

Neural Network Modeling of Climate Change Impacts on Irrigation Water Supplies in Arkansas River Basin

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Abstract: The evidence of climate change is mounting. Climate change in the region that includes the Arkansas River basin may have profound effects on water users. The potential impacts of climate change include changes in snowfall, snowmelt and rainfall amount and intensities. Snowmelt is the main source of water supply in the region. Water supply is a key factor in determining agricultural potential. In scientific studies dealing with modeling irrigation water budgets, water supply is usually assumed sufficient. Such an assumption leads to critical uncertainties in these water budgets. The water supply may be affected by changes in quantity, type (snow or rain) and timing of precipitation. The possible effects of climatic changes on surface water supplies for irrigation in the Arkansas River basin are investigated using Artificial Neural network (ANN). ANN models have been found useful and efficient, particularly in problems for which the characteristics of the process are difficult to describe using physically based models. ANN is capable of identifying complex nonlinear relationships between input and output data sets without prior knowledge of the internal structure of a system. This study presents a procedure for modeling the impacts of climate change on irrigation water supplies and demonstrates the potential of ANN models for simulating such nonlinear hydrologic behavior. Precipitation over the mountains and the basin area coupled with stream flow is used to quantify the impacts of climate changes on surface water supply for irrigation. A feedforward neural network is trained to map the relation between the water diverted for irrigation (output) and the streamflow/precipitation (inputs).

1. Introduction

Increasing amounts of CO₂ and other greenhouse gases will raise global temperatures causing what is known as global warming (IPCC, 2001). Global warming, if it occurs as projected, might have important impacts on water resources and agriculture. The change in temperature is expected to alter precipitation and evapotranspiration, the prime drivers of water availability and agricultural production. Naturally, climate-water-agriculture interactions are of concern not only to the scientific community but to policy makers as well. Proper understanding of these interactions might help to mitigate the adverse impacts of global warming while selectively reinforcing the positive impacts. Indeed, potential climate change impacts have been assessed for decades. As our understanding about the extent and magnitude of climate change has improved, the need for more detailed modeling of what its impact might be has become increasingly urgent.

Water shortage is already a problem. Climate change is expected to further stress water resources. Climate change might widen the gap between the demand for and supply of water for irrigation. The changing climate and elevated atmospheric CO₂ are expected to influence irrigation by changing evapotranspiration, precipitation, and available water supplies. The combined effect of these changes would impact the supply and the demand. Generally, under warmer conditions the water supply is expected to decrease as demand increases due to rising rates of evaporation and transpiration (Peterson and Keller 1990). Moreover, in an environment of increased temperature and evaporation, the lack of available water will decrease soil moisture. Reductions in soil moisture can greatly reduce agricultural yield (Rosenzweig and Hillel, 1998).

The future availability of water for agriculture will depend on possible changes in hydrological regimes at smaller regional scales such as watersheds and river basins. An effective model of climate change that combines weather scenarios with supply and water demand simulations will help with regional planning for environmental change and will give policy-makers a tool for evaluating different choices.

Potentially, climate change will decrease the supply of water available for agriculture while it increases the demand. As both factors are critical to the future of agriculture, in any projection of regional water budgets, both must be considered (Frederick, 1993). Water supply is a key factor in determining agricultural potential. In scientific studies of models dealing with irrigation water budgets, water supply is usually assumed sufficient. Such an assumption leads to critical uncertainties in these water budgets. The water supply may be affected by changes in quantity, type (snow or rain) and timing of precipitation. Therefore, detailed regional studies are needed of the relation between climate variables such as snow and rain to surface water supply and the sensitivities of water supply to changes in these climatic variables (Ojima et. al, 1999).

In this study the possible effects of climatic changes on surface water supplies for irrigation in the Arkansas River basin are investigated using Artificial Neural network (ANN).

2. Description of Study Area

2.1 Location and Physiography

This study focuses on the Arkansas River basin in Colorado. The Arkansas River basin is part of the Great Plains area bounded on the west by the Rocky Mountains and by Kansas, New Mexico and Oklahoma on the east and the south (Figure 1). It covers approximately 72,742 km² (28,415 square miles) about 27 percent of the state of Colorado. It is about 400 km (250 miles) long (east to west) and average about 240 km (150 miles) wide (north to south).

The headwaters of the Arkansas River are near Leadville, at an elevation of over 3,050 m (10,000 feet) above sea level. The river's elevation

drops rapidly until it emerges from the mountains near Pueblo, then runs in an easterly direction until it reaches the Colorado-Kansas border near Holly, Colorado at an elevation of about 1,036 m (3,400 feet).

2.2 Climate

Temperature

Temperature and precipitation vary widely in response to topographic differences and the areal extent of the region. Average annual temperatures ranges from 2° C at Leadville in the mountains to 12° C at Lamar in the lower valley. Seasonal variations in temperature are very large, and the region as a whole is characterized by high temperatures in the summer and low temperatures in the winter and spring. Table 2.1 shows some mean temperatures for selected locations in the basin.

Precipitation

Precipitation is distributed unevenly throughout the year with ranges from 9 to 12 inches per year in the middle and the eastern part of the region, 16 to 20 inches in the western part, and as much as 45 inches in the highest mountain ranges. Much of the precipitation at high elevations occurs as snow. Runoff from this snowfall is at a maximum in late spring and early summer. This runoff constitutes the water supply for different water uses.

Growing Season

Summers are cool in the mountains and warm in the plains portion of the basin. A maximum temperature over the last thirty years of 35° C has been recorded at Las Animas during July. An average January minimum temperature of -13° C has also been recorded in Las Animas which implies that large temperature variations occur. The average frost free season (between 32 °F threshold) varies from 85 days at Leadville to 167 days at Canon City, 161 days at Las Animas and 162 days at Lamar.

2.3 Water

Surface Water

The greatest runoff in the basin comes from snowmelt in the large mountain systems at the western border of the region. Water supply varies from year to year depending on the winter snow pack in the mountains. In general, more than 60 percent of the average annual runoff occurs during April through July, and 20 percent during August through October.

Trans-Basin Diversions are a significant addition to the basin water supply. There is an extensive system of canals, tunnels, and reservoirs for collecting and transporting water from the western side of the Continental Divide to the Arkansas Basin.

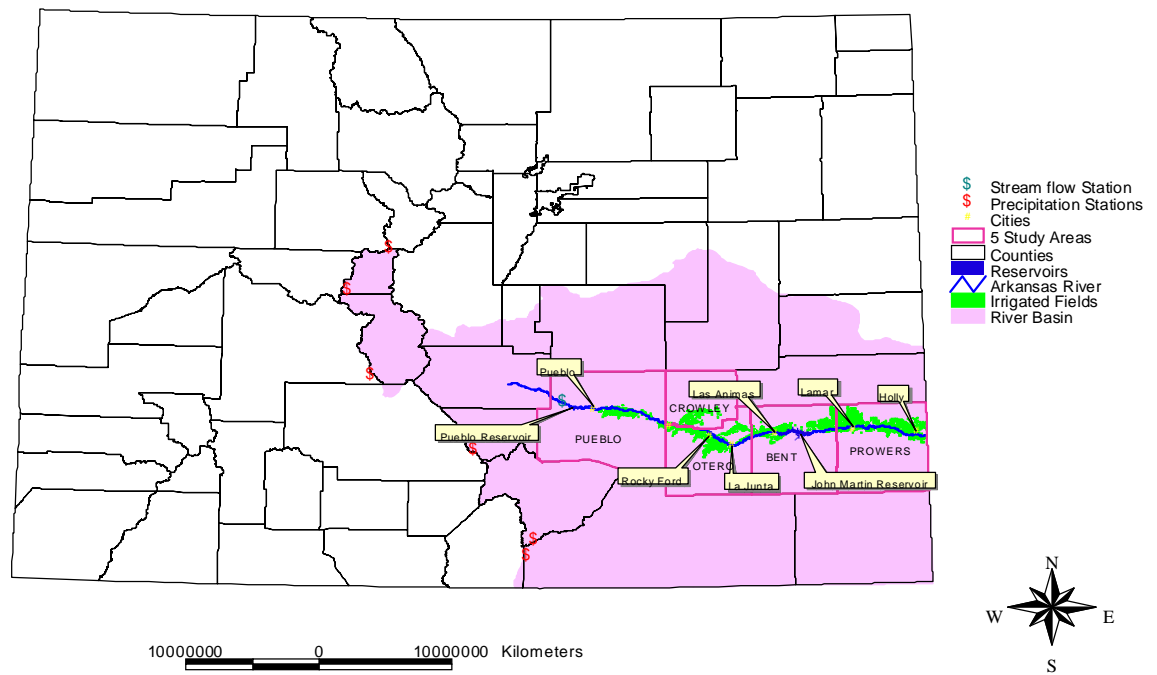


Figure 1: Features of the study area in the Arkansas River basin, Colorado

Lakes and reservoirs in the basin serve an important function of controlling natural runoff. Runoff from snowmelt generally peaks during the month of May and early June, but peak demand for water generally occurs in July and August. These bodies of water are used to store water to meet part of the demand.

Diversions

Diverted water is applied to crops and pasture land in the basin through a huge system of ditches and canals. In this study 21 of these canals are used. These are the major canals serving the farmland in the valley that extends from Pueblo to Kansas. Table 1 shows a summary of diversions for the study area by Water District. In general, the amount of water diverted by these systems averaged 3.5 acre feet per acre for 300,000 acres served (21 canals). The surface diversion data was summarized from records in the Colorado State Engineer Office in Denver.

Table 1. 1997 Irrigation Diversions

Water District	Acres Served	Diversions (AF)
14	80,000	303,875
17	150,000	596,271
67	70,000	205,611

3. Methods

In this study historical and scenarios of climate data were used to quantify the responses of water supplies for irrigation to changes in climate. Artificial Neural Network (ANN) methodology was used to model the surface water supply system. The ANN is trained to approximate the relation between the amount of water diverted for irrigation and the river flow and precipitation on the river basin being modeled. In order to meet the research objectives the following steps were involved:

1. Selection of a region vulnerable to climate change with reliable records of data.
2. Selection of climatic cells representative for the whole river basin.
3. Selection of climate scenarios with high spatial resolution to meet the objectives of this study.
4. Development of a model from existing climatic and runoff records that adequately simulated diverted water.
5. Use of this model to determine the effects of climate change.

3.1 Selection of Study Area

Region Selection

Generally, in developing a database for this kind of research, preliminary considerations should be given to issues like scale of analysis, the availability, accuracy, and adequacy of the data for the modeling and validation processes. Such considerations eventually led to selection of Arkansas River basin as study area.

In general, the basin was selected to fulfill a number of criteria required for development and testing of the modeling system. It is especially important that the basin:

- 1) Have enough records of diversions and river flow for modeling and validation.
- 2) Have a surface irrigation system adequate for reproducing the surface water supplies under historical, current and climate change effects.
- 3) Have an area that encompasses a variety of land covers and acreages to reflect the variability in responses to climatic effects.
- 4) Have a river system of flow records that reflect the natural runoff.

Irrigated agriculture is the dominant surface management in the basin. The study area contains two major reservoirs and twenty one ditches which transmit water to an irrigated area of 270,000 acres out of a total area of 390,000 acres.

Climate Stations

Substantial water supply (runoff) occurs only where mountain ranges are high enough to receive adequate precipitation. By far the greatest runoff comes from snowmelt in the large mountain system at the western borders of the region. Therefore, consideration was first given to locating climatic stations in the mountains that representative to the runoff in Arkansas River. For stream flow it is especially important that the flow records reflects the natural runoff and with high correlation with amount of water diverted over the whole basin. The best stations (recommended by USGS) are listed in Table 2 and shown on Figure 1.

Table 2. Characteristics of Precipitation Stations

Station	Latitude (deg)	Longitude (deg)	Elevation (ft)
Apishapa	37.33	105.07	10,000
Brumley	39.08	106.53	10,600
Fremont Pass	39.38	106.20	11,400
Prophyry	38.48	106.33	10,760
South Colony	37.97	105.53	10,800
Whiskey Creek	37.22	105.12	10,220

Climate Scenarios

Generally, historical and scenario-driven approaches are used to design and conduct climate change impacts simulations. In this study two GCMs were used to evaluate the climate change impacts. The two GCMs are the transient HAD, which was developed by Hadley Center for Climate Prediction and Research, United Kingdom and the transient CCC, which was developed by the Canadian Center for Climate Prediction and Analysis. The two models projections were generated assuming 1% increase in CO₂ concentrations. The National Center for Atmospheric Research (NCAR) regionalized (downscaled) the output of these two models to a resolution of 0.5°X0.5°. The data from the two models cover historical period 1895-1993 and projected period 1994-2099. The characteristics of the two downscaled GCMs are shown in Figure 2.

3.2 Modeling Water Supply

Artificial Neural Network (ANN) was used to model the monthly water supply in the basin. Artificial Neural Network is a technique able to learn, estimate and generalize a relationship between inputs and outputs of the same pattern in a system. The data set is usually divided into two parts. The first part is used to train the network to estimate the relationship between the inputs and outputs while the second part is used to validate that relationship. In this study a feedforward neural network was used to map the relation between the water diverted for irrigation in the region (output) and the streamflow/precipitation (input).

The hydrological variables modeled are the precipitation on the mountain (PPT_m), the precipitation on the basin area (PPT_b), river flow (Q_r) and the amount of water diverted for irrigation (D). The diversion D at time (t) is treated as a function of Q_r, PPT_m and PPT_b at time (t) and (t-1) as follows:

$$D(t) = f(Q_r(t), PPT_m(t), PPT_m(t-1), PPT_b(t), PPT_b(t-1)) \quad (1)$$

4. Model Testing and Validation

Usually, part of the data used in developing the neural network is used to validate the model since it has the same pattern of the training data. In the validation stage, the network after having been trained is being checked to see if it still performs satisfactorily with data that was not used during the training of the network. Thus the network developed was tested using data whose pattern is the same as the data used for training. The performance statistics shown in table 3 were used to summarize the relationships between the output of the network and the target values being modeled.

5. Effects of Climate Change

Results of the model simulations are shown on Tables 4 and 5 and Figures 3-5. Figure 3 depicts the average of 10 years of historical seasonal water diversions compared to the diversions projected by the two GCMs CCC and HAD. Figure 4 shows the seasonal changes due to climatic change in years 2060 and 2090 compared to changes in the base line (1960-1990). Figure 5 shows the deviations of monthly diversions in 2060 and 2090 from baseline diversions (1960-1990).

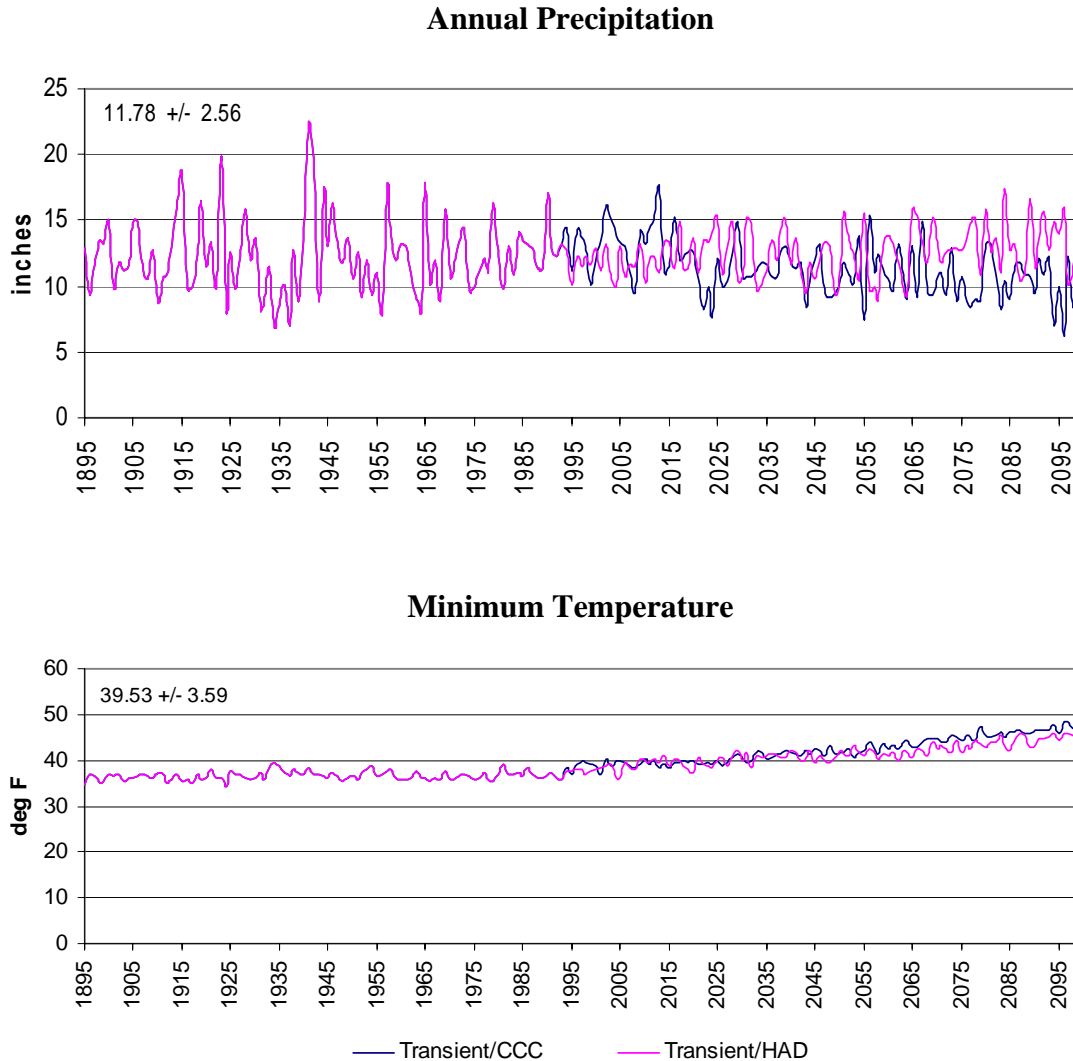


Figure 2. Time series of Annual Precipitation and Minimum Temperature. The figure includes both historical data from 1895-1993, and projections for 1994-2099.

Table 3. Summary of the Model Validation and Testing

Month	Training			Testing		
	R	R ²	RMSE	R	R ²	RMSE
APRIL	0.989	0.979	0.022	0.909	0.826	0.095
MAY	0.951	0.904	0.104	0.845	0.715	0.120
JUNE	0.989	0.978	0.039	0.896	0.802	0.109
JULY	0.983	0.967	0.042	0.895	0.801	0.086
AUG.	0.998	0.997	0.011	0.910	0.827	0.088
SEPT	0.973	0.946	0.052	0.906	0.821	0.133

Generally, as shown in Figure 3, the projected amount of water for irrigation moderately decreases to the end of this century. The GCMs projected an average decrease of 20 percent from the current amounts of water available.

Table 4. Simulated Seasonal Diversions Averages in acre-feet

Month	Base line Avg. 1960-1990	CCC Avg. 2080-2090	HAD Avg. 2080-2090
April	93316	92532	89989
May	140887	111400	111985
June	182017	144757	144584
July	174398	130778	125817
August	145014	126126	124225
September	89149	49710	52678

Table 5. Simulated Seasonal Diversions in 2060 and 2090 in acre-feet

Month	CCC		HAD	
	2060	2090	2060	2090
April	106878	73100	96287	70946
May	151685	116177	144733	111767
June	153140	166573	163386	88562
July	73386	90824	60629	88562
August	54916	94263	54242	93599
September	42456	49844	42456	26484

The 10-year diversion averages projections decrease in every month in the season except in April (Figure 3). This is due to the high projected temperature which leads to early snow melt. The amount of the snowmelt is large enough to offset the effect of the evapotranspiration (ET) and becomes runoff boosting the water supplies.

The two GCMs scenarios gave almost the same average annual projections of water diversions. Since the two GCMs have the same range of temperature projections, this indicates that temperature is more dominant

than precipitation in projecting annual water supplies, because temperature is controlling other factors involved in the hydrologic cycle such as humidity and vapor pressure gradient.

Based on the data from the two GCMs, moderate increases in diversions are projected to occur in the months of April and May in 2060 and then the amount of water decreases during the rest of the season (Figure 4). The increase in water supplies comes from the early snowmelt in the mountains. Both of the GCMs project increases in winter snow and a decrease in summer precipitation by the year 2060. The increase of snow is very significant reaching approximately 70 percent of the current amounts while the decrease in precipitation amounts to 40 percent. The increase in winter snow coupled with high projected temperatures results in early snow melt and early seasonal water availability while the decrease in summer precipitation results in water shortage especially during the growing season. These conditions continue and prevail in 2090. In 2090 due to the prevailing climatic conditions there is a reduction in water supplies over the whole season (Figure 4).

Figure 5 shows the simulated deviations from monthly baseline diversions in 2060 and 2090. In 2060 the deviations of the first two months in the growing season (April and May) are positive which indicates increases in water supplies while the negative values indicate a decrease. In 2090 the early snowmelt reduces the summer runoff and hence the water supplies over the whole season.

6. Summary

The two GCMs used in this study, CCC and HAD, project an increase in temperature ($4 - 7^{\circ}\text{C}$) and winter precipitation and a decrease in summer precipitation. Based on these projections the study region is expected to get drier. These dry conditions have adverse effects on water supplies in the region.

Following the projected precipitation patterns, a decrease in water supply occurs. In 2060 a reduction in water supplies occurs from midseason (April/May) to the end of the season (June-Sept.). In 2090, based on the projections, water is short over the whole season. High projected temperature increases ET and alters snowmelt time causing a shift in water availability to late winter and early summer.

The study region is one of the regions most vulnerable to climate change. Water shortage is already a problem in the region. If precipitation amounts and timing change as projected the water resources in the region will be under more stress. The results of this study are intended to give insights into changes of seasonal water supplies under two GCM projected scenarios.

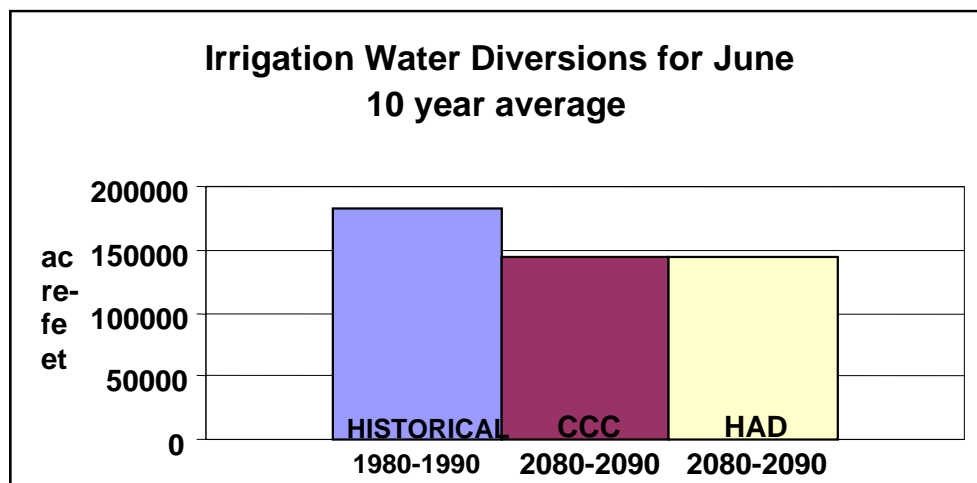
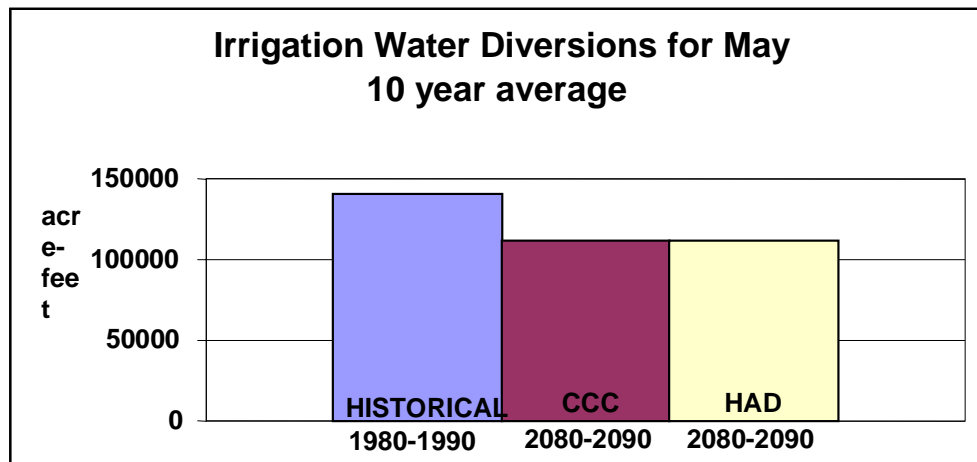
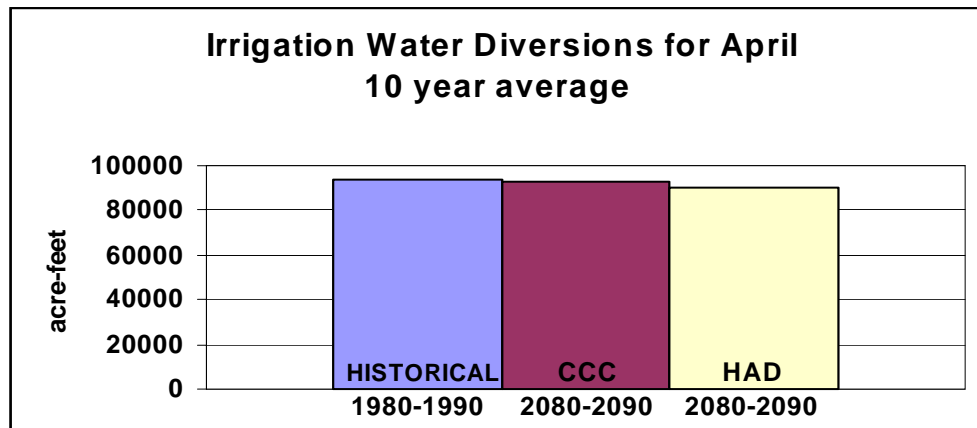


Figure 3. Changes in 10 year Averages of Water Diversions

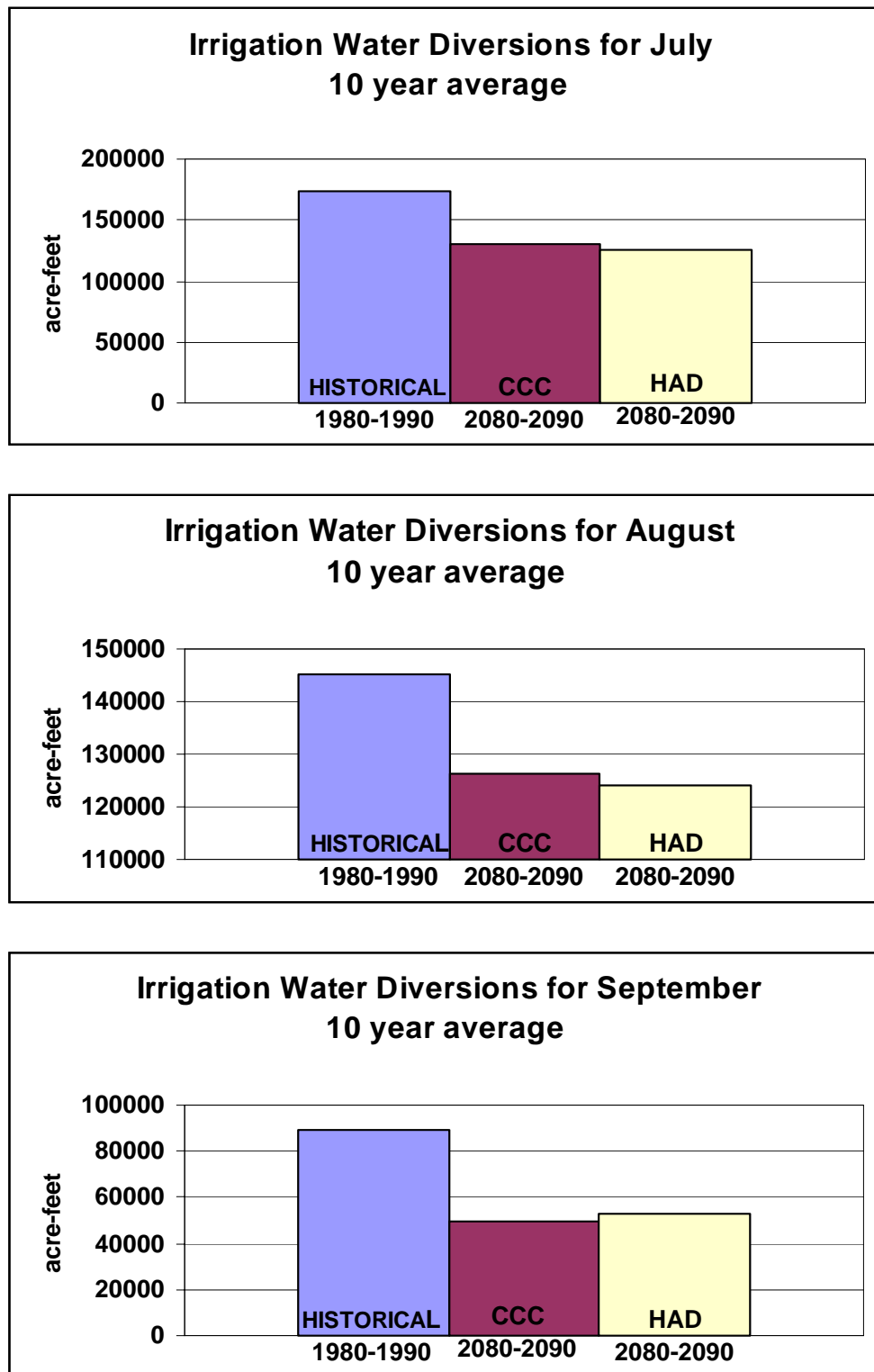
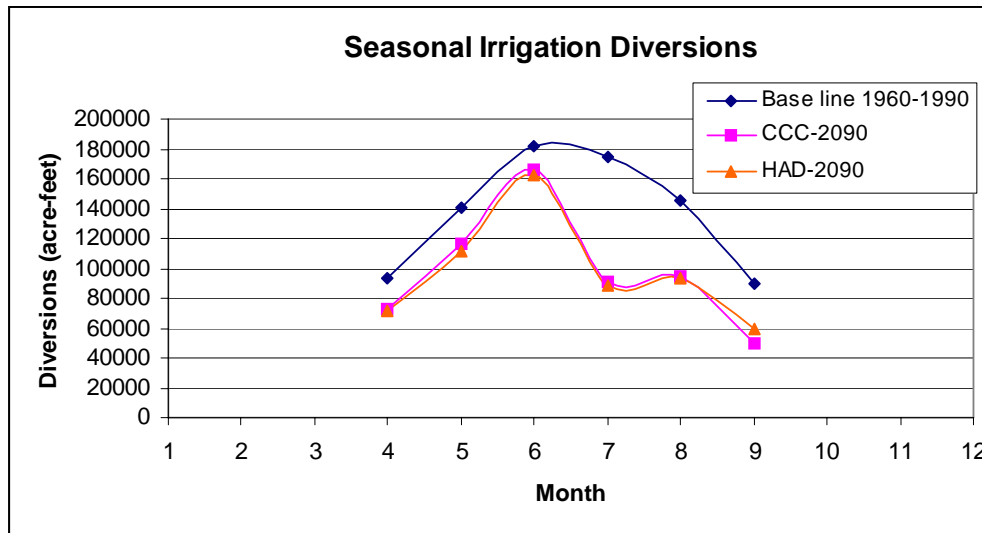
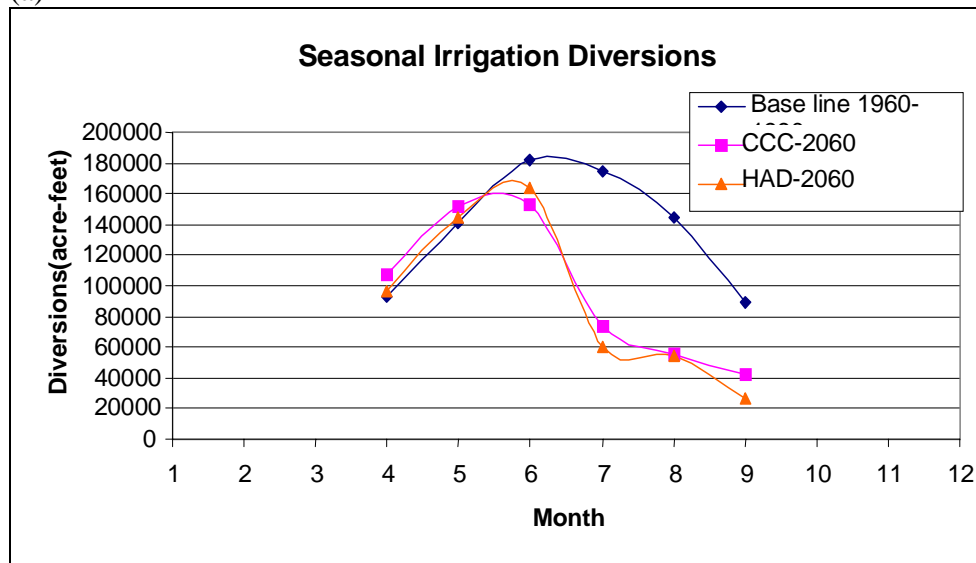


Figure 3. Continued Changes in 10 year Averages of Water Diversions

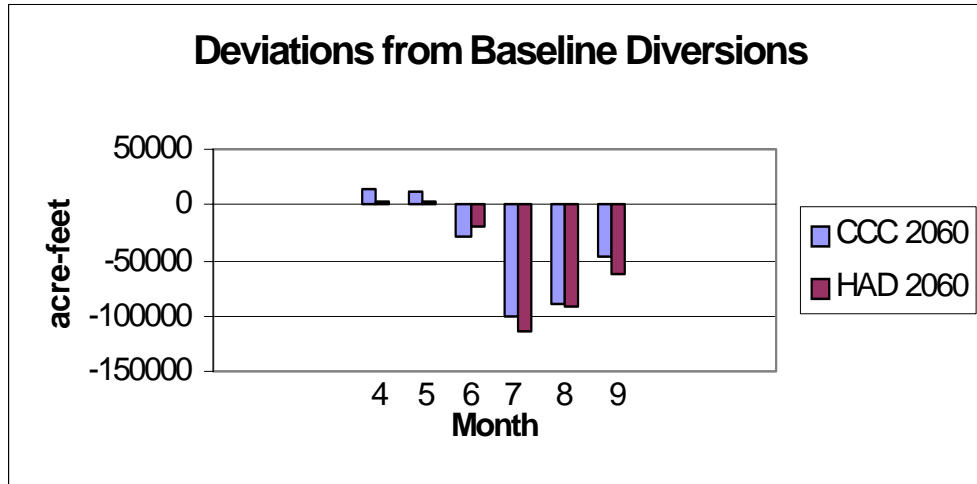


(a)

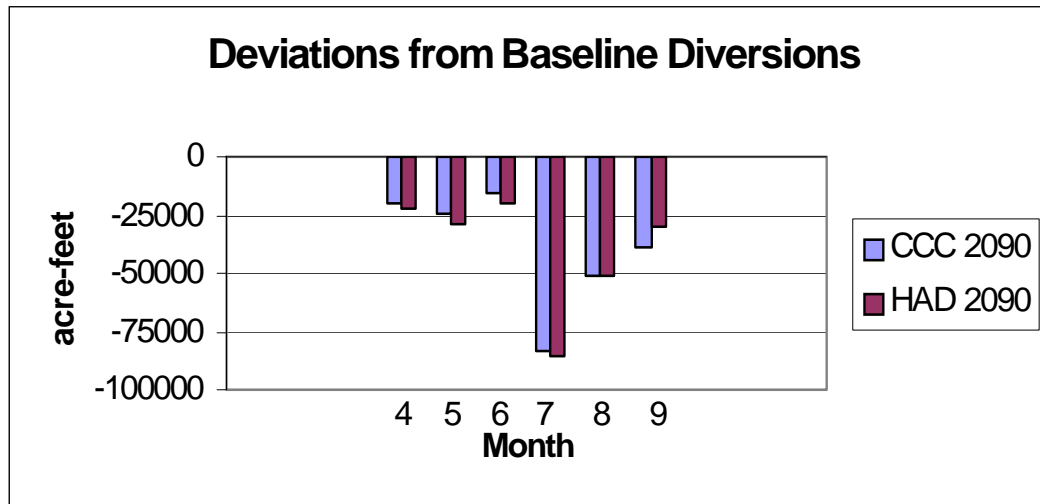


(b)

Figure 4 (a) Simulated Changes in Water Diversions in 2090 (b) Simulated Changes in Water Diversions in 2060



(a)



(b)

Figure 5. Simulated projected deviations from baseline diversions in (a) 2060 and (b) 2090

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