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The Effect of Climate Change on Water Markets in Colorado

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The Effect of Climate Change on Water Markets in Colorado

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Abstract

This study attempts to empirically test the effect of climate change on water markets in Colorado through the use of 2059 water transfers which occurred between 1987 and 2008. Climate change has adverse effects on the annual snowpack, the main source of water for the citizens of Colorado and other Western states. The analysis of this data revealed a non-Gaussian data set resulting from bulk transfers caused by the high transaction costs of water transfers, introducing bias into all statistical inferences made. This issue was compounded by models which oversimplified the causality of water market activity. A yearly agricultural production value derived from the value of 11 major crops in Colorado agriculture failed to adequately value farmers’ willingness to sell. Other variables such as the effect of drought were not included, a factor which most likely would have helped explain the extremely low water market activity in the sample between 2001 and 2004. Further empirical research is needed to accurately predict the effect of climate change on water market activity, information vital for the long term planning and execution of state water plans.
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Chapter 1: Introduction

Water is a scarce resource in the Western United States due to the prevalent semi-arid climate. The system governing water law, Prior Appropriation, was designed to provide secure water rights and enable the development of non-riparian lands. Water rights were established as an individual property right governed by a priority system administered by state officials. Water markets developed to allow for the trading of water rights. Much research has been dedicated to the dynamics and transaction costs of these markets. These analyses have focused on trends in transfers with changes in the intended beneficial use purpose of the water right, pricing differentials between various beneficial use types transfers, the effects of water transfers on third parties and the economic impact on farming communities of ag-to-urban water transfers. (Howe, Lazo, & Weber, 1990, Brewer, Glennon, Ker, & Libecap, 2006, Brown, 2006)

One key factor which has been omitted from the empirical analysis of water markets is the effect of climate change. The rising temperature associated with climate change has a multitude of adverse effects on the annual snowpack. Snowmelt from the annual snowpack supplies the majority of water captured, stored and used by humans across the Western United States, including Colorado. Understanding how climate change effects water transfer activity will be vital for accurate long term planning and execution of state and local water plans.

This study seeks to establish the effect of rising temperatures, driven by climate change, on water transfer amounts. The first section outlines the causality and evolution of water law in Colorado and the effects it has had on water management, agriculture, and population location. It will then describe the basis for the variables used in the study.
The next section develops the underlying assumptions of the OLS regression models used to test the effect of climate change on water markets. The following sections provide an econometric analysis of these models. The final section provides a series of recommendations for water managers and communities to cope with the adverse effects of climate change.
Chapter 2: Background

Colorado’s Topography and Climate

As a result of Colorado’s topography the climate is broken up into two general zones. The Rocky Mountains divide these two topographical regions. Moving westwards from the eastern edge of the state, the terrain is dominated by plains. These continue all the way to the edge of the eastern Rocky Mountains. Western Colorado’s topography is comprised of two zones: the Rocky Mountains, which have highly variable terrain, and the high plateau of far western Colorado. Figure 2-1 illustrates Colorado’s topography.

**Figure 2-1**

![Map of Colorado](image)

*Source: Colorado Resource Center*

The Rocky Mountains are a topographic barrier for the Pacific Maritime air masses which advance from the west. (Hauer, Stanford, & Lorang, 2007) The mountains cause orographic lifting of the air carried by these air masses, the central cause for the different climates, precipitation and other weather patterns experienced on either side of
the Rocky Mountains. The eastern plains have a relatively uniform, semi-arid climate, characterized by low humidity, abundant sunshine, low precipitation, medium to fast winds and a large diurnal temperature range. Between 70-80% of total precipitation falls between April and September through summer thunderstorms, which are often intense. The foothills of eastern Colorado experience much higher winds, lower diurnal temperature ranges, and higher precipitation amounts than the plains. (Climate of Colorado, n.d.)

The heterogeneous topography of western Colorado generates a variety of climates. Changes in elevation result in highly variable temperatures. Precipitation totals are much higher and more evenly distributed than in the east. The majority of precipitation occurs during the winter. Cooler temperatures caused by high elevations result in a high percentage of precipitation falling as snow. (Climate of Colorado, n.d.)

See Figure 2-2 for the distribution of precipitation in Colorado.

**Figure 2-2**

Average Annual Precipitation
Colorado

![Map of Colorado showing average annual precipitation](image)

*Source: NOAA*
The high elevation and steep gradient of the Rocky Mountains relative to the surrounding lands led to the formation of river systems on both slopes of the mountain range. The accumulation of water as snow throughout the winter months produces the annual snowpack. When temperatures rise above freezing, this snow melts and is drained via gravity. Over time, water eroded channels in the landscape, sculpting the various river systems through which water drains today. (Butler, 2005) Figure 2-3 illustrates the various rivers originating in Colorado and provides a visualization of the total flow of each river. These rivers provide water utilized by millions of people and a large percentage of wildlife across 19 Western states. (Water Facts, 2014)

**Figure 2-3**

[Image of a map showing historical average annual stream flows in Colorado, labeled with data values in acre feet (AF). The map includes various rivers and their flow data, with a total leaving Colorado listed at 9,967,000 AF. Prepared by the Hydrographic Branch (2011 Revision) and from the Office of the State Engineer, Colorado Division of Water Resources. Source: Colorado Division of Water Resources]
Population and Precipitation Disparity

The extreme terrain, harsh climate and extreme weather conditions of the Rocky Mountains make them unsuitable for settlement. Consequently, 80% of the population resides in the plains of eastern Colorado. The topography of Colorado causes close to 80% of precipitation to fall in Western Colorado. The scarcity of water in eastern Colorado stagnated economic growth for decades. Throughout the 20th century, the U.S. Bureau of Reclamation undertook a number of major infrastructure projects to divert, deliver and store water in order to encourage the settlement of the West, including Colorado. These projects greatly enhanced the availability of water in eastern Colorado, spurring economic and population growth. Colorado’s population increased from around 500,000 residents in 1900 to over 5 million residents by 2010. The population of Colorado is expected to double by 2050. (Lopez, 2010) The current and expected population increase and the subsequent demand for water have strained water resources in eastern Colorado.

An Overview of Colorado Water Law

The Origin of the Prior Appropriation Doctrine

When Colorado and other Western states were first explored, they were thought to be unfit for settlement due to their semi-arid climates. At this time, most water law was governed by the Riparian Doctrine, based on English common law, whereby ownership of land adjacent to a water body bestows the right to use that water. While this legal system works in water abundant Eastern states, Colorado’s pioneers quickly realized that this doctrine would be inadequate. In response, Colorado’s early settlers developed a new
set of laws for the determination of water right ownership. This set of laws is known as
the Prior Appropriation Doctrine, the basis of water law in the West. (Hobbs, 2003)

Throughout the middle of the 19th century, Congress enacted legislation,
including the Homestead Act of 1862 and the Mining Act of 1966, to encourage the
settlement of the Western United States. This legislation vastly increased the total supply
of water by allowing for the diversion of water on public lands. Individual states and
territories were given autonomy to create their own legal systems governing water rights.
(Hobbs, 2003) The origin of the Prior Appropriation Doctrine stems from the decision
handed down in *Yunkers v. Nichols*, 1 Colo. 552, a Territorial Supreme Court case
adjudicated in 1872. In Chief Justice Moses Hallet’s opinion, he stated that, “in a dry and
thirsty land it is necessary to divert water of the streams from their natural channels.”

The Prior Appropriation Doctrine established four key principles of Colorado
water law: (1) all surface and groundwater is a public resource which may be put to
beneficial use by public agencies or private individuals, (2) a water right is the right to
use water, a public resource, (3) the owners of water rights may use streams and aquifers
for the transportation and/or storage of water and (4) the owners of water rights may
build on the private land of others (with just compensation) if the facilities built are
responsible for the extraction and movement of water from the water’s source to the
owner’s intended destination. (Hobbs, 1997) Assumption two does not bestow ownership
of water, merely the right to use it, a key tenant of Colorado water law.

Prior Appropriation was formally institutionalized in Article XVI of the Colorado
Constitution, enacted in 1876. Section 5 of this article states, “the water of every natural
stream, no heretofore appropriated, within the state of Colorado is hereby declared to be
the property of the public, and the same is dedicated to the use of the peoples of the state, subject to appropriation...” (Colorado Constitution, art. XVI, § 5) Section 6 expands upon this, stating, “the right to appropriate the unappropriated waters of the natural streams of the state for beneficial use in order of priority shall never be denied.” (Colorado Constitution, art. XVI, § 6)

The Colorado Constitution’s vague framework of how water rights would be adjudicated and appropriated led to the Adjudication Acts of 1879 and 1881. This legislation established an identification system that determined the priority and quantity of individual water rights through water courts. These courts, administered by state water officials, are responsible for mediating disputes over water claims. (Hobbs, 1997) Prior Appropriation was formally recognized as the only water law system in Colorado in 1882, in the case of Coffin v. Left Hand Ditch Co., 6 Colo. 443. The court ruled that the right to water is established under the priority system and that any water rights claimed under the Riparian Doctrine in the previous twenty years were invalid. The establishment of the prior appropriation system began the adjudication of water rights.

**Determination of Water Rights and Priority Status**

A water user must apply to the regional water court to obtain a water right. The court sets the priority date, source of supply, amount of water, point of diversion, type of beneficial use and place of use. During this process, the court ensures that the adjudication of the water right in question will not infringe on any established water rights. There are two main water right types: (1) direct flow rights, where the water user takes water directly from a stream to its point of use, and (2) storage rights, which allow water users to store water in a reservoir for use at a later time. (Hobbs, 2003) If the water
is not immediately put to beneficial use, a conditional water right is granted. In order to gain the absolute water right, the water user must take steps to prove the water designated by the water right is being put to beneficial use. Upon doing so, an absolute water right is bestowed. An absolute right exists in perpetuity as long as the water being diverted is put to beneficial use. (Hobbs, 1997)

A water right has two primary components: a consumptive value (in acre-feet) and a priority status. To obtain the right to divert water (a water right), the water under consideration must be put to beneficial use and be currently unallocated. The Prior Appropriation Doctrine is based on the theory of “first in time, first in right.” According to this theory, the first individual/entity to stake a claim on a water right has a legal priority to that water. This is indoctrinated in the Colorado Constitution, which states, “priority of appropriation shall give the better right as between those using the water for the same purpose.” (Colo. Const., art XVI, § 6) Priority rank is determined by two dates. Initial rank is based on the date the application was filed, with a secondary ranking based on the date the water right was formally adjudicated to the claimant. (Grantham, 2011)

Beneficial Use: Meaning and Applications

The beneficial use clause was included in Colorado water law to limit claims and reduce speculation. According to the Colorado Water Conservation Board, beneficial use is defined as the, “use of that amount of water that is reasonable and appropriate under reasonably efficient practices to accomplish without waste the purpose for which the appropriation is lawfully made.” (2014) As settlements developed, they filed for water rights intended for domestic purposes. A series of lawsuits between municipalities of other water users over water claims resulted in three important legal developments:
(1) water rights could be bought and sold, (2) a water right’s intended beneficial use and point of diversion could be altered pending approval of the regional water court and (3) senior water rights could not be taken or infringed upon without payment or just compensation. Over time, the variety of allowed beneficial use purposes has expanded due to various state court decisions. Acceptable beneficial use purposes currently include stock watering, domestic, municipal, commercial, industrial, power generation, flood control, minimum in-stream flows (as determined by the Colorado Water Conservancy Board), dust suppression, mined land reclamation, fish ladders, nature centers, wildlife and fish culture, recreational, residential environments, storage release for fishing and boating purposes, and augmenting depletions. (Hobbs, 1997) The determination of water rights as a tradable property right led to the emergence of water markets and water transfers.

Water Markets and Water Trading

Without water trading, the prior appropriation system provides little incentive for conservation. The development of water markets to oversee water transfers has led to a more efficient allocation of water. (Chong & Sunding, 2006) A water transfer involves the sale of a water right from one entity to another. Although there are cases where a water transfer occurs between two parties without any formal change to the water right itself, the majority require at least one change to an aspect(s) of the right. Colorado, like other western states, has an evaluation and approval process to ensure the appropriation hierarchy is not affected by the change in the water right. In general, there are four aspects of a water right which can be altered: (1) the nature or purpose of use, (2) the place of use, (3) the point of diversion, and/or (4) the season of use. Each right is not
mutually exclusive and applications can attempt to change any combination of the aforementioned aspects. (Colby, McGinnis, & Rait, 1989)

The evaluation and approval process is both time consuming and costly. After a water right application is filed with the regional water court, public notice of the proposed transfer is posted. Third parties may file protests with the Colorado Division of Water Resources if they believe that the posted transfer negatively infringes upon their water right(s). These protests may be settled through either private deliberations or an administrative hearing. If an administrative hearing is held, the regional water court is responsible for rendering a ruling on the dispute in question. This ruling can be appealed. Completion of this process formally adjudicates the water transfer, bestowing a conditional water right to the buyer. Time limits for completing intended projects to put water to beneficial use are imposed on a case by case basis. (Colby et al., 1989) The inherent high transaction costs of water transfers inhibit water trading activity.

Trans-basin Water Transfers and the Colorado-Big Thompson Project

Water rights to water supplied by trans-basin diversions have a unique property. The introduction of water from one basin to another classifies it as “foreign water.” Under Colorado water law, “foreign water” can be fully consumed, meaning there are no return flow requirements. Due to this fact, other users downstream cannot lay claim to these return flows, allowing for transfers to avoid the formal water court review process. This greatly reduces transaction costs, encouraging water trading activity. (Howe & Goemans, 2003)

The disparity between population location and water sources led to the development of a number of trans-basin diversions. A special case of trans-basin
diversions, trans-mountain diversions, divert water from the western slopes of the Rocky Mountains beneath the Continental Divide via a series of reservoirs, tunnels and pumps for use in eastern Colorado. There are 32 active trans-mountain diversions which were built in a series of projects by the U.S. Bureau of Reclamation. Figure 2-4 shows the locations of the active trans-mountain diversions in Colorado. These projects began in two general phases. The first phase occurred during the 1930s for the purpose of providing irrigation water to agricultural users. The second phase occurred during the 1960s and 1970s for the purpose of delivering water for municipal and domestic use by growing cities and municipalities. In 2000, these diversions were responsible for diverting over 590,000 acre feet of water. (Winchester, 2012)

Figure 2-4

The largest trans-mountain diversion, the Colorado Big-Thompson (C-BT) project, supplements the South Platte River Basin. The project began in 1938 but was not
completed until 1957. It was originally intended to reduce the strain of a drought being experienced during the early 1930s. The project diverts water from the headwaters of the Colorado River, underneath the Continental Divide, to the eastern edge of the Rocky Mountains. It is responsible for collecting and delivering close to 200,000 acre feet of water utilized by 850,000 people and responsible for irrigating 640,000 acres of ranch and farm lands in northeastern Colorado. (Colorado-Big Thompson Project, n.d.)

The water delivered by the C-BT project accounts for 30% of the water used within the South Platte River Basin and is administered by the Northern Colorado Water Conservancy District (NCWCD). The NCWCD is responsible solely for the administration and management of water delivered by the C-BT and Windy Gap diversion projects.

The development of the NWCWB water market provides a unique insight into the deregulation of water markets. The unique characteristics of transbasin water rights allow urban areas and other factions to easily purchase water rights in smaller increments as needed, rather than having to plan for long term growth and make bulk purchases. As a result, the NCWCD is the most active water market in the Western United States. (Howe, 2011) Urban demand driven by population growth has increased the number of yearly transfers and the value of individual water rights. (Howe & Goemans, 2003) Figure 2-5 illustrates water share pricing in the NCWCD CB-T water market from January 1994 to October 2013.
An Overview of Agriculture in Colorado

The semi-arid climate that persists in eastern Colorado poses significant challenges to agriculture, with average rainfalls between 5 and 25 inches per year. Early settlers soon realized that the soil of the plains of eastern Colorado was quite fertile. However, the lack of precipitation meant the only crops that could be grown without irrigation were small grains such as wheat and barley. In the early years, individuals were responsible for diverting water to their fields. As development increased, individuals banded together and formed ditch companies to share the work and pool together their capital resources, as longer, more complex ditches and canals were required to reach farmlands established at increasingly farther distances from water sources. (Rettig, 2012)

Farmers found that cereal crops and certain types of produce grew well when irrigated. (Agriculture in the South Platte, 2012) Over the past century, eleven crop types have dominated Colorado agriculture: hay, corn, wheat, barley, oats, sorghum for grain, potatoes, sugar beets, beans, sunflowers (which became a major crop in 1991), and proso millet (which became a major crop in 1999). The majority of the earliest water rights were adjudicated to agricultural users, who remain the largest population of water
consumers. According to the Colorado Watershed Assembly, agriculture accounted for 86% of water deliveries in Colorado in 2014.

**The Economics of Ag-to-Urban Water Transfers**

Several properties of water rights discourage water conservation. Colorado law states that any water not consumed by a user must be allowed to return to the water source as a return flow. These flows are then used to augment the appropriations of other apportionments downstream. Furthermore, any water not needed by a water user, regardless if their water right decrees it, cannot be taken at the time of the actual diversion. This is classified as waste water and is not a measurement included in a water right. (Hobbs, 2003) This regulation was intended to avoid water hoarding and speculation. Failure to utilize water rights for beneficial use can lead to that right be reduced or lost entirely, known as the use it or lose it policy. (Hobbs, 1997) An unforeseen consequence of the last two properties is that water users are incentivized to use as much of their water right as possible.

A key determining factor of the total water supply is consumptive use. Consumptive use is the portion of a water right that does not return to the water source after use. (Estimating Consumptive Use, n.d.) Changes in consumptive usage can lead to over-appropriation. A stream or watershed is classified as over-appropriated if the amount of decreed water exceeds the available supply. (Hobbs, 2003) During a time of water shortage, a senior water user may place a “call” on the river. The Colorado Division of Water Resources then begins administration of that water source, closing the diversions of junior apportionments until more senior ones are filled. (Colorado Water Rights, n.d.) Prior to 1903, the only legitimate claim to establish beneficial use was for
agricultural purposes. (Hobbs, 1997) The most senior and as a result, most secure water rights are held by agricultural users.

There is a large disparity between the value of water rights and the profits derived from irrigated agriculture. Agricultural subsidies in the United States support the overproduction of corn, wheat, rice, cotton and soybeans, leading farmers to grow these crops as opposed fresh produce, which are financially unsuitable to grow in the current agricultural economic climate. (Pollan, 2007) A farmer growing alfalfa, which requires 3 acre-feet/season per irrigated acre, could sell his/her water right for upwards of $51,000 (based on NCWCD C-BT share prices). This drastically outweighs the value of the agriculture produced using irrigated water. Furthermore, climate change is expected to decrease agricultural production by 2% per decade in the yields of staple crops such as corn, wheat and rice. (I.P.C.C., 2012)

Municipalities in Colorado have had to purchase water rights to secure current and future water needs as the population has exponentially increased. The majority of the rights purchased by municipalities were originally established for agricultural purposes. (Howe, 2011) While urban areas have reduced some of their demand through various conservation policies to improve efficiency in water use, population growth and growth trends continue to spur water market activity. Given this information, farmers are faced with a conundrum: do they continue to use their water for irrigation and maintain a relatively modest lifestyle or do they cash out and sell their water rights?

Climate Change and the Annual Snowpack

The water management system of Colorado is reliant on the annual snowpack, the accumulation of snow throughout the winter months. While larger snowpacks represent
favorable water supplies, smaller ones can lead to drought. (Northern Water Conservancy District, 2013) Anthropocentric climate change, caused mainly by greenhouse gas emissions and land use changes, has increased and will continue to increase average temperatures around the world. (I.P.C.C., 2007) The state of Colorado experienced an average temperature increase of approximately 2°F between 1977 and 2006, although the amount of warming varied by location. (Climate Change, n.d.) Higher temperatures have a multitude of effects on the annual snowpack, causing issues with water management in river systems that are fed through snowmelt runoff.

The flow regime of mountain streams and rivers is reliant upon the amount and timing of snowmelt. (Li & Williams, 2008) Increasing temperatures are correlated with both more rain-on-snow events and fewer days of snowfall. (Ye, Yang, & Robinson, 2008) Rain-on-snow events are particularly harmful to the annual snowpack. These events cause sub-snowpack soil temperatures to increase. If the sub-snowpack temperature rises above 0 °C, the melt process for the snowpack can accelerate. (Putkonen & Roe, 2003) Fewer snowfall days result in a lower percentage of precipitation falling as snow. Both of these events decrease the size and snow water equivalent (SWE) of the annual snowpack.

Higher temperatures also cause the snowpack to begin melting earlier in the season, leading to earlier snowpack melt initiation and peak runoffs times. This has led to an increase in streamflows in March and April and a decrease in streamflows in May and June, a trend that has been well documented across the Western United States. (Regonda et al., 2004) Earlier snowmelt times have caused a higher percentage of annual flow to occur 1 to 4 weeks earlier in the water year (March-October). (Stewart, Cayan, &
These factors result in major issues for future water availability. According to a study by Christensen et al., downscaling current climate projections to the Colorado River Basin and under current greenhouse gas emissions rates, total basin storage is expected to decrease 40%, annual runoff is expected to decrease 17%, and reservoir levels are expected to decline 33% by the end of the twenty-first century. (2004) The expected decrease in water availability has a drastic effect on long term water management planning.

Implications

Snowmelt dominated rivers derive between 50% and 80% of their annual flow from spring and summer runoff. The Western United States’ economy relies almost entirely on snowmelt runoff. The runoff is put to various uses, such as irrigation, hydroelectric power generation, human consumption, coolant for conventional power plants, among other things. A smaller annual snowpack and earlier melt timing can cause a number of issues for water managers. Not only is the total available amount of water decreased, but less is available during the summer months when the peak water demand occurs due to irrigation. A dwindling water supply coupled with increasing demand driven by population growth has led to postulations that decreases in future water availability are likely to be severe. (Barnett, Adam, & Lettenmaier, 2005)
Chapter Three: Methods

Scope of Study and Current Market Trends

To test the effect of climate change on water markets, two OLS regression models were used. The study utilizes water transfers adjudicated in the state of Colorado from 1987 to 2008. To eliminate any bias in transfer totals due to variations in water law across the western United States, the sample was limited to the state of Colorado. The study period was chosen based on the availability of water transfer data, outlined in the next section.

Senior water rights are the most valuable because of their appropriation date and its corresponding status in the hierarchy of the prior appropriation system, improving water security. The majority of these are held by agricultural users. Urban demand has driven water transfer activity, leading to the majority of transfers changing from agricultural to urban users. Figure 3-1 breaks down the percentage of transfer types that occurred in Colorado water markets between 1987 and 2008.

**Figure 3-1**

*Colorado Water Transfers by Type 1987-2008*

*Water Transfer Database*
Four variables were used in this study. Water transfer activity was introduced as the dependent variable. Temperature, population and agricultural production value were introduced as independent variables. The underlying assumptions and the source of values for each variable are explained in the next section.

Data Sources and Underlying Assumptions of the Model

The data on water transfers was obtained from the Water Transfer Database, a comprehensive accounting of water trading in the 12 Western states of the continental United States between 1987 and 2008. (Bren School of Environmental Science & Management, 2014) The Water Transfer Database is an aggregation of every water transfer reported by the Water Strategist. The Water Strategist was a monthly trade journal published between 1987 and 2010 which collected and published information on water transactions, litigation, legislation and other water market activities. (Brewer, Glennon, Ker, & Libecap, 2006) The Water Strategist’s reporting is incomplete, with no studies having been published analyzing the scope of the transfers reported. Additionally, individual transfer reports sometimes included multiple transfers adjudicated to the same buyer in one year for the same intended purpose. Taking these reporting issues into account, numerous studies have still concluded that the Water Strategist’s water transfer reporting is the most comprehensive data set on water market trading in the Western United States. (Brown, 2006) A total of 2059 transfers fit the scope of the study. Median transfer size in the sample was 17.5 acre feet, with a high and low of 205,000 acre-feet and .5 acre-feet, respectively acre-feet. Table 1 provides a yearly breakdown of the total water transferred.
Agricultural production value was introduced under the assumption that farmers are more inclined to sell their water rights when their yearly income decreases.

**Hypothesis 1:** *Increased agricultural production values will reduce the amount of water transferred.*

For each year, an agricultural production index was determined utilizing data from the National Agricultural Statistical Service. These yearly values were calculated by adding up the production value of the 11 major crops which make up the agriculture industry in Colorado: corn, hay, sorghum, wheat, barley, oats, sugar beets, sunflowers and proso millet. These values were then converted to 2008 dollars to eliminate any inflationary bias.

According to the Natural Agricultural Statistical Service, the 11 crops studied account for 70% of the water consumed by agricultural activities. The other 30% of irrigated water was consumed by corn for silage and pastureland. Corn for silage values were not calculated because the price paid per ton varies with the moisture content of the corn. Additionally, the market for corn silage is not routine, making prices varied across transactions. (Hendrix, 2002) For these reasons, the NASS does not report corn for silage sale prices in Colorado. The value of pastureland being irrigated could be calculated by determining the yearly value of livestock, poultry and other animal products produced on Colorado farms. However, there is no government agency which reports the percentage of forage produced in Colorado which is consumed in-state. In order to avoid multicollinearity issues, this data was not included. Table 2 summarizes the agricultural production value for each year.
Population was introduced under the assumption that population growth was driving demand for water since the majority of water transfers changed the beneficial use type from ag-to-urban.

**Hypothesis 2:** Population growth drives urban demand for water, increasing water transfer activity.

Yearly population estimates for the state of Colorado were produced by the Federal Reserve Economic Data (FRED). A summarization of the population data is provided in Table 3.

Temperature values were included to test the effect of climate change, under the assumption that higher temperatures decrease water availability, increasing water trading as users seek more senior, and thus more secure, water rights.

**Hypothesis 3:** Increased temperature will increase water trading activity to provide a more efficient allocation of water rights.

Temperature was the only climatic variable used for two reasons: (1) a lack of regionalized information on annual hydrological balance amounts (evaporation, transpiration, etc.) and (2) the lack of a clear consensus among climate models and scientists of the effect of climate change on precipitation rates. Average yearly temperature values were estimates produced by the National Oceanic and Atmospheric Administration (NOAA). Table 4 provides a summary of the temperature data.

**The Models**

Two OLS regression models were used to test the relationship between transfers and population, agricultural production value and temperature. The natural logs of
population and agricultural production values were used to normalize the data. These models were represented by the following equations:

\begin{align*}
(1) \quad \text{WaterTransfer} &= a + \beta_1 \ln(\text{pop}) + \beta_2 \ln(\text{agproduce}) + \beta_3 \text{temp} + \epsilon \\
(2) \quad \ln(\text{WaterTransfer}) &= a + \beta_1 \ln(\text{pop}) + \beta_2 \ln(\text{agproduce}) + \beta_3 \text{temp} + \epsilon
\end{align*}

Individual transfers amounts (as reported by the Water Transfer Database) were assigned temperature, population and agricultural production values based on the year in which they occurred. Model 2 utilized the natural log of water transfers as the dependent variable in an attempt to normalize the data.
Table 1: Water Transfer Totals

<table>
<thead>
<tr>
<th>Year</th>
<th>Water Transferred (Acre-Feet)</th>
<th>Year</th>
<th>Water Transferred (Acre-Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>42,932</td>
<td>1998</td>
<td>42,866</td>
</tr>
<tr>
<td>1988</td>
<td>11,251</td>
<td>1999</td>
<td>327,608</td>
</tr>
<tr>
<td>1989</td>
<td>24,709.75</td>
<td>2000</td>
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<td>224,866</td>
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<td>11,659</td>
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<td>1993</td>
<td>35,915</td>
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<td>1995</td>
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<td>1997</td>
<td>58,937</td>
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Table 2: Agricultural Production Value

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<thead>
<tr>
<th>Year</th>
<th>Ag Production Value (2009 $)</th>
<th>Year</th>
<th>Ag Production Value (2009 $)</th>
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<td>2,383,259,300</td>
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<td>1,497,295,800</td>
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<td>2,256,146,620</td>
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<td>1,499,560,960</td>
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<td>1989</td>
<td>1,920,925,200</td>
<td>2000</td>
<td>1,901,965,000</td>
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<td>1990</td>
<td>1,677,660,290</td>
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<td>1,376,685,970</td>
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<td>1991</td>
<td>1,576,634,820</td>
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<td>1,347,796,380</td>
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<td>1992</td>
<td>1,941,301,440</td>
<td>2003</td>
<td>1,171,204,440</td>
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<td>1993</td>
<td>1,856,275,200</td>
<td>2004</td>
<td>1,536,722,280</td>
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<td>1994</td>
<td>2,164,936,320</td>
<td>2005</td>
<td>1,797,371,400</td>
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<td>1995</td>
<td>1,872,778,600</td>
<td>2006</td>
<td>2,309,504,050</td>
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<td>1996</td>
<td>2,083,746,710</td>
<td>2007</td>
<td>2,151,199,440</td>
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<td>1997</td>
<td>1,869,753,900</td>
<td>2008</td>
<td>2,026,926,000</td>
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Table 3: Population

<table>
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<tr>
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<td>1998</td>
<td>3,968,967</td>
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<td>1988</td>
<td>3,262,281</td>
<td>1999</td>
<td>4,056,133</td>
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<tr>
<td>1989</td>
<td>3,275,818</td>
<td>2000</td>
<td>4,326,921</td>
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<td>1990</td>
<td>3,303,862</td>
<td>2001</td>
<td>4,425,687</td>
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<td>1991</td>
<td>3,367,567</td>
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<td>4,490,046</td>
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<td>1992</td>
<td>3,459,995</td>
<td>2003</td>
<td>4,528,732</td>
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<td>1993</td>
<td>3,560,884</td>
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<td>4,575,013</td>
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<td>1995</td>
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<td>2006</td>
<td>4,720,423</td>
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<td>1996</td>
<td>3,812,716</td>
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<td>1997</td>
<td>3,891,293</td>
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<td>4,889,730</td>
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</table>

Table 4: Temperature

<table>
<thead>
<tr>
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<th>Temperature (°F)</th>
<th>Year</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>45.3333</td>
<td>1998</td>
<td>46.4083</td>
</tr>
<tr>
<td>1988</td>
<td>45.1667</td>
<td>1999</td>
<td>46.9917</td>
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<td>2000</td>
<td>47.375</td>
</tr>
<tr>
<td>1990</td>
<td>45.6917</td>
<td>2001</td>
<td>47.0833</td>
</tr>
<tr>
<td>1991</td>
<td>44.925</td>
<td>2002</td>
<td>46.325</td>
</tr>
<tr>
<td>1992</td>
<td>45.0667</td>
<td>2003</td>
<td>47.5417</td>
</tr>
<tr>
<td>1993</td>
<td>43.6167</td>
<td>2004</td>
<td>46.2167</td>
</tr>
<tr>
<td>1994</td>
<td>46.2583</td>
<td>2005</td>
<td>47.075</td>
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<tr>
<td>1995</td>
<td>45.6667</td>
<td>2006</td>
<td>46.7917</td>
</tr>
<tr>
<td>1996</td>
<td>45.7667</td>
<td>2007</td>
<td>46.3</td>
</tr>
<tr>
<td>1997</td>
<td>44.8333</td>
<td>2008</td>
<td>44.966\textsuperscript{a}</td>
</tr>
</tbody>
</table>
Chapter 4: Analysis

Both models estimated the same correlational effect for each variable, with the effects being much lower in Model 2. Table 5 provides the coefficient matrix generated by the models. While every variable had statistical significance at every major significance level in Model 1, temperature was the only variable maintain its statistical significance in Model 2. Table 6 provides a summary of the p-values for both models. Key assumptions of the models failed when the OLS regressions were run. Population was negatively correlated and agricultural production was positively correlated with water transfer amounts, failing to reject the null hypothesis for Hypotheses 1 and 2. Temperature had a positive correlation with water trading in both models, rejecting the null hypothesis of Hypothesis 3.

Table 5

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>8273.309*</td>
<td>18.43743</td>
</tr>
<tr>
<td></td>
<td>(28638.37)</td>
<td>(8.501216)</td>
</tr>
<tr>
<td>Ln(population)</td>
<td>-1833.47*</td>
<td>-2.87108</td>
</tr>
<tr>
<td></td>
<td>(1387.052)</td>
<td>(.411742)</td>
</tr>
<tr>
<td>Ln(agprod)</td>
<td>485.4253*</td>
<td>1.246041</td>
</tr>
<tr>
<td></td>
<td>(868.782)</td>
<td>(.272464)</td>
</tr>
<tr>
<td>Temperature</td>
<td>218.0141*</td>
<td>.038717*</td>
</tr>
<tr>
<td></td>
<td>(190.6101)</td>
<td>(.056582)</td>
</tr>
</tbody>
</table>

*Coefficient is statistically significant at every major significance level

Table 6

<table>
<thead>
<tr>
<th>P Value for:</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>.772695</td>
<td>.030212</td>
</tr>
<tr>
<td>Ln(population)</td>
<td>.596955</td>
<td>5.09E-06</td>
</tr>
<tr>
<td>Ln(agprod)</td>
<td>.186368</td>
<td>4.17E-12</td>
</tr>
<tr>
<td>Temperature</td>
<td>.252852</td>
<td>.493888</td>
</tr>
</tbody>
</table>
Major statistical tests inferences varied between models. Table 7 provides a summary of these statistics. Model 2 was statistically significant, while Model 1 was not. Model 2 had a much higher F stat value due to reduced variation in water transfer amount values. Model 1 explained less than 1% of the variation in water transfers. Model 2 was slightly more accurate in predicting variation, explaining slightly over 4% of the variation in water transfers. Both models failed the chi-square test at every major significance level. The non-Gaussian data weakens all statistical inferences made using OLS regressions.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical Test</strong></td>
<td><strong>F stat</strong></td>
<td><strong>R²</strong></td>
</tr>
<tr>
<td><strong>Model 1</strong></td>
<td>.72167</td>
<td>.001052</td>
</tr>
<tr>
<td><strong>Model 2</strong></td>
<td>30.37863</td>
<td>.042465</td>
</tr>
</tbody>
</table>

Data Issues

There were a number of issues with the data which introduced bias into the results. First, the sample consisted only of water transfers reported by the *Water Strategist*. The *Water Strategist* underreported the total number of transfers and did not report many short term and inter-organization leases. (Brown, 2006) Second, the transaction costs associated with individual transfers led to a non-normal distribution of the data. The lengthy, expensive adjudication process alters market behavior. Buyers of water rights often make bulk purchases to reduce the transaction costs per acre foot transferred. These bulk purchases lead to large fluctuations in the amount of water transferred per year which cannot be eliminated as anomalies.
Second, between 2001 and 2004, the highest yearly water total of water transferred was slightly less than 20,000 acre-feet. The record drought experienced during 2002 probably led to this low transfer activity. The effect of drought on water market activity was not included in the scope of this study. The bulk purchases and the low transfer totals between 2001 and 2004 are illustrated in Figure 4-1. The exponential increase in population, bulk purchases made during earlier years of the study and the low transfer amounts between 2001 and 2004 caused the negative estimated correlation between population and water transfer amounts.

**Figure 4-1**

![Annual Water Transfer Totals In Colorado](image)

Agricultural production values were also affected by the bulk purchases made in early years and the low transfer totals between 2001 and 2004, which corresponded with low agricultural production values. As a result, the effect of agricultural production values on transfer totals did not correspond as predicted. These flaws were exacerbated by the use of agricultural production value as the sole supply side variable. When water
rights were first transferred from agricultural to urban uses, municipalities engaged in a “buy and dry” policy. After purchasing the water rights and altering the diversion of flow, the previously irrigated lands are abandoned. A study conducted by James Pritchett and Jennifer Thorvaldson found that the economic activity generated by agriculture in eastern Colorado ranged from $428 to $1,235 per acre. (2008) The adverse impacts of transfer on other industries make permanent transfers unpopular among many farming communities. (Pritchett, Thorvaldson, & Frasier, 2008) There are many other factors to take into account when determining an individual farmer’s willingness to sell, including family and ancestral values tied to farming, other transfers occurring within the river basin and/or agrarian community, and price trends for water rights in that region.

Finally, yearly agricultural production, population and temperature values were assigned to individual transfers. These variables oversimplify the causation of water market activity. The myriad of other factors which affect water trading not included in the models caused the statistical inferences drawn to be weak at best, if not wrong. Thus, the models were unable to empirically explain the effect of climate change on water market activity.
Chapter 5: Conclusions

In order to run a more accurate regression, a complete analysis of water transfer data records of the six water divisions of Colorado should be undertaken to reduce the underreporting issue described in the Chapter 3. The inclusion of additional independent variables, such as the effect of drought, in addition to the development of a more encompassing agricultural production value, could provide additional insights and more concrete models than the ones used. The non-Gaussian distribution made every statistical inference insignificant. The use of non-parametric significance testing could eliminate this issue.

The failure of the models to accurately predict water transfer activity does not imply that climate change does not have an impact on water market activity. While much research has been dedicated to understanding the dynamics of water markets, there has been very little on the effect of climate change. The lack of empirical research has not precluded water managers from factoring climate change into their long term scenario planning.

The current water management infrastructure is predicated on the annual snowpack delivering snowmelt runoff throughout the summer months, when water demand is at its highest. This infrastructure is not designed to maximize capturing rainwater runoff, which is expected to increase as an overall percentage of precipitation as the average temperature increases. Water availability is expected to decrease as a result. The current institutional framework of water law in Colorado inhibits many policy choices which could address this issue.
While no definitive trends were determined by the models, there is an inherent intuitiveness in understanding how climate change will affect water availability. Due to over-apportionment of the current system, a decrease in the availability of water of acceptable quality could cause a crisis. Most state agencies in Colorado which have a stake in water resources have been working to incorporate climate adaptation into their planning and activities. (Averyt et al., 2011)

The expected increase in population is already a cause for concern among water managers. Other studies have shown a strong correlation between increasing population and ag-to-urban water transfers (which account for over 75% of all transfer activity). (Brewer et al., 2006) Operating under the auspices that the total water supply will remain constant is shortsighted and potentially catastrophic. Further research must be conducted to empirically predict the effect of climate change on water market activity. The production of concrete scientific research on this relationship is vital for the long term planning and securing of a stable water future for the citizens of Colorado and other Western states.
Chapter 6: Recommendations

The prior appropriation system was developed to minimize speculation of and allow for the diversion of water to non-riparian lands. While the legal system which developed is efficient in protecting these rights, it poses serious issues for long term water planning and management. The inflexible nature of the water distribution legal system can pose serious issues for users drawing from an over-appropriated water source. The effect of climate change on local and regional weather, in particular, precipitation, will play a large role determining how the water supply is affected. Most findings indicate that the total water supply will decrease by 2050. (Climate Change in Colorado, 2008)

As water becomes increasingly scarce, new supplies become economically viable. The construction of additional water treatment plants to make water of lower quality available for human use is one such option. Water managers must look at the long run cost benefit analysis of the construction of such projects, accounting for budget availability. Long term planning for the diversion of additional surface waters must account for by the effects of climate change on these supply sources.

While climate change will undoubtedly alter the water supply system, stressing the current water management system that is built upon it, there are many different scenarios to account for. State and local agencies have incorporated this into their planning, although there are more opportunities available to reduce the stress of climate change. Scenario planning has become increasingly complex and varied due to wide ranging predictions of precipitation patterns by climate models. How society will adapt depends on regional climatic influences, adaptation and mitigation techniques, human
engineering, and advancements in surface and groundwater hydrology. (Vorosmarty et al., 2008)

Prior Appropriation constrains the policy choices available to water managers. Any change to the legal system governing water law in the West will be extremely lengthy and face stiff opposition from senior water rights holders. Consequently, water managers must develop their long term plans under the current institutional framework. Scenario planners have focused on three central points in the majority of planned adaptation and mitigation strategies: finding new water supplies, using water more efficiently, and implementing conservation policies to reduce water demand and consumptive use.

**Potential Conservation Policies**

Water claim disputes between Western states have been settled by a series of interstate compacts. These compacts have established total allocation amounts of individual river systems, such as the Colorado and Arkansas Rivers, for individual states. The allocation totals determined by the compacts were often based on a small sample period which didn’t accurately reflect the average annual river flow totals. Additionally, these allocation totals often didn’t include provisions governing year to year variations in flow totals. Altering these compacts to allocate water based on a percentage of flow, rather than as fixed quantities could increase conservation efforts and develop a more secure water allocation for all parties subject to these compacts.

During 2012 in the Colorado River Basin, over 90% of farmland was irrigated, with around 60% of that farmland dedicated to the production of alfalfa and other forage crops used to feed cattle and horses. (Cohen, Christen-Smith, & Berggren, 2013) Federal
agricultural subsidies support the farming of staple crops that are not native to Colorado. These subsidies limit the financial viability of the farming of native, water efficient crops. Additionally, livestock account for approximately 2/3 of direct economic output of agriculture in Colorado. The value of these animals stimulates the production of forage crops used to feed livestock. Alfalfa, one of the main forage crops, requires high irrigation amounts when compared to native Colorado grains. The farming of water efficient plants, the production of less livestock and the implementation of other conservation practices can reduce the consumptive use of the agriculture industry, the largest owner and consumptive user of water in Colorado. Non-agricultural users have placed the impetus for water conservation at the feet of agricultural users. Although converting to more efficient farm-irrigation technology seems like a simple solution, implementation costs are prohibitively high. The use of other techniques such as crop rotation, conservation tillage, planting drought tolerant crops, and lining aging canals could help more efficiently reduce the systemic stress. (Lee & Plant, 2013)

Domestic demand can be reduced through block pricing and “cash for grass” programs. The use of block pricing, whereby the per unit water amount increases when monthly usage passes a set amount, encourages conservation. “Cash for grass” programs pay individuals and private entities to alter their private landscaping layouts to resemble the native landscape and fauna, thus lowering watering requirements.

**Encouraging More Efficient Re-Use**

There are multiple policy options to increase the water supply. Policies which encourage water re-use must walk a fine line between minimizing consumptive use, thus maximizing return flows, and providing water of acceptable quality to end users. The
maximization of return flows would increase the total water supply. However, implementation of a water management system based solely on the maximization of return flows doesn’t account for water quality issues. Colorado law states that senior water right users may not pollute the source of more junior apportionments. (Hobbs, 1997) Changing priority could require the building of additional water treatment plants to provide water of acceptable quality throughout the system, a costly venture.

To combat these issues, other factors would need to be included in the prioritization status of a water right. Water consumers could be given a water quality priority, based on the nature of their intended beneficial use. Initial appropriation rank would start at high quality uses and end with those requiring water of the lowest quality standard. Secondary rank could be based on the quality of water supplied by return flow, and could override the primary priority. Tertiary and tertiary appropriation ranks could be assigned based on the date the water claim was filed and the date it was adjudicated, just as priority status is currently determined. The allocation and use of water prioritized on the quality required could increase the total supply. The addition of other variables into the prioritization status system would increase the evaluation and approval process for water right transfers, inhibiting market activity which would lead to a more efficient allocation of water.

**Determination of New Supplies**

Supply can increased through either micro- or macro-level activity. Individuals can increase their private water supply by capturing rainwater via catchments. Colorado law currently requires any rainwater catchment to be immediately put to use, oftentimes
for landscaping purposes. The storage of rainwater is currently illegal. Easing of restrictions on rainwater catchment could provide relief to the system.

The construction of deeper wells and more complex diversion projects can increase the macro-level supply. As water becomes increasingly scarce, new supplies become economically viable. Increasing the water supply usually involves the addition of lower quality water. The introduction of new supplies will probably require the construction of additional water treatment plants on account of water quality issues. Water managers must look at the long run cost benefit analysis of the construction of such projects, accounting for budget availability. The diversion of additional surface waters must be tempered by the effects of climate change on these supply sources.

Individual policy and infrastructure changes address various aspects of the water management system. Expected demand will be unsustainable under current management techniques. Water managers and the various water users must be open to wide-ranging and multiple policy and infrastructural changes to address future water availability and security concerns. Failure to account for climate change will have disastrous consequences in the near and long term future.
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*Coffin v. Left Hand Ditch Co.*, 6 Colo. 443


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Colorado Constitution, art. XVI, § 6.


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