased irrigation efficiency to increased irrigation efficiency plus a reduction in crop area. It should be stressed that results have been shown as a single average trace for each of our adaptation scenarios based upon a reference year. Projections based upon a reference year might represent an average condition with potential variation above and below this average.

All of the scenarios were assumed to be immediately implemented to represent a "best case" of mitigation. The results of the simulation of these scenarios showed that all three have a relatively short term impact. Over the long term the increase in demand and the decrease in precipitation cause the system to be unable to meet the demands and therefore to be extremely water-stressed.

Between three adaptation scenarios, the increased efficiency and reduced crop area scenario had the longest impact and the largest in terms of magnitude of reduction of shortages. The effects of this scenario, in terms of avoiding unmet demands, were projected to last less than two decades. It may be unlikely this scenario could actually be implemented in time to have any appreciable impact at all. This indicates that global warming is a potentially very serious problem for water management in the Arkansas River Basin.

While this study shows the potential impacts on water availability in the study area of climate change, the results must be understood within the context of the assumptions of the study. It should be noted that watershed characteristics may change in the future. There may be more or less forests as a result of climate change. The projected stream flows based on the reference year might be higher or lower as a result of the changing characteristics of the watershed. The reservoir operational rules may change over time. However, the amount of water that can be released is a function of the total amount of inflow and changing operational rules might impact the distribution throughout the year but should not impact to a great extent the amount of water available in each year. Therefore the changes in the reservoir operational rules would likely have less impact on the results than potential changes in the watershed. If the watershed were to produce more streamflow, then the reservoir would have more water to release, and the amount of unmet demands would reduce and perhaps be delayed further in the future. If the watershed were to produce less streamflow the amount of unmet demands would increase and may occur earlier in the projected 30 year time frame. Therefore the results from this study should be interpreted in a general context which indicates that with increasing demand and reduced streamflow the amount of unmet demands will increase.

For future work, an improvement to the study would be to include more spatial definition in terms of the agricultural demands and the characteristics of the watershed. A more detailed definition of the individual water rights would better indicate where (or to whom) the unmet demands might occur. Another improvement might be to include estimates of uncertainty in terms of how the reservoir might be operated in the future, and the uncertainty in the types of crops that might be used in the future. While these improvements would help to make the model more detailed, the uncertainty in the climate predictions may overshadow these details. The major limitation of the current climate predictions is the lack of predictions of the variability of future climate. In water resources systems the variability of inflows is very important. While reservoir storage is used to mitigate the variability of inflows, it can only handle a portion of the variability. Without the ability to simulate variability of climate studies such as this one can only indicate general tendencies.

REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, M. Smith, (2000). Crop Evapotranspiration (guidelines for computing crop water requirements), FAO Irrigation and Drainage Paper No. 56
Arkansas River Basin Report, (1981). Colorado Water Conservation Board (CWCB) and USDA.
Anderson, D.R.; Sweeney, D.J.; Williams, T.A.. (1994) Introduction to Statistics: Concepts and Applications, pp. 5–9. West Group. ISBN 978-0-314-03309-3

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (eds.), 2008: Climate Change and Water. Technical paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, Switzerland, 210 pp.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. Science, 319(5866), 1080-1083.

Blasing, T.J., 2008: Recent Greenhouse Gas Concentrations. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. <http://cdiac.ornl.gov/pns/current_ghg.html>.

Climate Change Characterization and Analysis in California Water Resources Planning Studies (2010). Department of Water Resources, Natural Resources Agency, State of California, USA, (December).

Consuelo Varela-Ortega, Irene Blanco-Gutierrez, Christopher H. Swartz and Thomas E. Downing, "Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework," Global Environmental Change, doi:10.1016/j.gloenvcha.2010.12.001, pp. 604-619, Volume 21, Issue 2, May 2011.

"*Current Reservoir Data for Pueblo Reservoir, CO*", Bureau of Reclamation, Great Plains Regions, Retrieved June 12, 2012, from http://www.usbr.gov/gp-bin/arcweb_puer.pl

COlorado AGricultural Meteorological nETwork (CoAgMet), Retrieved June 12, 2012, from http://climate.colostate.edu/~coagmet/index.php.

Colorado Division of Water Resources, Colorado Department of Natural Resources, Retrieved June 12, 2012, from http://water.state.co.us/Home/Pages/default.aspx

Dugan, J. T., T. McGrath and R. B. Zelt. 1994. Water-Level Changes in the High Plains Aquifers- Predevelopment to 1992. U.S. Geological Survey. Water-Resources Investigation Report 94-4027. Lincoln, NE.

Elgaali, E. A. (2005). "Modeling regional climate change impacts on available water for agriculture". CSU Theses/Dissertations.

Esqueda, G. S. T., Jesus Efren Ospina, C. Gay-García and A. C. Conde, "Vulnerability of water resources to climate change scenarios. Impacts on the irrigation districts in the Guayalejo-Tamesí river basin, Tamaulipas, México," Atmósfera, Vol 24, No. 1, pp. 141-155, January 2011.
England, J. F, J. E. Klawon, R. E. Klinger, T. R. Bauer (2006). Flood Hazard Study Pueblo Dam, Colorado. U.S. Department of the Interior Bureau of Reclamation, (June).

Feng, S. and Q. Hu, 2007: Changes in winter snowfall/precipitation ratio in the contiguous United States. Journal of Geophysical Research, 112, D15109, doi:10.1029/2007JD008397.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, pp. 129-234.

Frederick, Kenneth D. and Peter H. Gleick (1999), Water and Global Climate Change: Potential Impacts on U.S. Water Resources, Arlington, VA: Pew Centre on Global Climate Change.

Fung. F., A. Lopez, and M. New, eds (2011). "Modelling the impact of climate change on water resources". Wiley-Blackwell, Chichester, West Sussex, UK ;, 187.

Groisman, P.Ya., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev, 2005: Trends in intense precipitation in the climate record. Journal of Climate, 18(9), 1326-1350.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, and D. Wolfe, 2007: Past and future changes in climate and hydrological indicators in the U.S. Northeast. Climate Dynamics, 28(4), 381-407.

Holger Hoff, Christopher Bonzi, Brian Joyce and Katja Tielbörger, "A Water Resources Planning Tool for the Jordan River Basin ," Water, Vol. 3, No. 3, pp. 718-736, doi:10.3390/w3030718, June 2011.

Huntington T.G., G.A. Hodgkins, B.D. Keim, and R.W. Dudley, 2004: Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). Journal of Climate, 17(13), 2626-2636.

IPCC, Climate Change 2001: the scientific basis-summary for policy makers and technical summary for working group 1 report. Cambridge University Press, UK, 2001.

IPPC, Climate Change 2007: A report of Working Group I of the Intergovernmental Panel on Climate Change, Summary for Policymakers, < http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf>.

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental

Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Karamouz, M., A. Ahmadi, and M. Akhbari (2011). “Groundwater Hydrology: Engineering, Planning, and Management. Book. CRC Press.

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. Journal of Climate, 19(18), 4545-4559.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov, 2007: Freshwater resources and their management. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, and New York, pp. 173-210.

Lettenmaier, D., D. Major, L. Poff, and S. Running, 2008: Water resources. In: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States [Backlund, P., A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw (eds.)]. Synthesis and Assessment Product 4.3. U.S. Department of Agriculture, Washington, DC, pp. 121-150.

Mote, P., A. Hamlet, and E. Salathé, 2008: Has spring snowpack declined in the Washington Cascades? Hydrology and Earth System Sciences, 12(1), 193-206.

Mugatsia, E. A. (2010). "Simulation and Scenario Analysis of Water Resources Management in Perkerra Catchment Using WEAP Model," Masters Thesis, Department of Civil and Structural Engineering, School of Engineering, Moi University, Kenya, (December).

Ospina, J. E., C. Gay-García, A. C. Conde and Gerardo Sánchez Torres Esqueda, "Water availability as a limiting factor and optimization of hydropower generation as an adaptation strategy to climate change in the Sinú-Caribe river basin," Atmósfera, Vol 24, No. 2, pp. 203-220, April 2011.

Pacala, S. and R. Socolow (2004), Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, Vol. 305 no. 5686 pp. 968-972, *DOI:* 10.1126/science.1100103

Peterson, D. F. and A. A. Keller. 1990. Irrigation. In P. E. Waggoner (ed). Climate Change and Water Resources. Wiley. New York. pp 269-306.

Rauscher, S.A., J.S. Pal, N.S. Diffenbaugh, and M.M. Benedetti, 2008: Future changes in snowmelt-driven runoff timing over the western United States. Geophysical Research Letters, 35, L16703, doi:10.1029/2008GL034424.

Rosenberg, N. J., D. J. Epstein, D. Wang, L. Vail, R. Srinivasas, and J. G. Arnold, 1999. Possible Impacts of Global Warming on the Hydrology of the Ogallala Aquifer Region. Climate Change 42(2): 677-692.

Santer, B.D., C. Mears, F.J. Wentz, K.E. Taylor, P.J. Gleckler, T.M.L. Wigley, T.P. Barnett, J.S. Boyle, W. Brüggemann, N.P. Gillett, S.A. Klein, G.A. Meehl, T. Nozawa, D.W. Pierce, P.A. Stott, W.M. Washington, and M.F. Wehner, 2007: Identification of human-induced changes in atmospheric moisture content. Proceedings of the National Academy of Sciences, 104(39), 15248-15253.

Santer, B.D., P.W. Thorne, L. Haimberger, K.E. Taylor, T.M.L. Wigley, J.R. Lanzante, S. Solomon, M. Free, P.J. Gleckler, P.D. Jones, T.R. Karl, S.A. Klein, C. Mears, D. Nychka, G.A. Schmidt, S.C. Sherwood, and F.J. Wentz, 2008: Consistency of modelled and observed temperature trends in the tropical troposphere. International Journal of Climatology, 28(13), 1703-1722.

Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B., 1990: Developing Climate Scenarios from Equilibrium GCM Results. Max-Planck-Institut für Meteorologie Report No. 47, Hamburg, Germany, 29 pp.

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

Sieber. J and D. Purkey (2011). User Guide of Water Evaluation And Planning System. Stockholm Environment Institute, U.S. Center, (May).

Solley, W. B., Pierce, R. R., and Perlman, H. A. (1993). "Estimated use of water in the United States in 1990." *U.S. Geological Survey circular*, no. 1081.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2004: Changes in snowmelt runoff timing in western North America under a ‘business as usual’ climate change scenario. Climatic Change, 62(1-3), 217-232.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. Journal of Climate, 18(8), 1136-1155.

Trenberth, K.E. and D.J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. Geophysical Research Letters, 33, L12704, doi:10.1029/2006GL026894.

United States Department of Agriculture, Retrieved June 12, 2012, from http://www.usda.gov/wps/portal/usda/usdahome

Water Supply and Needs report for the Arkansas River Basin (2006). Colorado Department of

Natural resources, (June).

Wigley. T. M.L. (2007). MAGICC/SCENGEN 5.3: USER MANUAL (version 2), (September).

Willett, K.M., N.P. Gillett, P.D. Jones, and P.W. Thorne, 2007: Attribution of observed surface humidity changes to human influence. Nature, 449(7163), 710-712.

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., “WEAP 21 — A demand-, priority-, and preference-driven water planning model: Part 1, Model characteristics.” *Water International* 30.4 (2005): 487-500.

Zakari Mahamadou Mounir, Chuan Ming Ma and Issoufou Amadou, "Application of Water Evaluation and Planning (WEAP): A Model to Assess Future Water Demands in the Niger River (In Niger Republic)," Modern Applied Science, (5)1, February 2011.