# A MULTI-DIMENSIONAL ANALYSIS OF THE UPPER RIO GRANDE-SAN LUIS VALLEY SOCIAL-ECOLOGICAL SYSTEM

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## ABSTRACT

A MULTI-DIMENSIONAL ANALYSIS OF THE UPPER RIO GRANDE-SAN LUIS VALLEY SOCIAL-ECOLOGICAL SYSTEM

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The Upper Rio Grande (URG), located in the San Luis Valley (SLV) of southern Colorado, is the primary contributor to streamflow to the Rio Grande Basin, upstream of the confluence of the Rio Conchos at Presidio, TX. The URG-SLV includes a complex irrigation-dependent agricultural social-ecological system (SES), which began development in 1852, and today generates more than 30% of the SLV revenue. The diversions of Rio Grande water for irrigation in the SLV have had a disproportionate impact on the downstream portion of the river. These diversions caused the flow to cease at Ciudad Juarez, Mexico in the late 1880s, creating international conflict. Similarly, low flows in New Mexico and Texas led to interstate conflict. Understanding changes in the

URG-SLV that led to this event and the interactions among various drivers of change in the URG-SLV is a difficult task. One reason is that complex social-ecological systems are adaptive, contain feedbacks, emergent properties, cross-scale linkages, large-scale dynamics and non-linearities. Further, most analyses of SES to date have been qualitative, utilizing conceptual models to understand driver interactions. This study utilizes both qualitative and quantitative techniques to develop an innovative approach for analyzing driver interactions in the URG-SLV. Five drivers were identified for the URG-SLV social-ecological system: water (streamflow), water rights, climate, agriculture, and internal and external water policy. The drivers contained several longitudes (data aspect) relevant to the system, except water policy, for which only discreet events were present. Change point and statistical analyses were applied to the longitudes to identify quantifiable changes, to allow detection of cross-scale linkages between drivers, and presence of feedback cycles. Agricultural was identified as the driver signal. Change points for agricultural expansion defined four distinct periods: 1852-1923, 1924-1948, 1949-1978 and 1979-2007. Changes in streamflow, water allocations and water policy were observed in all agriculture periods. Cross-scale linkages were also evident between climate and streamflow; policy and water rights; and agriculture, groundwater pumping and streamflow.

# PREFACE

The purpose of this dissertation was to present a multi-dimensional analysis of the Upper Rio Grande-San Luis Valley, a complex agriculture social-ecological system using both qualitative and quantitative analyses. To accomplish the task several steps needed to be completed prior to a final analysis; drivers had to be identified and longitudes within each driver had to be developed. The driver represents an essential element of the system whose interactions within the system cause change or through which change is facilitated. Longitudes are individual data sets of the driver that represent a specific aspect of that driver. For each driver several longitudes were developed and analyzed. For example, three longitudes of climate were developed in this dissertation: mean, minimum and maximum temperature, growing degree days (GDD) and freeze-free days. Temperature and GDD were further separated into annual and growing season periods with GDD also separated into three additional sub-categories by crop. Quantitative analyses of their changes are presented in Chapters 2, 3 and 4. Chapters 5 and 6 similarly present quantitative analyses of longitudes of water rights and streamflow. Utilizing the analyses in those chapters allowed the multi-dimensional analysis and integration of the 5 main drivers of the Upper Rio Grande – San Luis Valley social-ecological system presented in Chapter 1.

# CHAPTER 1

A MULTI-DIMENSIONAL ANALYSIS OF THE SOCIAL-ECOLOGICAL SYSTEM OF THE UPPER RIO GRANDE-SAN LUIS VALLEY, COLORADO

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Abstract: Understanding the complex dynamics of social-ecological systems (SES) has proven difficult as rigorous methodologies and methods for doing so are lacking. Social-ecological systems contain multiple linkages and pathways between drivers, which create feedbacks and occur across scale. Systems therefore are multi-dimensional and require a multi-dimensional analysis, which requires the identification of drivers and cross-scale linkages. This study presents a multi-dimensional analysis of the complex SES located in the Upper Rio Grande-San Luis Valley (URG-SLV). It also presents a methodology and methods for identifying drivers and cross-scale linkages. Data for several drivers in the system were available from as early as 1852 and extending to 2007. A driver identification process identified 5 major drivers in the URG-SLV: streamflow, climate, agriculture, endogenous and exogenous policy. Several of these possessed more than one longitude. No feedbacks were present; therefore no feedback signal was evident, though agriculture was identified as the driver signal. Changes in driver longitudes were detected via change point analysis and occurred at several points. Linkages were defined utilizing known relationships between drivers, e.g., streamflow and water rights. Cross-scale relationships between the SLV and downstream users occurred through policy changes and climate also presented a temporal cross-scale link. Using the relationships and cross-scale linkages, a historical evolution of the system was constructed throughout the 150-plus years of record to illustrate the effects of the driver signal and cross-scale linkages in the system.

**Keywords**: Social-ecological, drivers, longitudes, complex systems, feedback signal, cross-scale links.

**Introduction**

Humans and nature do not stand separate and alone. Rather, we are deeply embedded in the ecosystem and form regionally complex social-ecological systems (SES). Further, the success of the social system depends upon the natural resources provided by the ecosystem (Diamond 2005). The Upper Rio Grande-San Luis Valley (URG-SLV), in Colorado (CO), forms such an SES and contains the headwaters of the Rio Grande. This region has been implicated as the cause of two major water resource conflicts; one international with the U.S. and Mexico (Paddock 2001) and one internal between CO, and the states of New Mexico (NM) and Texas (TX). Each was caused by excessive water diversions for irrigated agriculture taking place in the SLV. First, water diversions caused the Rio Grande to run dry at Ciudad Juarez, Mexico in 1888 and 1889 (Paddock 2001), thus precipitating the 1906 Treaty between U.S. and Mexico guaranteeing the annual delivery of 74 $hm^3$ of water. Similarly, water diversions in the SLV created water scarcity in NM and TX and resulted in the 1938 Rio Grande Interstate Compact which assigns a portion of the headwater inflows to downstream states.

But understanding how and why these events took place and the relationships between the various drivers of change within the system is a difficult task. This is because complex social-ecological systems are inherently difficult to analyze. Complex systems are adaptive, meaning they change in response to endogenous or exogenous influences (Holland 1992). They contain elements of resilience to disturbance, thereby having the ability to withstand an influence that has potential to transform the system (Gunderson and Holling 2002). They contain feedbacks and cross-scale linkages; feedbacks are influences that increase or decrease the amplitude of change, while cross-scale linkages are connections that occur between elements of the system, and which can be geophysical or temporal (Walker et al. 2004). The most obvious cross-scale linkages occur at the temporal scale in social policy interventions as a response to change in the system. The cross-scale intervention lags the system's change and is frequently reactionary in the wake of ecosystem failures or catastrophes; e.g., The Clean Water Act and Endangered Species Act each lagged major system changes by decades. Geophysical cross-scale links occur across the boundaries of systems, e.g., acid rains in the maritime regions of the U.S. and Canada which are generated by coal burning power stations in the Ohio River Valley (Dutkiewicz et al. 2000). Lastly, complex systems are non-linear (Holling 2001), the relationships between the various elements may not be easily observed as the dependent and independent relationships common to cause-effect analysis; and they are also characterized by large-scale dynamics (Olsson et al. 2004), which may be a long cycle similar to a Kondratieff Wave, or a major disturbance such as war. Unexpected emergent elements can result from feedbacks (Funtowicz and Ravetz 1994) and further reduce the ability of linear modeling and prediction. Besides being unexpected, emergent properties can act to ameliorate or exacerbate the feedback mechanisms, thus hiding or exaggerating them (Millennium Ecosystem Assessment 2005).

The tendencies of complex SES to contain one or more of these conditions often leads to their mismanagement. These influential elements in SES are referred to as drivers, and the proper management of human dominated ecosystems requires identifying and defining those drivers crucial to the SES long-term viability. According to Dörner (1996), incomplete understanding of the complexity of a system is often responsible for management failures. Management failures are evident in more than one instance; fishery collapses and overexploitation (Mullon et al. 2005, FAO 2006), soil salinization in catchments of Victoria, Australia (Greig and Devonshire 1981) and the draining of the Aral Sea (Micklin 1988) are just a few of many examples. Some failures also present security issues; for example, conflicts over water access near Lake Chad (Odada et al. 2003) and access to northern cod fisheries (Mitchell 1976) have both resulted in international disputes. Superficially these may appear simplistic; a result of over fishing, deforestation, etc. Those are proximal causes; however other elements, social, economic, policy, etc., set the stage for the proximal event to occur. It is these elements that create the complex dynamics and opportunities for success or failure; therefore understanding the dynamics that result from the combination of elements is paramount to preventing systems collapse.

This complex dynamic often produces unexpected consequences (Holling 2001) and has prompted research into the complexity of SES, particularly because of the difficulty natural resource managers have encountered in attempting to control complex systems (Holling and Meffe 1996). The dynamics of a system create the multi-dimensional qualities that make understanding, defining, controlling and measuring SES parameters difficult. As a result researchers have relied more heavily on qualitative approaches to define social-ecological processes (Holling 2001, Olsson et al. 2004) and illustrate the evolution of a social-ecological system in regard to policy changes in resource management (Abel and Langston 2001, Allison and Hobbs 2004). Although understanding potential linkages between drivers qualitatively is important, to manage an SES properly, it is necessary to understand the evolution and complexity of driver interactions (E. P. Odum 1984, Hillman et al. 2005). Thus, there remains the need to quantitatively define the interactions of drivers in an SES to improve the understanding of the systems dynamics and for scenario development of potential futures.

Early work by H. T. Odum (1973) on complex systems maps the movement and transformation of energy through a system. However, the model used was a branching linear (dendritic) model lacking multi-dimensional aspects. Holling (2001) indicated the key to understanding the complexity of a system and its cycles of release and reorganization is to develop a framework with a handful of drivers, 3-5 or "The rule of hand." This set of drivers was postulated as fundamental number of drivers necessary to govern the system. However, no method was offered to determine how changes in the cycle can be determined or qualified, nor methods for identifying drivers. Walker et al. (2002) utilized longitudinal data to describe changes in a system as did Abel and Langston (2001). Each of these studies employed temporal constructs to define periods of release and reorganization. Without quantitative methods one can justify this approach and in hindsight can easily identify when an event took place that precipitated change. However, it is more difficult to determine when that event no longer influences the system as new conditions develop. In general, these and similar studies apply arbitrary boundaries in the timelines of the SES, often employing artifices of decades (singular or multiple). These artifices and omissions are not failures of scientific quality, but frequently scientific criticism decries the lack of quantification and demands statistical verification. Though the aforementioned research employed a dendritic model, or lacked methods for driver identification and quantification of changes in drivers, each still provided insight regarding complex systems and, more importantly, to the functioning of

SES. More recently there has been a realization that natural resource management and the analysis of complex SES must become multi-dimensional.

A multi-dimensional approach to management takes into account non-linear relationships, cross-scale linkages, feedbacks, lag effects and multiple drivers simultaneously. As such it includes several surrounding interconnected aspects of the environment and society (Millennium Ecosystem Assessment 2005, Hillman et al. 2005) and, combined with qualitative and quantitative methods, a much improved assessment of a system can be achieved. Since several drivers typically compose an SES and possess multiple linkages with more than one other driver, which often creates feedbacks, such an approach is necessary. Furthermore, it has been noted by Troncale (2009) and the Millennium Ecosystem Assessment (2005) that there is a definitive need for methodologies and methods that identify drivers in a system and evaluate their linkages.

The purpose of this study is to develop a multi-dimensional analysis of the URG-SLV social-ecological system in regard to how the system has evolved over time as drivers have changed by asking a series of key questions: What are the main drivers of change in the system? Do they create feedback cycles? If so, what driver is the feedback signal? How has the system evolved over time in response to changing drivers? Is there an external driver that acts independently of the system, but forces change on the system? A multi-dimensional analysis that employs both quantitative and qualitative methods is necessary to answer these questions properly, particularly one that can cope with cross-scale linkages and feedbacks. Further, a driver identification process has to be developed.

**Study area**

The Upper Rio Grande – San Luis Valley (URG-SLV) is a well defined system geographically and temporally. It is defined geographically by the watershed of the URG, and temporally by data from 1852 to 2007, depending on the aspect of interest. The URG-SLV is located in south central Colorado (CO); the valley is roughly bisected by the Rio Grande (Figure 1.1). The river rises in the western San Juan Mountains, which form the western boundary of the SLV, and the eastern boundary is formed by the Sangre de Cristo Mountains. The drainage area, approximately 20,719 sq km, was created from the Rio Grande Rift, formed as the two mountain ranges began moving apart from each other approximately 300 mya. The elevation of the valley floor is approximately 2200 m, making it one of the highest inhabited and developed deserts in the world, with the surrounding mountain peaks rising to above 4200 m.

Much of the moisture in the prevailing westerly winds precipitates in the San Juan Mountains as orographic events, while the moisture in the easterly winds precipitates in the Sangre de Cristo Mountains. Thus, each range effectively creates a rainshadow for the valley floor. Therefore, the Valley receives less than 20 cm of precipitation annually because of the rain shadow effect, while the San Juan Mountains to the west receive 100-200 cm of precipitation annually (Baker 1944, Emery 1979, Mitchell 1993). The area is characterized by periodic droughts, some being intermittently severe and long-lasting (Ryerson et al. 2003). According the National Climate Data Center (NCDC), the region regularly experiences wintertime temperatures of less than -20°C and as low as -40°C. It ranks in the top 20 coldest locations in North America (King 2007). Warm season temperatures can exceed 30°C, but the warm season only lasts 90-110 days. During the summer it is not uncommon to have a 20°C diurnal temperature change.

Even though the SLV is cool and arid, it is a major agricultural region for the state of Colorado. Agriculture is the dominant economic endeavor, generating more than 30% of the SLV revenue. Approximately 240,000 hectares are under cultivation in the Valley, and produce the majority of the state's potato crop (14,000-30,000 ha) and a large portion of its alfalfa crop (80,000-100,000 ha) (CSUa). All of the Valley agriculture is irrigated by surface or groundwater to compensate for the prevailing aridity (CSUb). There are approximately 10,000 unmetered wells in both the confined and unconfined aquifers, and more than 250 km of surface water irrigation canals.

## Methodology

### *Framework*

The framework used in this study is comprised of a three-part methodology that includes drivers, quantification, and historical narrative. Each part provides insight into the system's functioning and its interactions (Figure 1.2):

Drivers: All systems contain drivers with specific longitudes pertinent to the system; these drivers and their longitudes must be identified. Longitudes are data aspects of the driver e.g., the driver 'population' may have longitudes of birth rates, death rates and adult education levels for the period of study.

Quantification: The changes in driver's longitudes must be identified and quantified to aid in the identification of linkages between drivers. This can be conducted via such methods as change point detection, and followed with any requisite statistical analyses necessary for validation. Change point detection was recently suggested by

Anderson et al. (2009) as valuable, but as of yet overlooked, method for identifying thresholds and regime shifts. Further, quantification substantiates the changes lending additional credence to the analysis and providing stronger justification for linkages.

Historical narrative: The analysis of a system utilizes historical narratives to integrate the changes in drivers and longitudes into a cohesive explanation of the system's dynamics, feedbacks, cross-scale linkages and evolution.

**Methods**

***Driver identification***

The process of driver identification is stepwise, beginning with the main driver, then extending to other exogenous and endogenous drivers. Each driver should have at least one plausible relationship with the primary resource driver. In the setting of a social-ecological system, there is an implied reliance on a single primary, or a few proximal natural resource elements, since all human systems rely on ecosystem resources initially for their sustainability (Diamond 2005). This is also consistent with the Millennium Ecosystem Assessment (2005) statement that it is typical of researchers to identify a proximal resource as a main driver in a system.

The overall driver identification process present below is similar to a heuristic questionnaire presented by Bennett et al. (2005), in which the dynamics of an ecosystem are identified through the process of asking questions pertinent to the system. Bennett et al. (2005) identified 5 steps, each containing more than one question, to assist in the identification of resilience surrogates. Similarly, the driver identification process below (steps 2-5) also draws from the work of Anderies et al. (2004), who presented a conceptual model of driver interactions in an SES containing four drivers, including resources, resource users, infrastructure providers, and infrastructure, as well as the elements linking the drivers. Step 6 reflects the work of Walker et al. (2002), which exposed policy as a major driving influence in SES evolution and resource utilization. Step 7 reflects the considerations of Barrett et al. (1976) regarding the inclusion of renewable resources as drivers when considering the structure and function of an ecosystem. As such, it also is included in the driver identification presented here. Further, to prevent inclusion of drivers *ad infinitum* the stepwise process below utilizes the principle of simplicity espoused by William of Occam "*Entia non sunt multiplicanda praeter necessitatem.*" The process below identifies the major driver/resource, with the drivers staying within one degree of separation from the resource in order to maintain simplicity. One degree of separation means each driver is directly connected to the resource.

***Stepwise process of driver identification:***

Step 1 – Define the boundaries of the system.

Step 2 – Identify the primary resource necessary for the functioning of the social system – Driver 1.

Step 3 – Identify the secondary resources necessary for the functioning of the social system – Driver 2.

Step 4 – Identify the primary user or extractor of the resource – Driver 3.

Step 5 – Identify other social aspects: demographics, economics, etc dependent on the primary or secondary resource – Driver 4.

Step 6 – Identify policy and laws governing the resource and its extraction, and rights to the resource - Driver 5. (If there are both endogenous and exogenous policies and laws then this should be divided into 2 drivers as the forces are independent)

Step 7 – Identify the contributory process(es) that renews or maintains the resource or that impacts the resource within the temporal scale of interest, if present and determine whether they are endogenous or exogenous – Driver 6.

Step 8 – Identify and develop data for relevant longitudes of each driver.

***Change point detection***

Change point detection identifies the periods within each longitude that are significantly different from other periods and quantifies them. The first step in applying the change point detection process is to develop the longitudinal data for each driver so the analysis can identify the point(s) in the data record where the values depart from the mean values, thereby creating distinct subsets of data from the original data. Change point analysis has been used to identify subsets of long-term data in several studies including, climate change (Bărbulescu and Băutu 2009), hydrology (Zanchettin et al. 2008) and detecting changes in soil phosphate concentrations (Cavanagh et al. 1988).

***Final integration of the longitudes***

A thorough knowledge of the system, its drivers and potential interactions of the drivers is necessary at this point. Without an in depth understanding of the system's drivers it would be difficult to apply changes in one driver as the cause of changes in another, particularly since change may occur as cross-scale temporal link, as is the case in the policy changes. Once the change point analysis is complete for each driver's longitudes, an assessment of linkages is conducted. Identification of the linkages, though somewhat subjective, is bolstered by simultaneous or congruous changes and a thorough understanding of the potential effects of one driver on another.

**Results**

***Driver and longitude identification***

Five drivers were identified within one degree of separation (Figure 1.3) from the primary resource; surface water. More than one longitude was identified for 4 drivers (Table 1.1). Surface water, in the form of streamflow, was identified as the primary resource for the URG-SLV SES. Two longitudes were developed from stream gauge data; annual and growing season streamflow. Agriculture is essentially the secondary resource of the URG-SLV SES and it also represents the primary user of water. Agriculture also is the major revenue generator in the URG-SLV and uses more than 85% of the primary resource. Because it is the secondary resource and primary resource user it was considered a single driver, and identified as Driver #2. Two longitudes were developed from crop data; total annual acreage and total annual alfalfa acreage. No major contributing factors were found to be present within the non-agriculture community and they were deemed outside one degree of separation. Internal water laws as moratoriums and water rights represent Driver #3, because they control the timing and quantity of water extraction. The internal water laws were not developed into longitudes as these are discrete events and not continuous data. Water rights, however, represent continuous data, in the form of allocations (rate). Three longitudes were developed from water rights data: surface water allocations and ground water allocations from both unconfined and confined aquifers. External laws and policy in the form of treaties and compacts were identified as Driver #4, influencing the quantity of water the URG-SLV must provide to downstream users. These were not developed into longitudes as they too represent discrete events, not continuous data, but were applied to the analysis of other longitudes when relevant. The contributory process with potential to impact Driver #1 and #2 was identified as climate, Driver #5. Climate change is a relevant process throughout the period under study and it has potential to impact stream flows via changes in precipitation patterns and increases in crop water use. Further, it impacts crop production via changes in temperature which determine growing degree days (phenology). Climate data from seven stations on the floor of the SLV were developed into three longitudes of means of annual maximum, minimum and mean temperatures and growing degree days (GGD). These were developed from climate data to be utilized in understanding the impact of climate change on crop and pest phenology. Also, one longitude was developed for the freeze-free period, to establish changes in the length of the growing season.

***Change point analysis***

Change point analysis was conducted on all driver longitudes with continuous data. Change point analysis revealed several change points in driver longitudes (Table 1.2). Three change points were detected for streamflow, two for climate variables, one for surface water rights, three for groundwater rights, and two for total acreage and one for alfalfa acreage. Policy changes were discreet events; therefore, no change point analysis was conducted.

## Discussion

The URG-SLV is a complex social-ecological system. By utilizing the methods presented here, the relationships, feedbacks and cross-scale interactions are more evident. The driver and longitude identification process, change point analysis and linkage identification facilitated the following multi-dimensional analysis of the URG-SLV system.

### *Feedback, linkages and cross-scale interactions*

Although the URG-SLV social-ecological system exhibited no systemic feedbacks, there is evidence that minor feedbacks and cross-scale interactions are present (Figure 1.3). Minor feedbacks appear to occur between streamflow and exogenous and endogenous water policy, as explained in the following discussion. No systemic feedback was observed in the system because no feedback signal was present to instigate changes in all drivers. A feedback signal is the driver whose signal is reduced (negative feedback) or amplified (positive feedback) by the effects it has on other drivers in the system. In the URG-SLV social-ecological system, although no systemic feedback signal was present during the period of record, a signal was present that affected change in the system. Agriculture essentially acted as a "driver signal", a driver whose signal instigated change in all other drivers. Unlike a feedback signal it was neither amplified nor dampened by changes in any other driver. The details of the relationships are presented in Figures 1.4-1.7, which illustrate the linkages that occurred and influences of increases in agricultural acreage.

The arrival of permanent settlements and agricultural development initiated surface water allocations. As surface water withdrawals increased in the SLV downstream users were deprived of water, which started conflict and initiated treaties and agreements for water delivery. This reduced additional opportunities for surface water, but cultivated acreage continued to increase (the driver signal) as groundwater was available as an alternative water source. Groundwater extraction further reduced surface water flow via hydrologic connectivity of the streams to the aquifers. This led to moratoriums on new well development in the SLV; but after the moratoriums agriculture expanded by another 30,000 ha.

Streamflow was identified as the primary resource driver; therefore all other drivers were linked to it (Figure 1.3). Climate was linked (Link 4) to streamflow and agriculture (Link 1) through a geophysical cross-scale link (Figure 1.3). Link 1, between climate and agriculture, is mostly related to air temperature, which controls crop phenology and water demand. Link 4, between streamflow and climate, is in the form of the contribution of precipitation to streamflow. Thus, changes in precipitation will appear as streamflow changes. Agriculture is also linked (Link 2) to streamflow as the driver signal. As agricultural acreage increased, a parallel increase in water extraction occurred and streamflow decreased. Further, agriculture is also linked (Link 3) to endogenous water policy, which governs water allocations and groundwater development moratoriums. Water use in the SLV initiated 2 biophysical and temporal cross-scale links (Links 5 and 6) with policy. Link 6, between exogenous policy and streamflow, occurred after streamflow to downstream users in 1888-1889 was sufficiently diminished to generate conflict that resulted in the 1906 Treaty with Mexico, guaranteeing annual delivery of 74 $hm^3$ of water to Ciudad Juarez. Similarly, the 1938 Rio Grande Compact, guaranteeing water delivery to NM and TX, was generated after streamflow in those states created conflict. Link 5, between endogenous water policy and streamflow, includes a temporal cross-scale link. One aspect of the link is related to Colorado's water rights laws of prior appropriation. The temporal aspect of the link is the result of changes in water appropriation and allocation policy that occurred after the system experienced change. This was in the form of changes in groundwater policy in 1972 and 1981 that placed moratoriums on groundwater development after several decades of groundwater extractions were suspected of reducing streamflow. Groundwater in the URG is hydrologically connected to Rio Grande (Emery 1979).

***Full system analysis – The Effects of Agriculture as a Driver Signal on the URW-SLV social-ecological system***

*1852-1923*

Beginning in the 1850s, permanent settlement began in the SLV, with agriculture being the common business venture. However, the SLV is an arid valley, with average precipitation less than 20 cm annually. Therefore the local community instituted irrigated agriculture and began appropriating surface water from the Rio Grande (Figure 1.4). Agricultural acreage expanded with the continued allocation of Rio Grande water from near 0 ha in 1850 to 137,000 ha by 1923. With the expansion was the concurrent acquisition of surface waters. By 1923, more than 85% of all surface water allocations had been assigned. The level of water allocation led to the Rio Grande running dry in 1888 and 1889 at Ciudad Juarez. This created international conflict, which was resolved by the 1906 Treaty with Mexico, which guaranteed the delivery of 74 $hm^3$ to Ciudad Juarez. It also led to the temporal cross-scale linkage to the initiation of the Rio Grande Compact of 1938. By 1923, the annual diversion (water not leaving the URG-SLV as streamflow) of waters in the URG-SLV was 683 $hm^3$; approximately 45% of the total annual inflow, of which 672 $hm^3$ was diverted in the growing season. Agricultural acreage, however, continued to expand. Since surface water allocations had been exhausted by 1923, agriculture began using groundwater as it is the only alternative water source in the valley.

*1924-1948*

During this time an additional 80,000 ha had been added to cultivation, with an approximate requisite annual water need of more than 247 $hm^3$, and groundwater was the only available source (Figure 1.5). The increase in agricultural reliance on groundwater allocations, which began in the 1920s, continued during this period. By 1935, agriculture had begun taking advantage of the vast underlying confined and unconfined aquifers in the SLV. Between 1935 and 1981, 92% of all groundwater allocations took place. The cross-scale effects of groundwater pumping during this period can be seen in the streamflow change point 1925-1957 (Table 1.2), when the URG annual streamflow was reduced by unaccounted-for diversions of more than 60 $hm^3$. This volume is over and above diversions accounted for in surface water. The URG streams are hydrologically connected to the confined and unconfined aquifers (Emery 1979), which explains the cause of additional losses in streamflow from groundwater pumping. Return flows from groundwater extraction begin to appear in the streamflow change points during the 1958-1964 growing seasons and the annual streamflow during 1965-2007. The combination of surface and groundwater allocations resulted in continued water shortages downstream in NM and TX. The continuing conflict over the SLV water diversions during this period produced the Rio Grande Compact of 1938, whereby the state of Colorado was obliged to deliver a portion of inflows to the URG downstream to NM and TX. Additionally, the Bureau of Reclamation initiated the Closed Basin Project, a project designed to take water from the closed basin portion of the SLV and deliver it to NM and TX to augment the low level of flows occurring at the Lobatos streamflow gauge (the gauge that determines CO downstream delivery) from diversion to irrigated agriculture. Colorado did not comply with the Compact during this time period.

*1949-1978*

During this period, an additional 41,000 ha were placed in production, requiring approximately 136 $hm^3$ additional water, which could only be obtained from groundwater sources (Figure 1.6). As such, the greatest amount of allocated groundwater pumping occurred during this period, with the continued additional groundwater pumping creating an unaccounted-for annual loss of 60 $hm^3$ in streamflow. Also during this period, a drought occurred in the SLV in mid 1950's and early 1960s, resulting in low surface water availability. This exacerbated agriculture's need to rely on groundwater, with more than 20% of total groundwater allocations taking place in the 6 year drought period. The impact of groundwater extraction during the drought period can be seen in the streamflow change point 1958-1964, where a 14 $hm^3$ annual reduction of streamflow occurred (Table 1.2). During this same change point in streamflow, continued increases in groundwater pumping caused return flows (water returning to the stream after land application) from groundwater extraction to artificially inflate streamflow during the growing season by adding an unaccounted-for additional 32 $hm^3$ of water to the stream. It should be noted that 10 $hm^3$ of water is sufficient to irrigate 3300 ha, which would generate an annual revenue of approximately US $8 million.

New technological advances in the form of center pivot irrigation also arrived in the SLV in the late-1960s. Approximately 50% of the irrigation systems in the SLV were center pivot systems by 2007. Center pivot systems are 25-50% more water efficient than flood systems; the only other method employed in the SLV. As new land was cultivated, it is more than likely that the increase in water use efficiency with center pivot systems reduced the full impact of increased groundwater extraction.

With the continued reduction of streamflow are at the Lobatos gauge and Colorado's continued non-compliance with the Rio Grande Compact, the states of NM and TX initiated a lawsuit against CO in 1966 with the U.S. Supreme Court to enforce compliance. The litigation was not resolved during this time period.

*1979-2007*

Agriculture continued to expand the acreage in production by 31,000 ha during this period, demanding another 93 $hm^3$ of water for irrigation, and further influencing changes in other drivers (Figure 1.7). As center pivot irrigation systems increased in number, the actual water demand was probably less, since it is more efficient. However, the continued expansion of agriculture was likely made possible by the availability of groundwater to irrigate landlocked acreage. Some of this increase in production was alfalfa, which results in higher water demands, needing 10% more water compared to other crops (Frank and Carlson 1999). Alfalfa production had increased by 12,000 ha by 2007, with a requisite need of 45 $hm^3$ of water for irrigation.

The apparent groundwater-surface water interaction which caused groundwater extraction to reduce surface flows resulted in the first moratorium on well development in both aquifers in the Closed Basin in 1972. Even though return flows from groundwater entered the stream, the total surface water flows were reduced. At times the groundwater pumping effectively prevented senior surface water rights holders to fully access their allocation. This moratorium was followed by a second moratorium in 1981 on new well development in both aquifers inside the closed basin.

Extraordinarily high precipitation occurred within the URG watershed during 1985-87, resulting in high streamflow. The streamflow volume was sufficient to fill Elephant Butte Reservoir in NM, causing it to spill during each of these years. In accordance with the Rio Grande Compact, a spill at Elephant Butte erased the accumulated water debt of CO and settled the 1966 lawsuit. Colorado has been in compliance with the Compact since that time. These high flows were also sufficient to account for an annual increase in flow at Lobatos of 12 $hm^3$, from 1967-2007. This increase in annual streamflow obscures the continued unaccounted-for losses in growing season flows of 52 $hm^3$. This is equivalent to an approximate US $40 million dollar loss of potential agricultural revenue in NM or TX. Other likely contributors to the increased annual streamflow are return flows from groundwater and increased water use efficiency with center pivot irrigation, which may reduce drawn down of the aquifer allowing some bed gain to occur.

Finally, starting in the 1990s, climate change impacts began in the SLV. The mean annual temperature has increased by about 1°C since 1994. The growing degree days also increased by about 120-200, depending on the crop (Mix et al. 2010), which is equivalent to about 20-25 additional calendar days. The freeze-free period also expanded by 15 days; extending both the growing season and crop water demand period. Herrington (1996) predicted a 12% increase in crop water demand for every 1°C increase in temperature. It appears the 1°C increase in annual mean temperature in the SLV caused a similar increase in water diversions as annual unaccounted-for diversions increased by 23 $hm^3$ (Table 1.3). The increase in the freeze-free period means that crops will be growing longer, therefore demanding more water; similarly, the increase in GDD would increase crop water demands.

**Conclusion**

Trancale (2009) listed 33 obstacles to the further development of systems science. He cited the lack of broadly applicable methodologies and methods to analyze a system therefore, the need is to develop methodologies and methods capable of ". . . elucidating significant features of a system." Further, the Millennium Ecosystem Assessment (2005) listed driver identification and assessing historic trends as a primary concern. This methodology and specific methods appear to have potential to be applied in that regard. Further, the methodology and methods are scale-independent and may be applied to nested systems or within multiple hierarchies.

The driver identification process described in this study identified 5 drivers with strong connections to processes within the SLV social-ecological system. The inclusion of driver longitudes improved the ability to detect cross-scale linkages, e.g., reductions in flow caused by groundwater extraction. The application of a change point analysis provided clearly delineated changes in longitudes that aided the identification of cross-scale linkages and feedbacks. The final analysis of the system, using a flow chart schematic as a tool for describing the system, indicated numerous interactions across scale and feedbacks.

Within this analysis, several relationships become evident within the URG-SLV system. At this time in the URG-SLV social-ecological system, agriculture is the primary driver; the driver signal. It directly affects water availability within the valley by diverting it. In doing so, it simultaneously affects downstream users, as demonstrated by the treaties, compacts and lawsuit. Both policy drivers affected water availability by changing the rules of water diversion, and adding water to the stream from the Closed Basin Project. More important are the current and potential effects of climate change on the system. Climate change increased annual water demands by about 10%, or 23 $hm^3$ (Table 1.3). These changes portend further impacts to water availability and agriculture in the system. The influence of climate change on the URG-SLV social-ecological system, though latent, bears further observation.

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**Tables Figures**

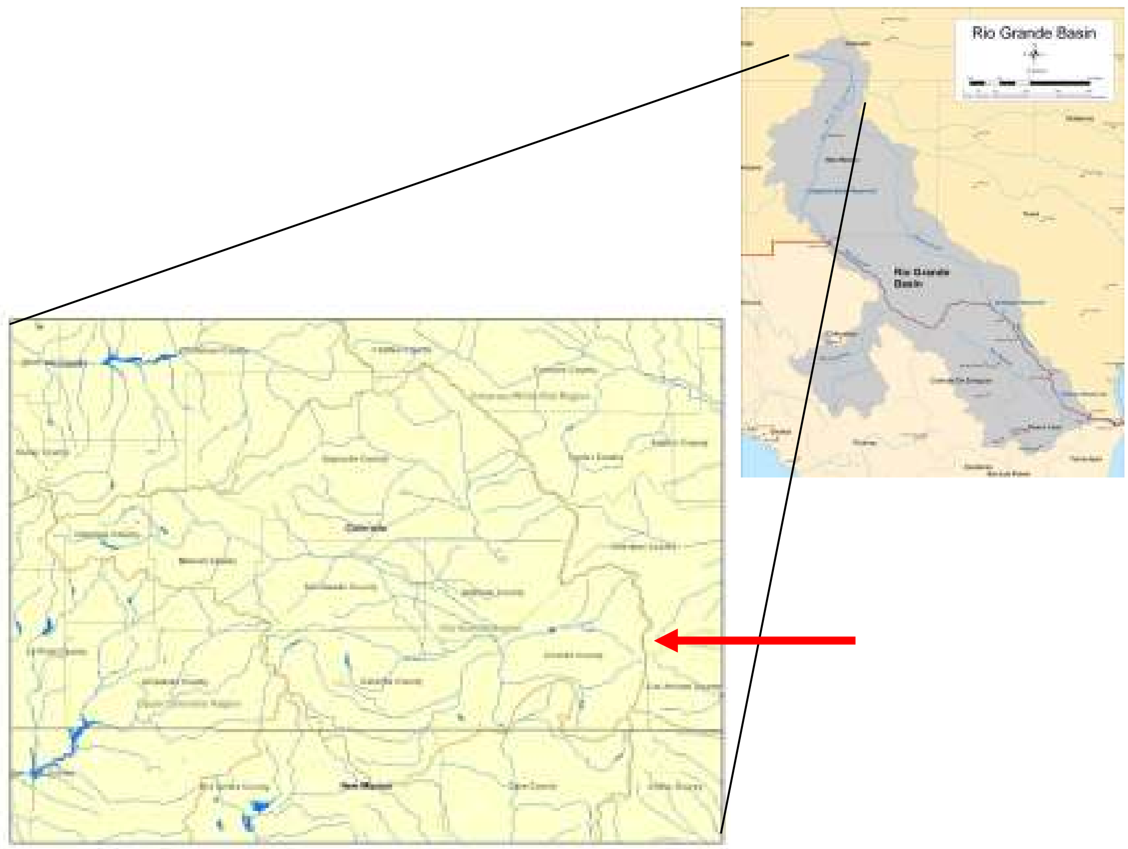


Figure 1.1. The Upper Rio Grande watershed, its tributaries and the San Luis Valley. Red arrow indicates the boundaries of the Upper Rio Grande watershed. Blue lines indicate streams and irrigation channels.

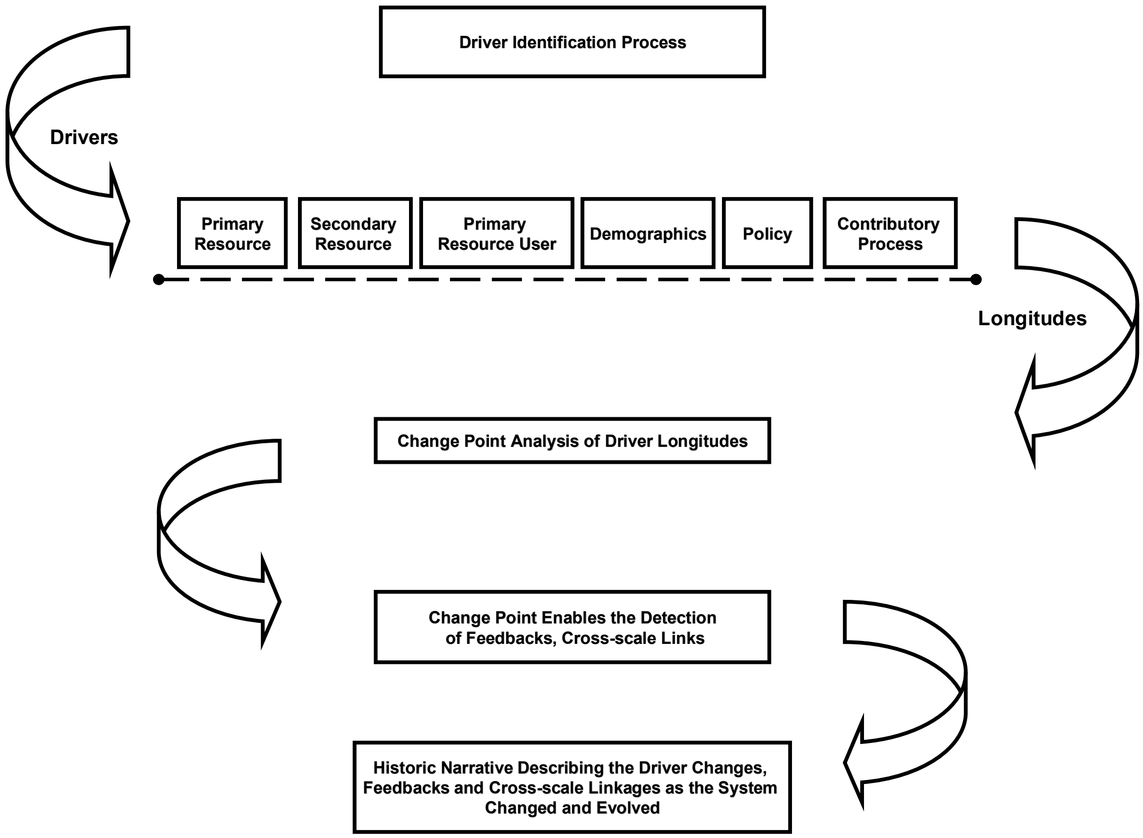


Figure 1.2. Conceptual model of the methodology for the analysis of SES.

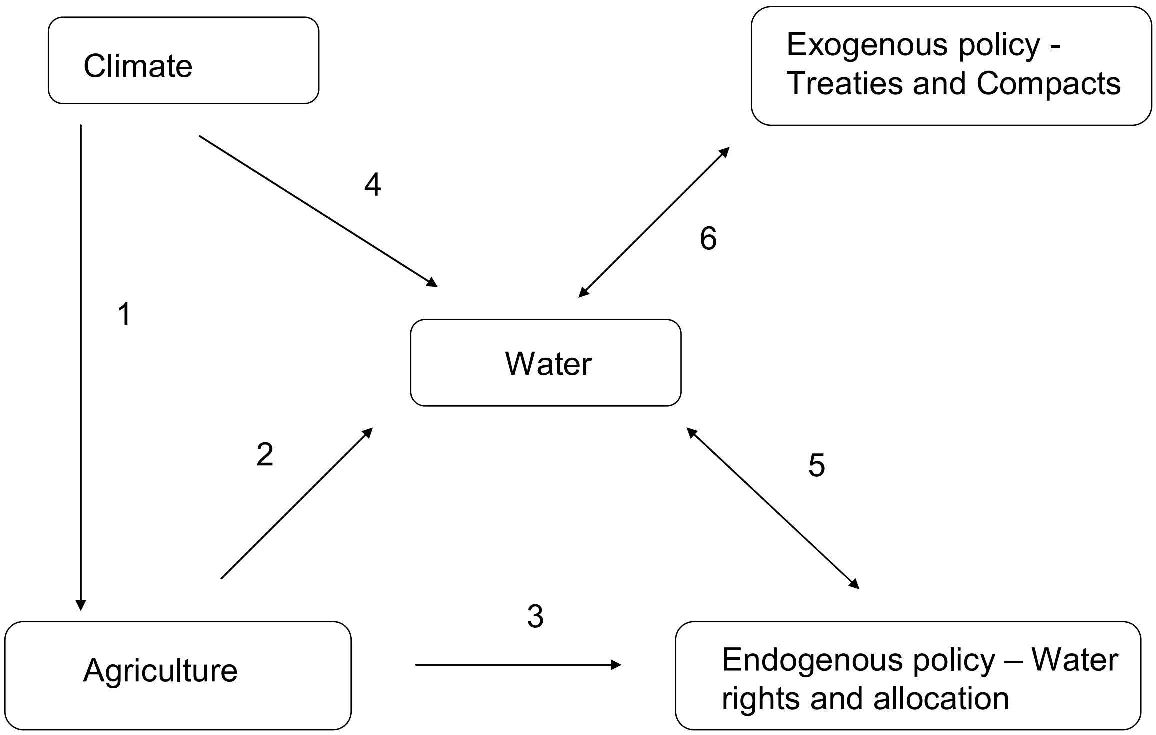


Figure 1.3. Simple model of the drivers of the URG-SLV system illustrating driver linkages. Bi-directional arrows indicate potential minor feedbacks.

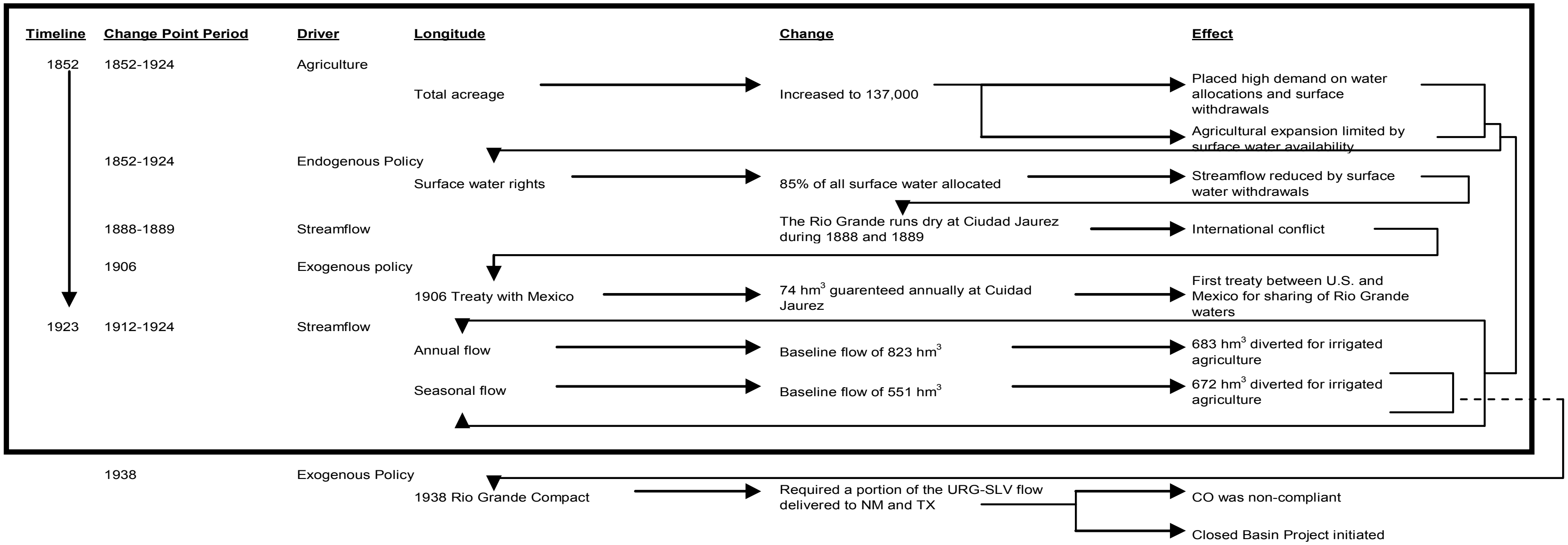


Figure 1.4. An illustration of the linkages between driver longitudes during the agricultural change point period of 1852-1923.

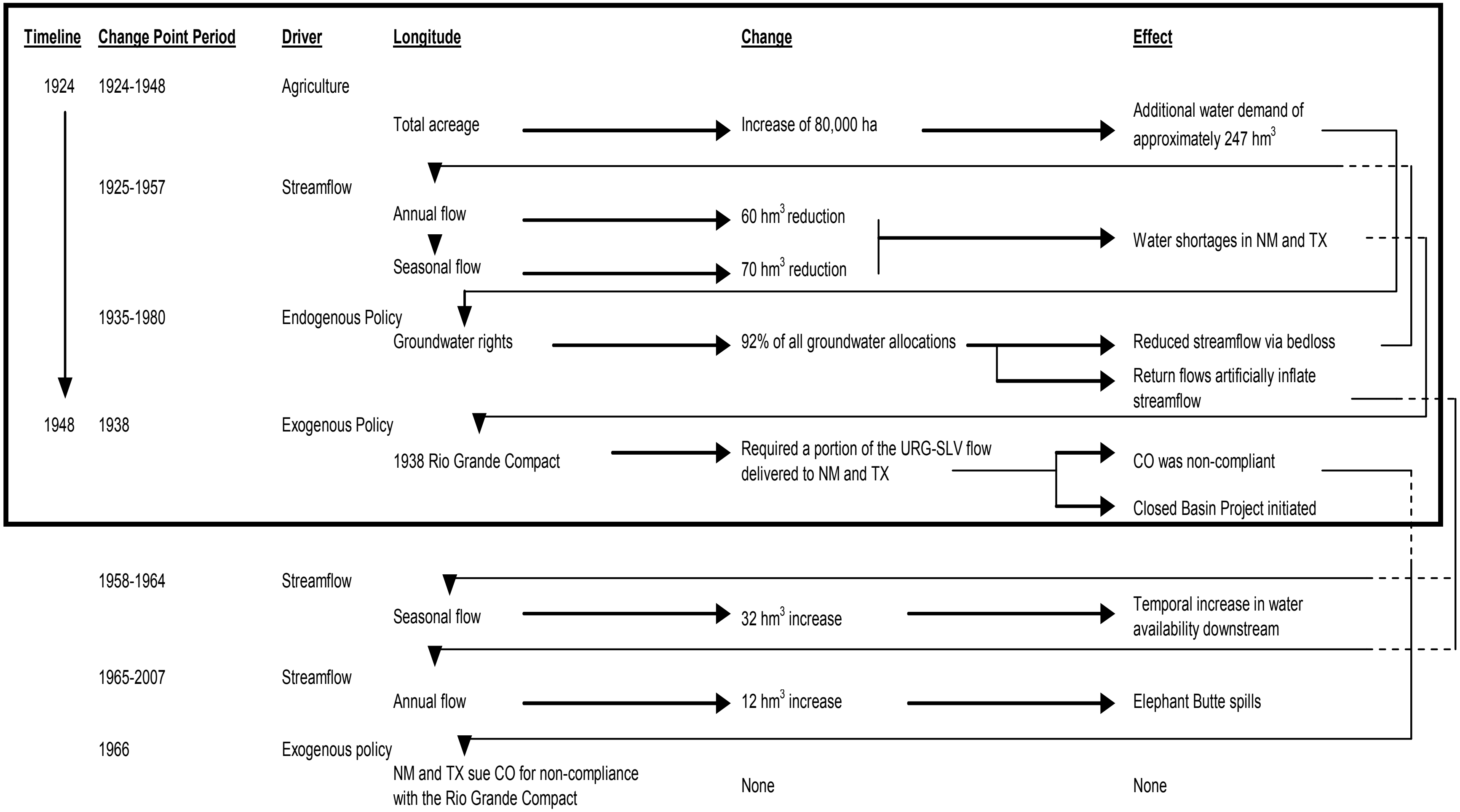


Figure 1.5. An illustration of the linkages between driver longitudes during the agricultural change point period of 1924-1948.

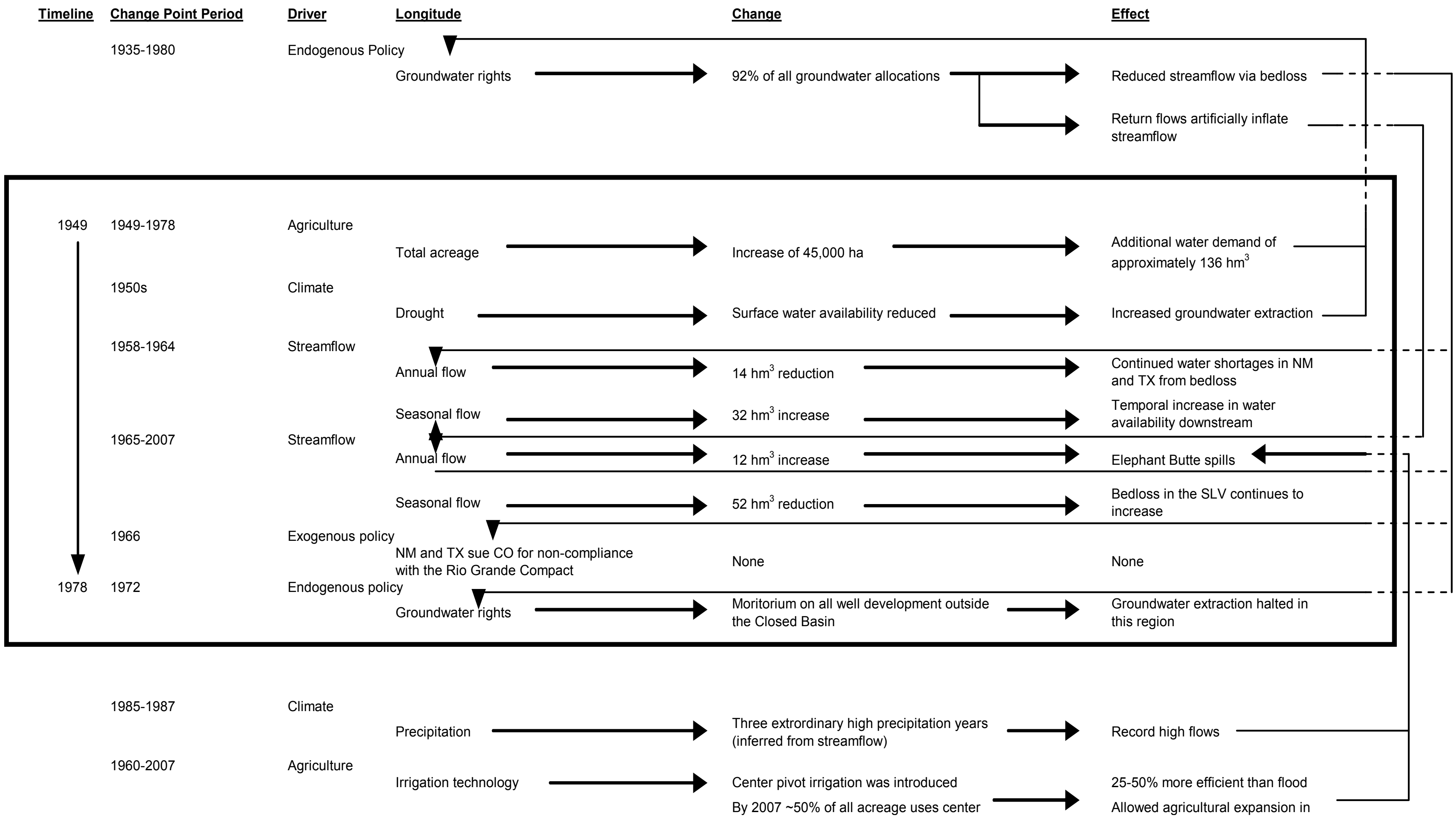


Figure 1.6. An illustration of the linkages between driver longitudes during the agricultural change point period of 1949-1978.

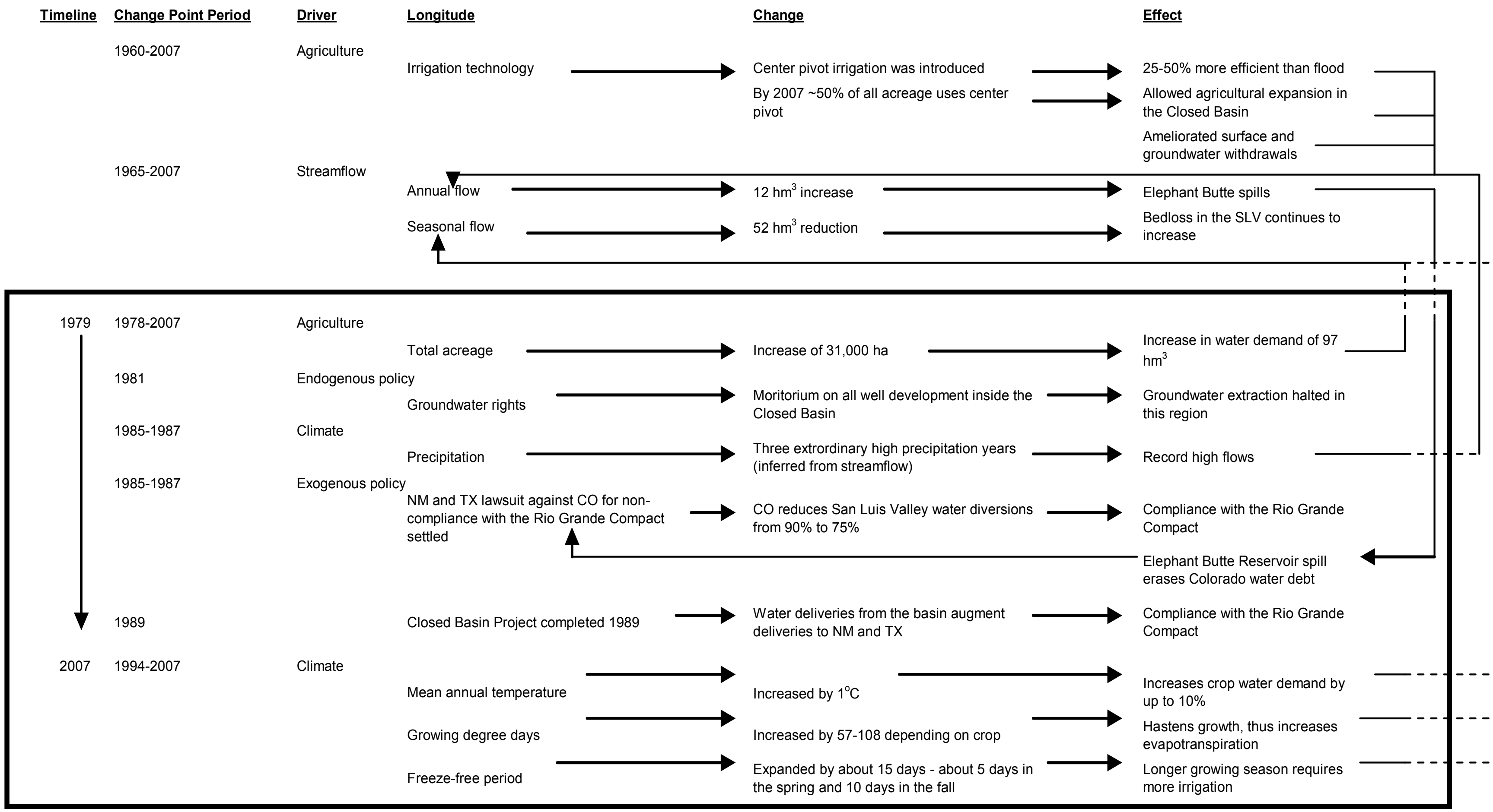


Figure 1.7. An illustration of the linkages between driver longitudes during the agricultural change point period of 1979-2007.

Table 1.1. Selected drivers and their longitudes.

| Driver type | System driver | Driver longitudes | Selection justification |
|---|---|---|---|
| Primary resource | Streamflow | Annual flow at Lobatos | Streamflows at Lobatos indicate the exiting volume of streamflow minus diversions within the system |
| | | Growing season flow at Lobatos | Growing season streamflow is indicative of the actual use during the main period of diversions |
| | | Timing of spring melt flow | Changes in spring melt timing affect the ability to divert water for agricultural use |
| Secondary resource and Primary user | Agriculture | Total acreage | Total acreage changes are related to water availability |
| | | Alfalfa acreage | Alfalfa has the highest crop water demand, therefore changes in alfalfa acreage have disproportionate impact |
| Endogenous policy | Water rights | Surface appropriations and allocations | Surface water allocations directly impact steramflow and are related to agricultural acreage |
| | | Groundwater appropriations and allocations | Groundwater allocations directly impact streamflow through hydrologic connectivity to the streams and are related to agricultural acreage |
| | Law | Moratoriums on well development | Discrete events which influence water use |
| Exogenous policy | Treaties | National | 1936 Rio Grande Compact. Influenced water use. Resulted in the drainage of the Closed Basin and a NM and TX lawsuit against CO |
| | | International | 1906 Treaty guarenteeing annual delivery of 74 $hm^3$ of water to Ciudad Juarez, Mexico. Resulted from the Rio Grande running dry at Cuidad Juanrez in 1888 and 1889 |
| | | | 1948 Treaty governing the shared waters of the Rio Grande with Mexico. Precipitated by 1906 Treaty events. |
| Renewing process | Climate | Valley mean annual temperature | Valley temperature potential indicates changes in crop water demand and related to agriculture and streamflow via crop water demand |
| | | Valley growing degree days and freeze-free period | Growing degree days indicate changes specific crop growing conditions, potential phenological impacts and related to streamflow via crop water demand. The freeze-free period is the length of the growing season |
| | | San Juan Mountains mean annual temperature | Validates observation of changes in spring melt timing of streamflow |

Table 1.2. Change points for driver longitudes of the URG-SLV social-ecological system.

| Driver longitudes | Change point periods | Period mean annual value | Increase (decrease) | |
|---|---|---|---|---|
| Total hectares | 1852-1923 | 137579 | baseline | |
| | 1924-1948 | 218611 | 81032 | |
| | 1949-1978 | 260121 | 41510 | |
| | 1979-2007 | 291903 | 31781 | |
| Alfalfa hectares | 1852-1924 | 24256 | baseline | |
| | 1925-1957 | 45429 | 21173 | |
| | 1958-2007 | 57085 | 11656 | |
| Annual and (growing season) streamflow at Lobatos in $hm^3$. | | | | |
| *= unaccounted for increase or decrease | 1912-1924 | 823.34 (551.48) | baseline | N/A |
| | 1925-1957 | 427.56 (257.92) | (395.78) | -59.98* (-69.74) |
| | 1958-1964 | 248.63 (94.62) | (178.93) | -14.11* (32.55) |
| | 1965-2001 | 393.15 (221.94) | (144.52) | 12.65* (-52.24) |
| Surface water annual allocations in $hm^3$ | 1852-1924 | 526.17 | | |
| | 1925-2001 | 96.00 | 96.00 | |
| Groundwater annual allocated pumping rate in $hm^3$ | 1852-1934 | 3.50 | baseline | |
| | 1935-1980 | 80.00 | 76.50 | |
| | 1981-2001 | 0.085 | -79.92 | |
| Moratoriums on well development | 1972 | | | |
| | 1981 | | | |
| National | 1938 | | | |
| International | 1906 | | | |
| Valley mean annual temperature in $^oC$ | 1895-1993 | 5.05 | | |
| | 1994-2007 | 5.98 | 0.93 | |
| Valley freeze-free period in days | 1895-1980 | 92.89 | | |
| | 1981-2007 | 108.68 | 15.79 | |

Table 1.3. Annual and growing season water balance of inflows and outflows of the Upper Rio Grande in the San Luis Valley based on change points in climate.

| | | Change in outflow | | Change in inflow | Diversions | Percent of inflow diverted during each period | Additional increase or decrease in diversions not explained by changes in inflow |
|---|---|---|---|---|---|---|---|
| Period | Mean outflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | Mean inflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | $Inflow_{pn} - Outflow_{pn}$ | $Cons_{pn} / Inflow_{pn}$ | $Change^{In}_{pn} - Change^{Out}_{pn}$ |
| *Climate* | | | | | | | |
| 1912-1993 | 476.96 | | 1,210.13 | | 733.17 | 0.61 | |
| 1994-2007 | 320.89 | -156.07 | 1,077.77 | -132.36 | 756.88 | 0.70 | 23.72 |

**CHAPTER 2**

# ANNUAL AND GROWING SEASON CLIMATE CHANGES IN THE ALPINE DESERT OF THE SAN LUIS VALLEY, COLORADO

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**Abstract:** Most alpine ecosystem climate change studies focus on changes in biota, few report temperature changes from several stations. The San Luis Valley (SLV) is a high alpine desert and the local community relies heavily upon the irrigated agriculture of the SLV for its livelihood. Because of the importance of agriculture to the local community and the effects climate change may have on agriculture, this study investigates differences in annual and growing season temperatures. Data from seven climate stations on the floor of the SLV were obtained from the National Climate Data Center (NCDC), adjusted for inhomogeneities and reconstructed – where necessary – from 1895 to 2008. Change point analysis was employed to identify distinct periods of different mean temperatures values. Change point analysis identified 1993-1994 as the change point in mean annual temperature. Maximum, minimum and mean annual temperature for each period, 1895-1993 and 1994-2008, were then compared using a one-tailed General Linear Model to determine the presence of significant increases in mean temperature values. Analysis of valley stations indicates significant increases in average annual mean temperature of approximately 1°C and significant increases in average growing season mean temperature of approximately 0.65°C in the 1994-2008 period.

**Keywords:** Climate change, alpine, San Luis Valley, agriculture, growing season

**1. Introduction**

Climate change, resulting from increased $CO_2$ concentrations, is indicated by increases in global mean annual temperatures (IPCC 2001 and 2007, Hansen et al. 2006). Global temperature increases are considered to be substantial and early findings indicated an increase of global mean temperature of 0.6 $\pm$ 0.2°C since 1861 (Folland et al. 2001, IPCC 2001). Later studies and data now indicate global temperatures have risen by roughly 0.1°C per decade (IPCC 2007) over the past century and nearly 0.6°C, in the past 3 decades (Hansen et al. 2006) resulting in a 0.74 $\pm$ 0.2°C increase in global temperature. Current data analysis indicates the greatest warming period on instrumental record is 1976-2007 (Hansen et al. 2006, IPCC 2001 and 2007) with 2005 now considered to be the warmest year on record.

Very few studies have documented climate changes in alpine ecosystems in terms of temperature alone (Parmesan 2006). Most have utilized changes in biota, such as increases in elevational distributions of plants or breeding birds (Pauli et al. 1996, Walther et al. 2002). Some utilize glacial retreat to describe and infer temperature changes (Haeberli and Beniston 1998). It is well known that temperature is distributed along an elevational gradient. In fact, it has been demonstrated in montane environments that temperatures decline by about 0.55°C/100 m increase in elevation (Ozenda and Borel 1991). This may buffer temperature increases resulting from climate change. Dettinger and Cayan (1995) speculate higher elevations were less sensitive to the increases in temperature that had occurred by 1995. The IPCC (2001) indicates temperature in the upper altitudes of the atmosphere are increasing more slowly than surface temperatures and Rebetez and Dobbertin (2004) report a possible lag effect of climate change in Alpine regions.

There are few instrumental studies regarding climate change in alpine environments. Luckman and Kavanagh (2000) utilized instrumental data from 1888-1994 and reported there was an increase in mean annual temperature in the Canadian Rockies of 1.43°C per 100 years. Vuille and Bradley (2000) found accelerated increases in mean temperature in the tropical Andes up to 0.34°C/decade from 1939-1998. Particularly they noted trends in temperature increase up to 2500 m. Another study of the mountain ecosystem of the Tian Shan in central Asia indicates permafrost warming of 0.3°C over the past 3 decades (Marchenko et al. 2007). Liu and Chen (2000) found an annual mean temperature increase of 0.16°C/decade on the Tibetan plateau from 1955-1996, and when altitudinally stratified the increase accelerated to near 0.35°C/decade.

The alpine desert of the SLV, Colorado, is located just below the headwaters of the Rio Grande. Irrigated agriculture is the dominant industry of the Valley, accounting for more than 30% of the Valley economy and, according to the San Luis Valley Development Resource Group (SLVDRG 2002), employing greater than 50% of the local populous and covering more than 1.4 million ha. The arid conditions of the Valley cause agriculture to be entirely reliant on surface waters of the Rio Grande, its tributaries and groundwater reserves underlying the Valley for its irrigation needs. Research on the impacts of temperature increase on agriculture production indicates irrigation needs will increase (Finnerty and Ramirez 1995). The economic dependence on irrigated agriculture in the SLV makes the community vulnerable to climate changes that affect crops.

Mix et al. (2010) found growing degree days (GDD) in the SLV increased at nearly every station annually and during the growing season. GDD are derived from daily mean temperature and temperature related growth thresholds specific to an organism. The growth stages of many organisms are closely tied to temperature and the utilization of GDD can predict phenological changes such as seed germination, flowering, maturation and senescence. Further, temperature changes, i.e. GDD, can influence phenology of agriculture pest and beneficial taxa (Brown et al. 1999, McCarty 2001, Winkler et al. 2002, IPCC 2007). Changes in temperature can cause changes in seed emergence, growth, flowering, seeding and timing of senescence (Post et al. 2008).

In addition to phenological changes higher temperature during the growing season has been shown to increase irrigation needs as crops will have increases in evapotranspiration rates (Finnerty and Ramirez 1995). Though, Finnerty and Ramirez (1995) point out crop production will need additional water to reduce the impact of increased temperatures, they also indicate increased $CO_2$ concentrations may result in a greater income per hectare as crop production increases, even in light of increasing water needs. Further, higher daily temperatures may affect crop pollination or speed maturation at the cost of yield (weight/volume). As result, increases in temperature in the SLV have potential to harm the local agricultural production either through increased needs in irrigation, reduced crop yield or changes in crop, crop pest or beneficial phenology. Ultimately, predictions of changes in agricultural production are equivocal (Fischer et al. 1996, Sombroek and Gommes 1996).

**2. Objectives**

The objectives of this study were to determine the presence, or absence, of distinct periods of change in annual and growing season temperature in the SLV during the 20th and early 21st centuries and quantify those changes statistically. The growing season is defined by the months of May, June, July, August and September. The parameters of interest were mean temperature values of the monthly maximum, minimum and mean.

**3. Study area**

Located in south central Colorado, the SLV is roughly bisected by the Rio Grande. The river rises in the western San Juan Mountains which form the western boundary of the SLV and the eastern boundary is formed by the Sangre de Cristo Mountains. The elevation of the SLV is approximately 2300 m. According the National Climate Data Center (NCDC) data utilized here, the region regularly experiences low wintertime temperatures of less than -20°C and as low as -40°C. It ranks in the top 20 coldest locations in North America (King 2007). Warm season temperatures reach the 30s°C, but the warm season only lasts 90-110 days. During this time it is not uncommon to have a 20°C diurnal temperature change. Further, the Valley receives less than 20 cm of precipitation annually as it is in the rain shadow of the San Juan Mountains to the west which receive 100-200 cm of precipitation annually.

Even though the Valley is arid, it is a major agricultural region for the state of Colorado, producing the majority of the state's potato crop (14,000-30,000 ha) and a large portion of its alfalfa crop (80,000-100,000 ha), according to Colorado State

University (CSU) Cooperative Extension (CSUa). Virtually all of the Valley agriculture is irrigated to compensate for the aridity (CSUb).

**4. Methods**

Mean monthly maximum, minimum and mean climate data for seven climate stations (Figure 2.1) were obtained from the NCDC database of COOP stations. Three stations are located along the Rio Grande riparian zone; Del Norte 2E (ele. 2396.9 m), Monte Vista 2W (ele. 2344.5 m), and Alamosa AP (ele. 2296.1 m) (in order from upstream to downstream). Two stations, Manassa (ele. 2343.9 m) and Center 4SSW (ele. 2338.7 m), are located south and north, respectively, in the interior of the Valley, while two stations, Blanca 4NW (ele. 2349.7 m) and Great Sand Dunes National Park (GSDNP) (ele. 2475.0 m), are located south and north, respectively, along the eastern edge of the Valley. The data were adjusted for inhomogeneities and reconstructed by the NCDC for this study as described in Menne and Williams (2009) (Figure 2.2 (a-g)). The extent of the data record is 1895 – 2008. Station names, locations and elevation in meters are presented in Table 2.1.

Change point analysis was utilized to identify the point(s) in the data record where the values departed significantly from the previous annual mean values, thus creating distinct subsets of data from the original data. Change point analysis utilizes an iterative cumulative sum (CUSUM) procedure in combination with a bootstrapping method of analysis. The CUSUM begins and ends at zero with the maximum distance the CUSUM deviates from zero being the measure of change. It then compares the CUSUM slopes of the original data with the CUSUM slopes of random reordering of the data (called bootstraps) to determine if there is a significant difference indicating a significant change. Because of this bootstrapping approach, the method is distribution free. If a change is detected, the time of the change is estimated and the data split at the change point. The analysis is then repeated on each segment to detect further changes. As a result more than one set of data is identified as being statistically separate from other sets. When identified, each set or sequence has a statistical distribution more similar to the data within than to data in other sets of the same series. One or more points are estimated that define the moment of change or shift in distribution and a range of points are provided as the likeliest period for change, along with the previous and new mean value. Previous studies indicated changes in means of time series data can be identified via this analysis (Page 1955 and 1957, Pettitt 1979). Change point analysis has been used in several climate studies to identify points of departure from mean values (Craddock 1979, Buishand 1981, Salinger and Mullan 1999). We utilized Change Point Analysis 2.3 software (Taylor Enterprises), utilized in many studies including, climate change (Bărbulescu and Băutu 2009), hydrology (Zanchettin et al. 2008) neurology (Cassidy et al. 2002). Utilizing the periods identified by the change point analysis, a one-tailed General Linear Model (GLM) was used to determine if annual and growing season (May-September) maximum, minimum and mean temperature values were significantly higher during the latter period than the earlier period at all stations. The GLM is a common and widely used statistical tool to evaluate 2 or more unbalanced data sets and according to Sexton et al. (2003),

> "The theory of GLMs has been developed across many scientific applications and has appeared in various guises in a wide range of climate studies. Bloomfield (1992) and Folland et al. (2001) used GLMs to

estimate linear trends in observed global mean temperature and their uncertainties, in the presence of autocorrelated noise. Allen and Tett (1999) show that optimal fingerprint detection is a GLM where modeled signals are regressed onto the observations in the presence of climate noise; a long integration of an unforced coupled ocean–atmosphere GCM is used to estimate the covariance structure of the climate noise for the estimation of the amplitudes of the modeled signals in the observations and their uncertainties."

**5. Results**

*a. Change Point Analysis:*

Change point analysis was used to identify the years where significant differences in mean values of temperature occurred. The analysis indicated changes in these values occurred at different times for several stations. However, the period between the years 1993 and 1994 were identified as the most recent and most common point where the changes took place (Table 2.2). All change points not identified as occurring between 1993 and 1994 did incorporate these dates within the confidence interval. Alamosa minimum temperature had no change, but for reason of consistency 1994 was applied for further analysis. Thus, the data periods most appropriate for use in the analysis were 1895-1993 and 1994-2008.

*b. GLM analysis:*

GLM analyses indicated the annual temperature values during the period 1994-2008 were significantly higher ($p < 0.05$) than the period 1895-1993 at all stations without exception (Table 2.3 and Figure 2.3 (a-c)). The analysis of the Valley floor stations indicated the following: at Alamosa AP an increase of maximum, minimum and mean temperature by 0.56, 0.45, 0.50°C was significantly higher during the latter period. All values for Blanca 4NW were significantly higher during the 1994 – 2008 period, with maximum, minimum and mean values higher by 1.44, 0.89, 1.17°C, respectively. The maximum, minimum and mean temperature values for Center 4SSW experienced similar increases during the latter period, with each value higher by 0.58, 0.93, and 0.76°C, respectively with only the latter two being significant at $p < 0.05$. Analysis indicated Del Norte 2E temperature values were significantly higher during the latter period by 0.69, 0.85, 0.75°C for maximum, minimum and mean values, respectively. GSDNP data analysis indicated all values were significantly higher during the 1994-2008 period, with the maximum, minimum and mean values differences higher by 0.83, 0.91, 0.87°C, respectively. Maximum, minimum and mean temperature values at Manassa also were higher during the latter period, each higher by 0.96, 1.96, 1.46°C, respectively. Analysis of Monte Vista data indicated significantly higher maximum, minimum and mean values of 1.32, 0.65 and 0.99°C, respectively, during the latter period. Seasonal analyses of the Valley floor stations indicated similar changes (Table 2.4 and Figures 2.4 (a-c)). In the seasonal analysis all stations experienced significant ($p < 0.05$) increases in all temperature values with two exceptions at Alamosa AP.

**6. Discussion**

Change point analysis indicated the most consistent change in temperature occurred around the years 1993-1994. Though, there were some estimates in the change point analysis with a time range of up to a decade within which the shift could have taken place it should be noted the population and distribution in the Valley, urban footprint and agricultural land use has been fairly constant since the early 1900's (SLVDRG 2002). Changes that have occurred have been more related to shifts in crop and the implementation of center-pivot irrigation starting in the 1960's resulting in some expansion of agriculture. Therefore the change points in temperature identified here are not likely attributable to changes in landscape or population. Further, the Alamosa AP station is located near the largest, growing urban center and would be the first to exhibit human induced local changes, yet it has the most stable change points or none.

Additionally, temperature change caused by the Pacific Decadal Oscillation (PDO) and its effects on the Western U.S. climate were ruled out because change point analysis indicated no changes consistent with PDO events between 1890 and 2008. Were the PDO to have been prominent features in temperature changes in the SLV then the several oscillations related to it; cooling from 1890-1924 and again during 1947-1976, and warming from 1925-1946 and 1977 through about the mid-1990's would have elicited change points within these periods (Mantua and Hare 2002). We also recognized the possibility of influences from either the North Atlantic Oscillation or the Atlantic multidecadal oscillation (Enfield et al. 2001), however, for the same reasons as above (no detection of related change points) we did not consider them an effect on the change point. Further, drought or evaporation from water applied for irrigation purposes could have affected the ability to detect temperature change. Should the former have done so then again, similarly to the PDO, several changes would have been evident as drought occurred many times during the temperature record; 1930s, 1950s, 1960s and 1977 (drought of record) (Ogburn 1996). Additionally, the effects of irrigation have a known tendency to ameliorate temperatures and may have reduced the ability to detect increases in temperature, particularly because irrigated acreage increased substantially since 1938. Studies indicate there can be extreme contrasts in temperature between locally vegetated, irrigated or mesic regions and nearby (30-40 km) arid regions (Dzerdzeevskii 1963). Segal et al. (1988) indicated mesoscale circulation can be affected by vegetation cover and soil moisture. Davenport and Hudson (1967) found temperatures on the leeward side of irrigated fields to be 1.5°C lower than readings nearby on the windward side. Further, De Vries and Birch (1961) indicate irrigated areas can have a local cooling effect of 1-2°C. Irrigation also does not appear to be an influence as no consistent change points were detected related to known shifts in irrigation practices which include expansion of irrigated acreage from 1935-1970 and increases in overhead irrigation via center-pivot systems after 1970.

It has been noted in the later half of the 20$^{th}$ Century global warming increased significantly after 1976 (IPCC 2001). The analysis of the annual mean temperature values of the seven SLV stations indicated all stations experienced significantly higher temperature during the 1994-2007 period than during 1890-1993, with increases similar to that occurring on the global scale. Thus, the SLV warming lagged behind global mean temperature increases by about 15 years. Each station exhibited higher maximum, minimum and mean temperature in the 1994-2008 period with increases in mean temperature ranging from 0.5-1.46°C. Across the total timeframe, increases approximate the global increase in mean temperature in the past century, with the upper end slightly exceeding the global increase of 0.74 $\pm$ 0.2°C over the past century. Increases in growing season temperature values were slightly lower than annual increases, with mean temperature increases ranging from no change to 1.29°C higher or 0.0-0.85°C. In contrast to our results, atmospheric temperature measurements indicate the lowest 8 km of the atmosphere only warmed 0.05 ± 0.10°C per decade since 1979, compared to 0.15 ± 0.05°C increases in near surface temperature (IPCC 2001).

Global trends also indicate asymmetrical diurnal increases in temperature values (Karl et al. 1993, IPCC 2001, Braganza et al. 2004). Currently, reported values indicate minimum temperatures increased 0.2°C per decade, and maximum temperatures increased 0.1°C per decade. The results of the analysis of the annual data for the SLV weather stations indicate that temperature increases in the 1994-2008 period do not categorically express a similar asymmetry. Two stations, Center 4SSW and Manassa, exhibited diurnal temperature change asymmetry, similar to global asymmetric diurnal temperature change ratio of 2:1 minimum:maximum. The remainder have ratios approximating 1:1 or smaller. Weber et al. (1994) indicated alpine regions of Europe have ratio of temperature increases of 0.8:1. Diaz and Bradley (1997) found montane climate change had a vertical lapse rate of approximately 0.1°C/km. Therefore, the changes in temperature in the SLV maybe attitudinally related, similar to alpine regions of Europe (Weber et al. 1994) and the elevation difference found by Diaz and Bradley (1997).

The higher magnitude of temperature increase in the SLV may be related to an alpine affect. The change point analysis of the SLV indicates warming lagged behind that date by 15-20 years with change occurring closer to 1994. There is evidence that upper elevations did experience the onset of warming trends later than lower elevations (IPCC 2001). Rebetez and Dobbertin (2004) reported die-offs of Scots pine (*Pinus sylvetris* L.) in Alpine regions began around 1996. Further, they indicated the cause was increases in temperature of nearly twice that of global increases and prolonged drought. The 20 year lag behind the detection of temperature changes at lower elevations may be the results of an elevational lag effect. This location is markedly lower in elevation than the SLV, at approximately 750 m, but is consistent with temperature changes detected in this study and may be an indication alpine systems are being affected later and at magnitudes greater than lower elevations. Further, Beniston and Rebetez (1996) found temperature change in the Swiss Alps to be greater than at lower elevations as did Diaz and Bradley (1997). In the Canadian Rockies Luckman and Kavanagh (2000) found temperature had increased 1.43°C/100 years, very similar to this study finding near 1.0°C increase since 1895. However, this study indicates the warming occurred in the past 15-20 years which more closely approximates Vuille and Bradley (2000) study finding temperature increases of up to 0.34°C/decade from 1939-1998 in the tropical Andes. Particularly they noted trends in temperature increased to 2500 m, near the same elevation of the SLV. Further, Marchenko et al. (2007) found a 0.3°C temperature increase in permafrost over the past 3 decades. And Liu and Chen (2000) noted an accelerated increase in temperature change of near 0.35°C/decade on the Tibetan Plateau.

Alamosa is the only station that did not exhibit significantly warmer minimum and mean temperature in the last period during the growing season. The SLV is shaped somewhat like a bowl, with Alamosa near the bottom. This station is the lowest elevation of all stations used and located near the lowest elevation in the Valley. This station also has the coldest temperatures recorded for the Valley; of the 30 coldest annual mean minimum temperature records in the SLV this station recorded 14. It is likely the topographic nature of the Valley pools cold air longer at this location and therefore temperature change here may not be taking place at the same temporal pace as other locations. Further, one other location, GSDNP, growing season minimum temperature did not increase significantly. The change point analysis indicated change was occurring for each of these values, but the GLM indicates it is not significant at this time.

**7. Conclusion**

The San Luis Valley has experienced climate change as increases in annual and growing season temperature values were evident. The annual increases in these values were greater than the global increases, similar to that noted by Haeberli and Beniston (1998) in European Alps. The studies of the European Alps, the Tien Shan of central Asia and our conclusions indicate mountain regions with arctic-like conditions may be responding to climate change similarly and with accelerated changes compared to lower elevations or global mean changes. Growing season increases in temperature were slightly less than annual increases indicating cool season temperatures are increasing too.

A departure from the late 20th Century global trend is the point when the Valley began to warm. The change point analysis identified a point near 1994 as the beginning of warming in the Valley, approximately 20 years later than that of the general late 20th Century global increases that began in 1976 (IPCC 2001, Hansen et al. 2006). The lagged onset of warming is substantiated by other alpine and altitudinal studies (Beniston and Rebetez 1996, Diaz and Bradley 1997). Overall, the SLV is significantly warmer since the 1895-1993 period, with a few exceptions.

The SLV economy is dominated by irrigated agriculture. The water needs of the Valley are substantial, with more than 240,000 hectares in irrigated crops, and 100,000 hectares in high water demand crops of alfalfa and hay. Growing degree days in the SLV have increased significantly (Mix 2010), indicating both the temperature and crop water needs have increased. Growing degree days are important values relevant to crop production, growth and timing (Hartz and Moore 1978, Derscheid and Lytle 1981, Breazeale et al. 2008). Predictions of climate change impacts on agricultural production are uncertain with both increases and decreases predicted (Sombroek and Gommes 1996). Although, applied climate change scenarios indicate global decreases in production, the model projects more variability in U.S. production (Fischer et al. 1996). Ultimately, climate change in the SLV has potential to increase crop water needs (Finnerty and Ramirez 1995) and Herrington (1996) predicts a 12 percent increase in crop water needs with every 1.1°C increase in temperature. Annually the SLV utilizes 600 $hm^3$ annually and current increase in temperature have resulted in a 10 percent, >20 $hm^3$, increase in surface water diversions, thus reducing outflows to downstream states.

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**9. Tables Figures**

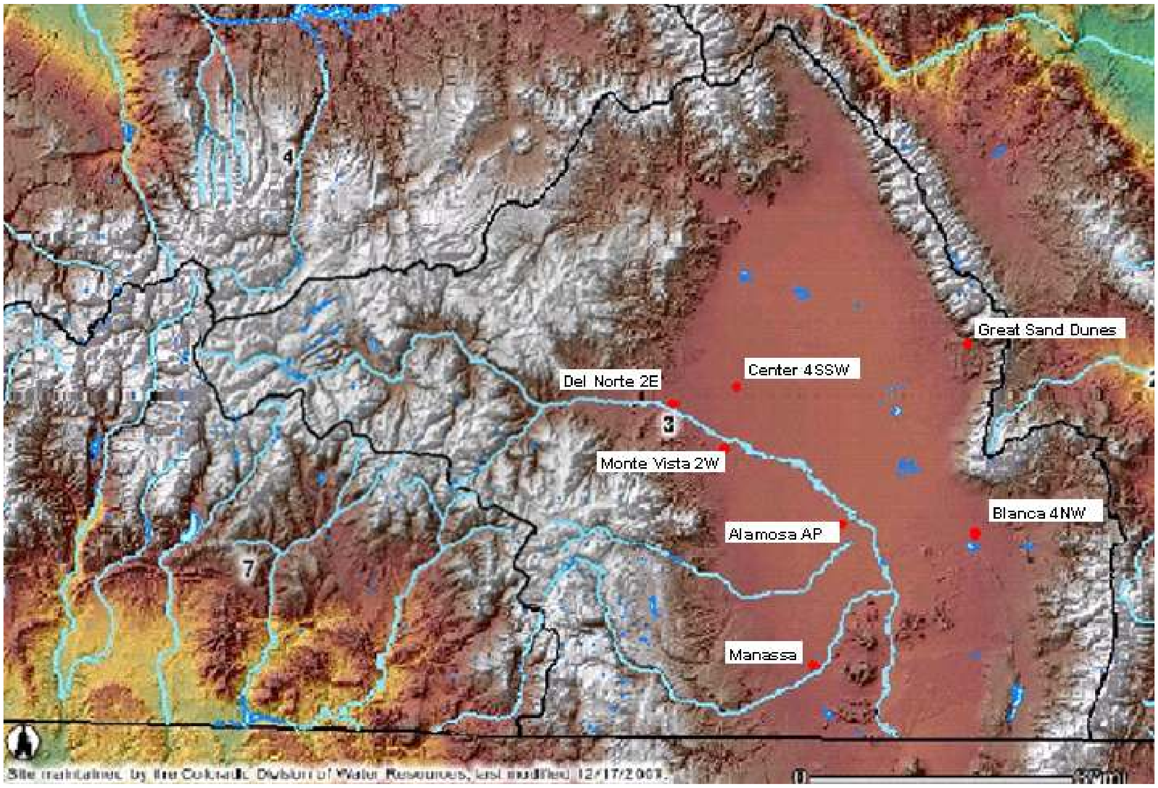



Figure 2.1. Locations of climate stations (in red) in the San Luis Valley, Colorado. Map source: Colorado Decision Support System.

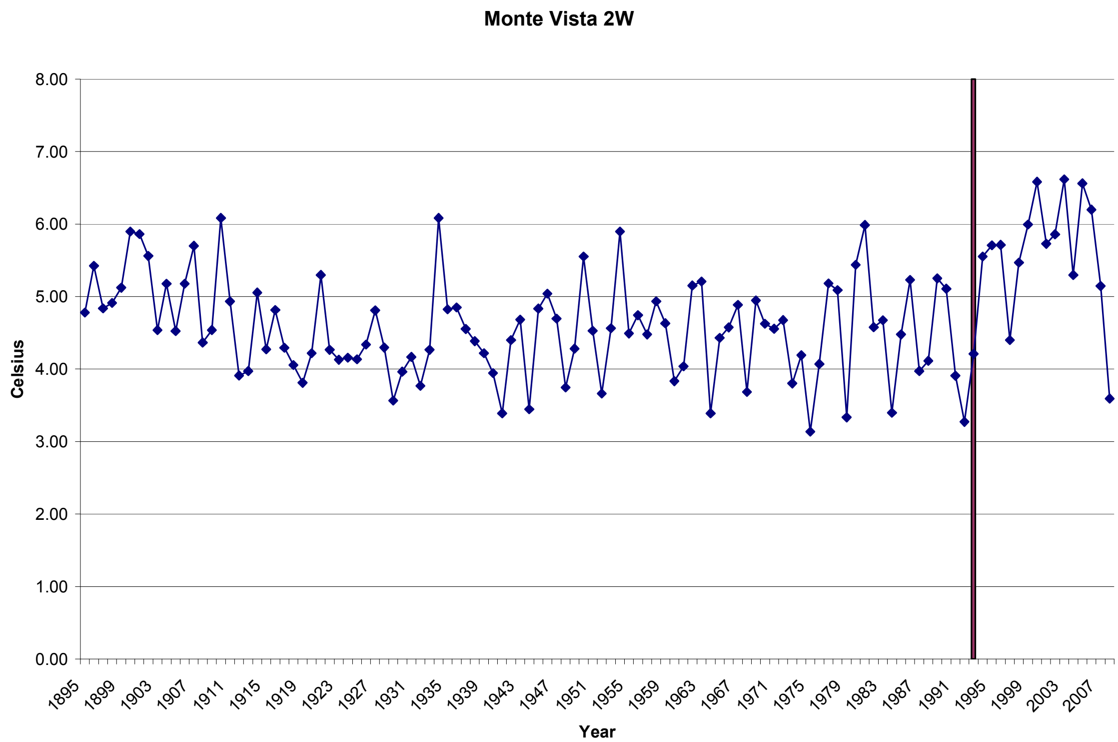



Figure 2.2a.

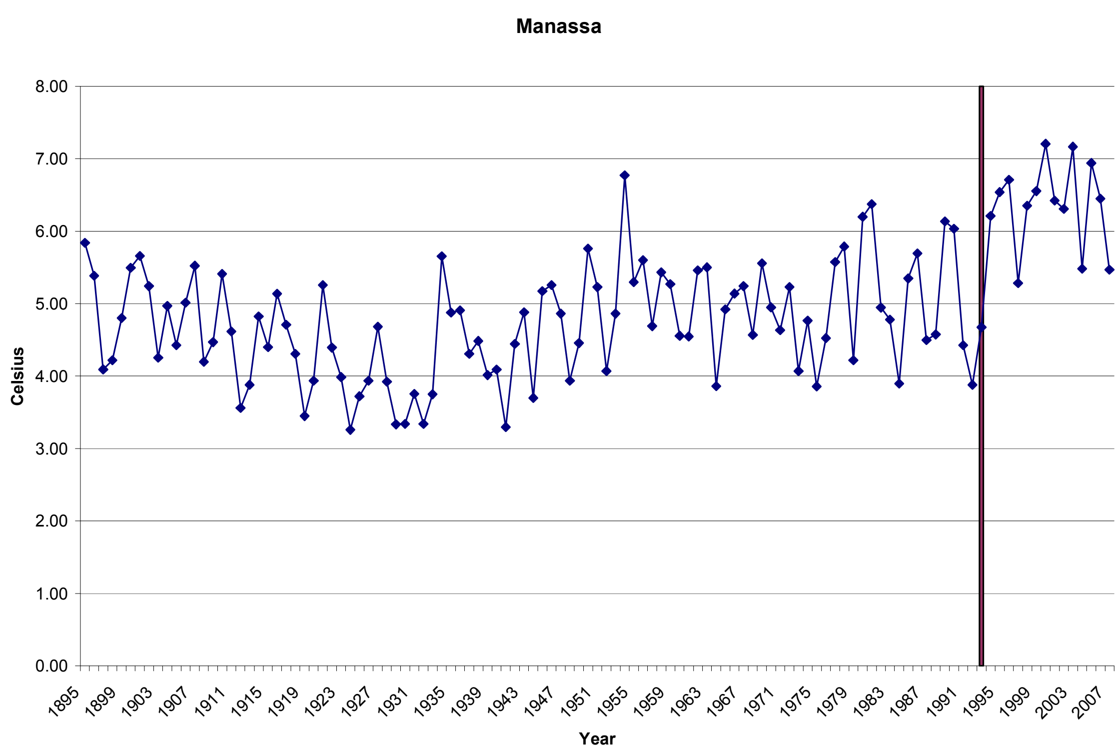
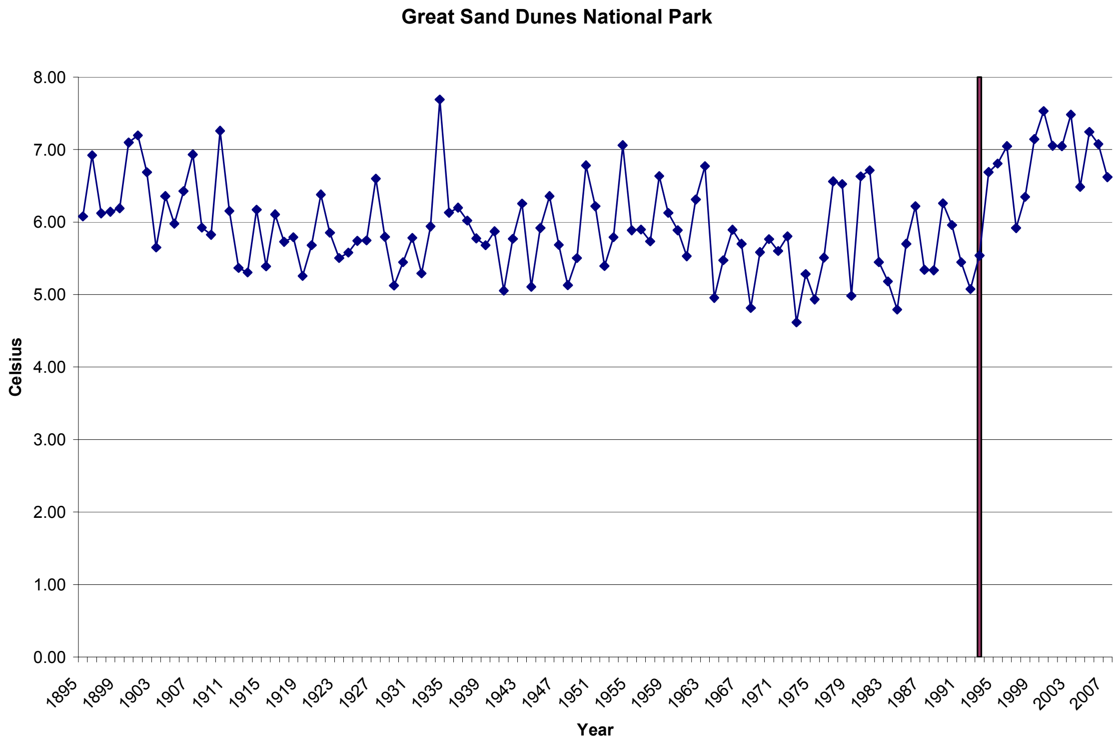



Figure 2.2b.

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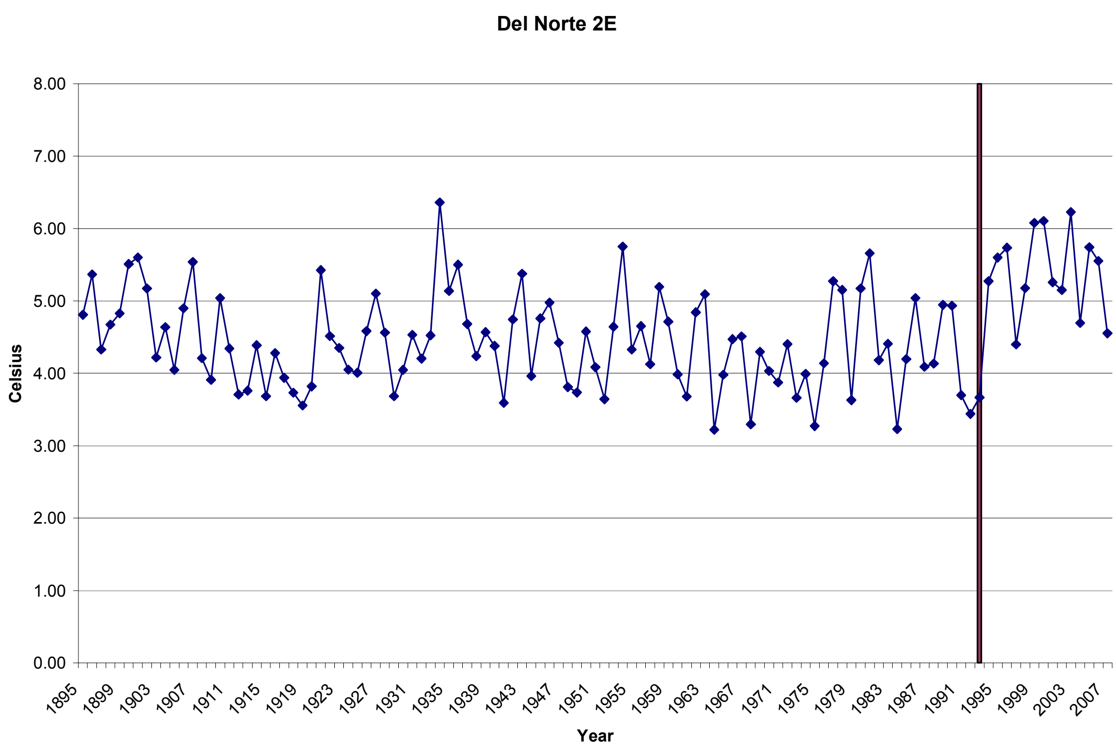
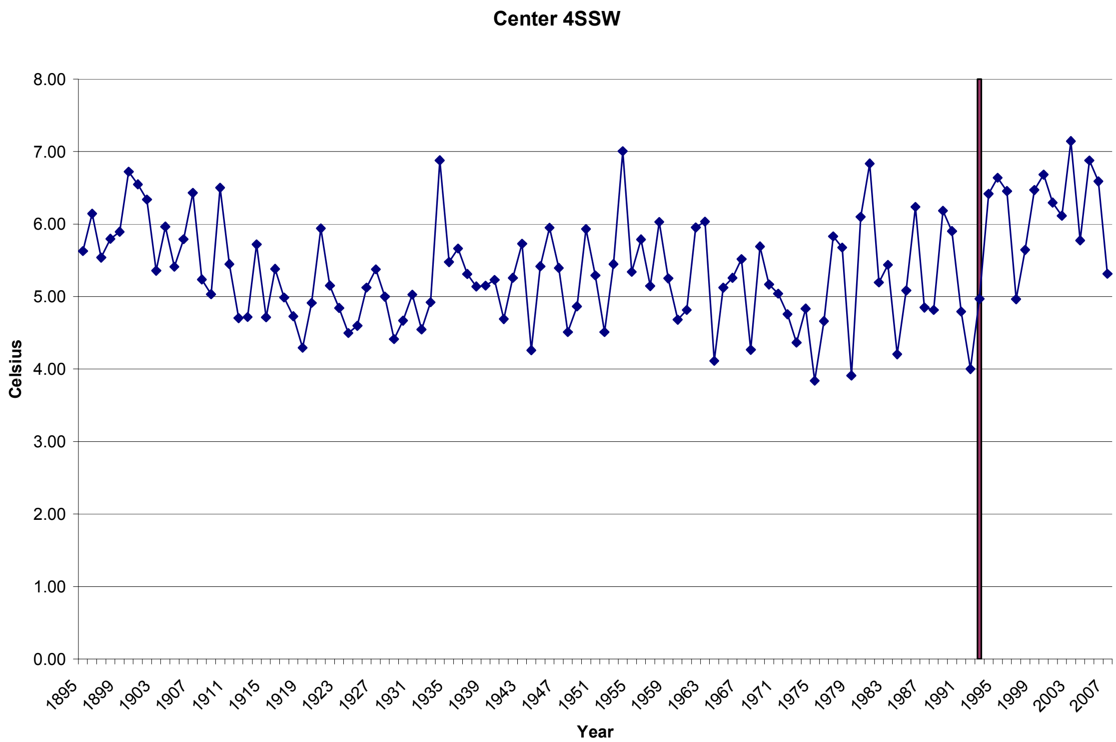



Figure 2.2d.

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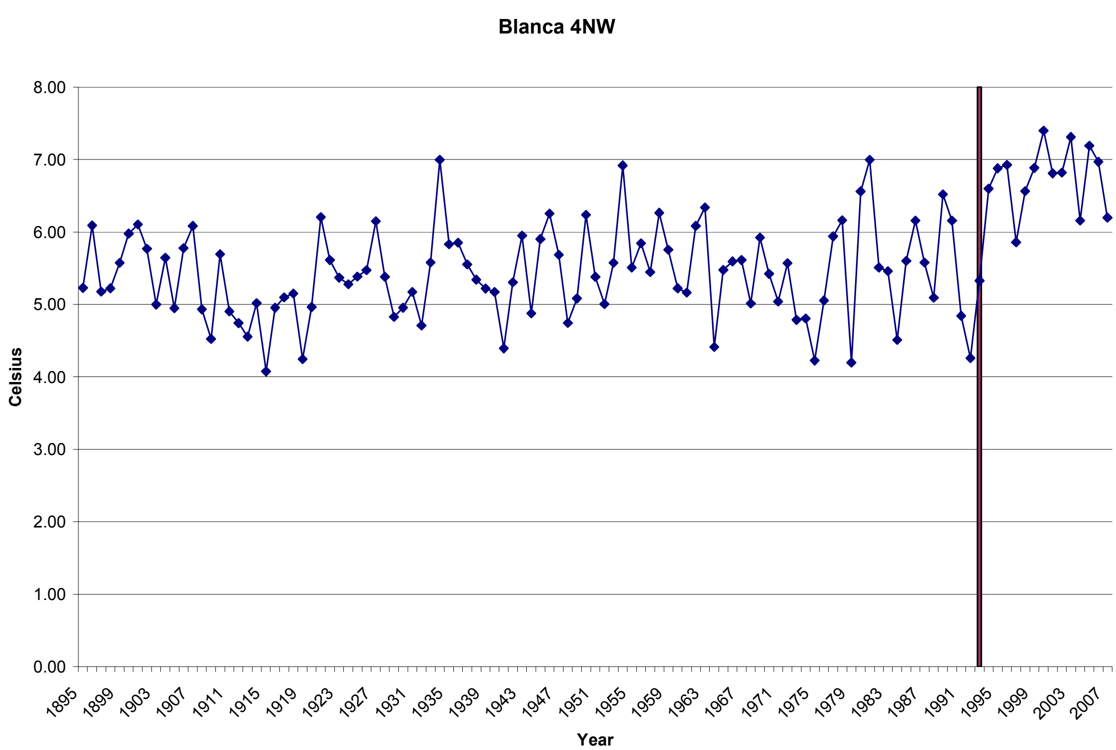


Figure 2.2f.

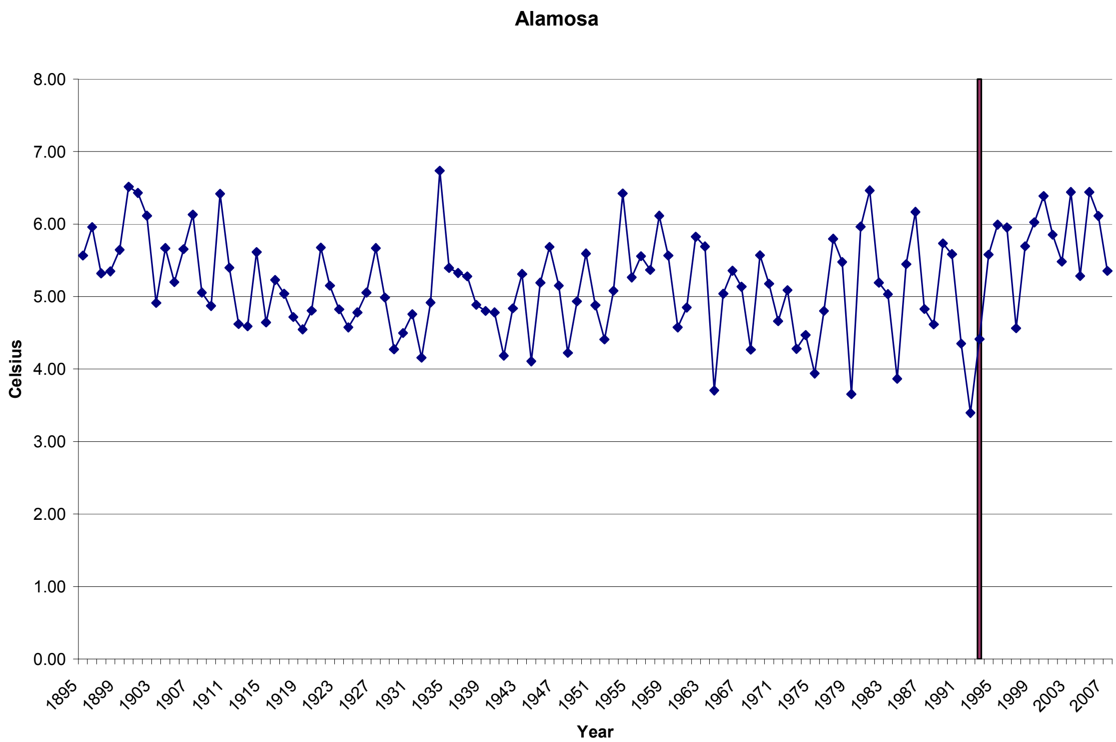


Figure 2.2g.
Figure 2.2, a-g. Time series of the average annual mean temperature for each station.

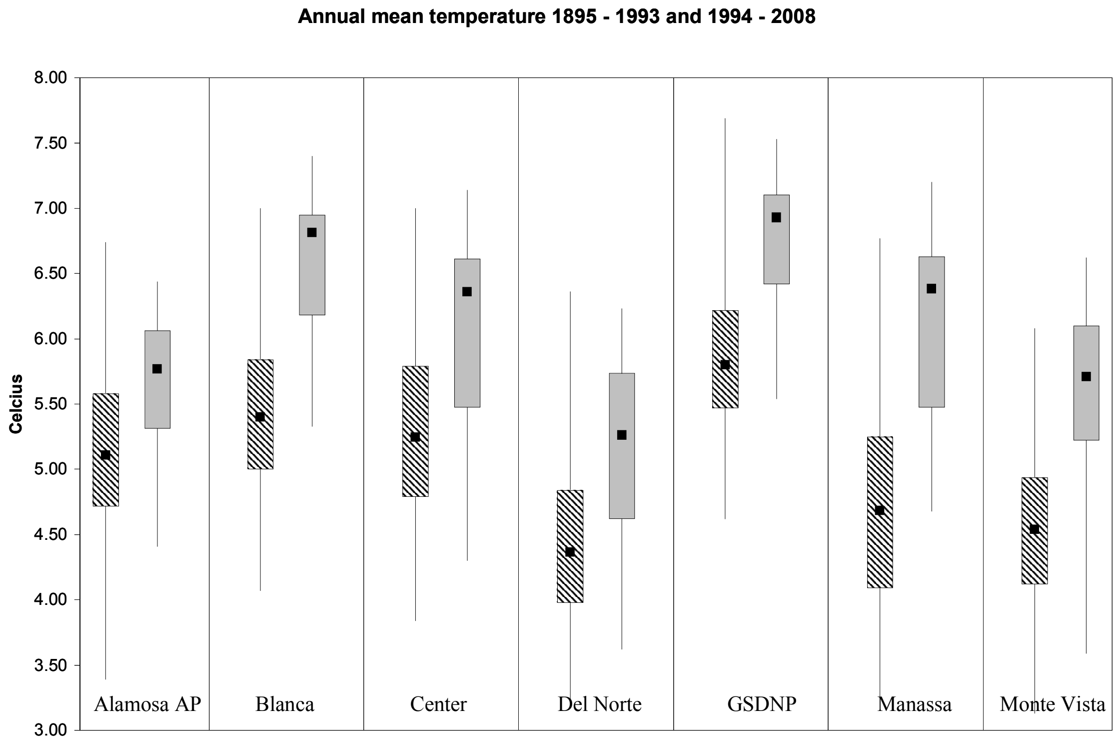


Figure 2.3a.

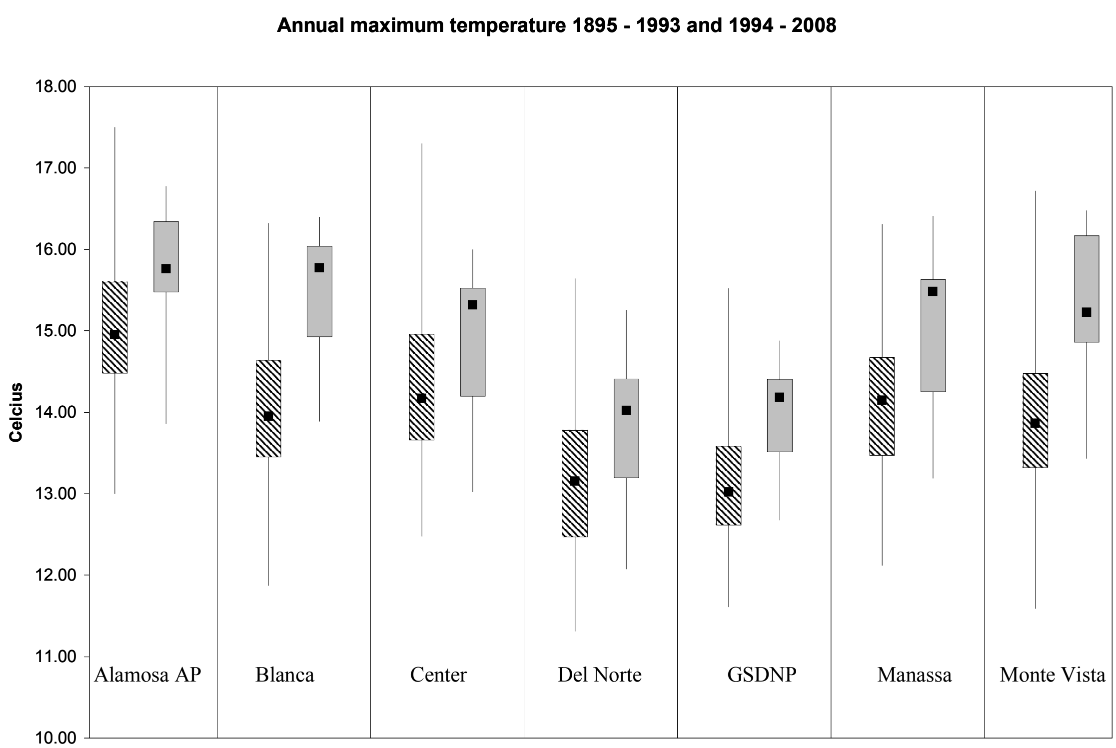


Figure 2.3b.

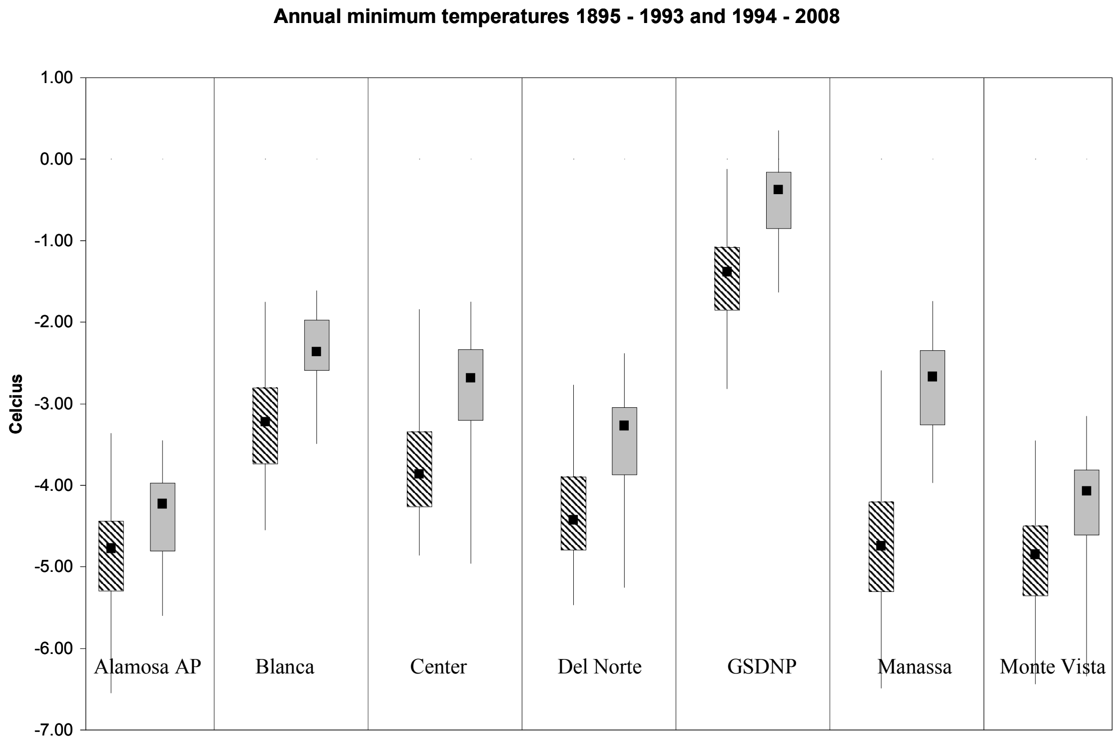


Figure 2.3c.

Figures 2.3 a, b, c. Annual temperature values during the periods 1895 – 1993 (cross hatch) and 1994 – 2008 (solid grey). Averages of: a) Mean temperature, b) Maximum temperature, c) Minimum temperature. All 1994 – 2008 temperature values were significantly ($p < 0.05$) higher than the 1895 – 1993 period. The box represents the interquartile range, the point in the box is the median, upper and lower lines are the maximum and minimum. From left to right: Alamosa, Blanca, Center, Del Norte, GSDNP, Manassa, Monte Vista.

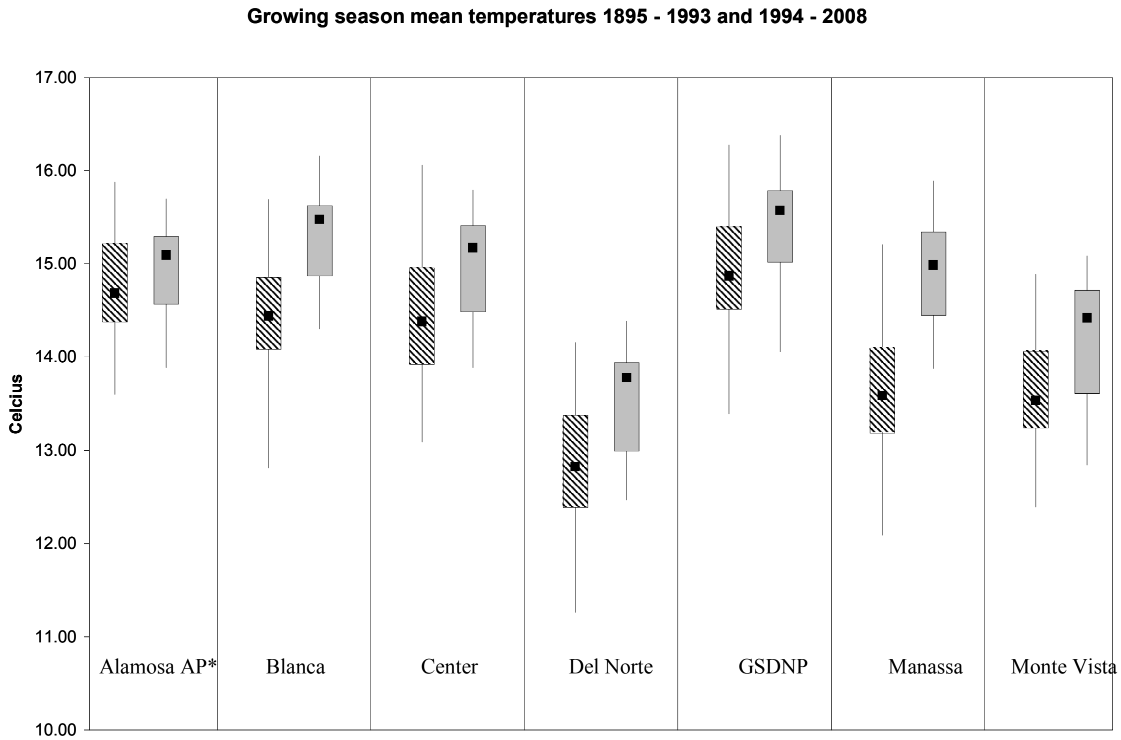


Figure 2.4a.

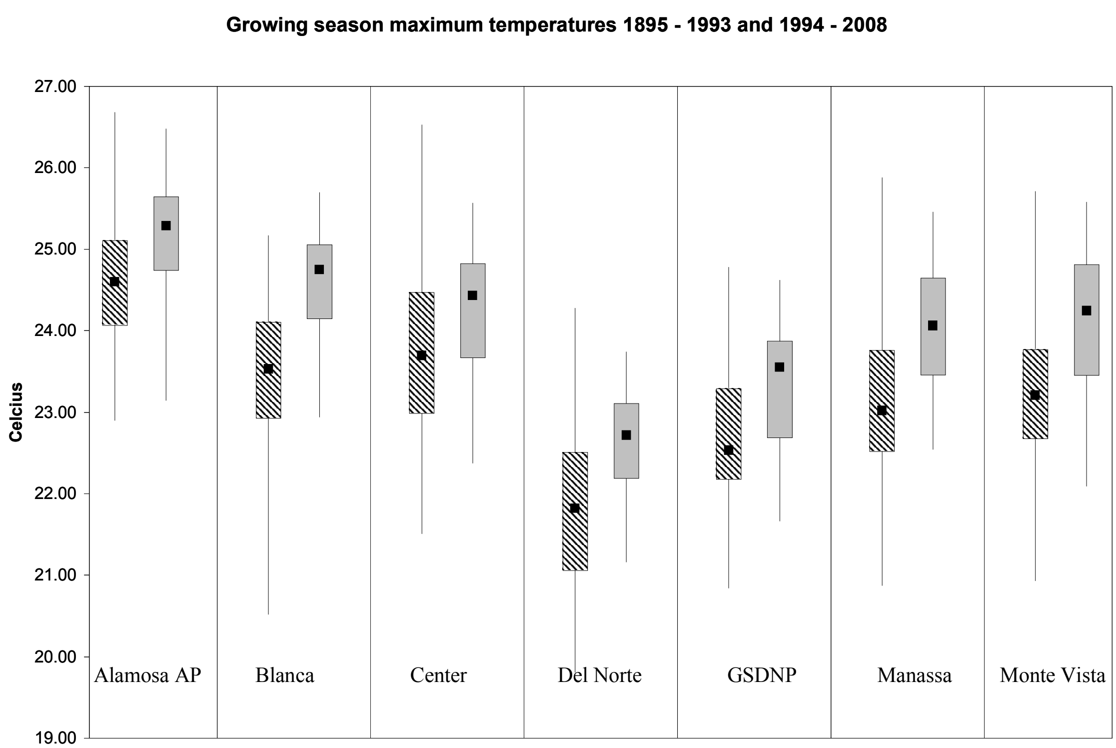


Figure 2.4b.

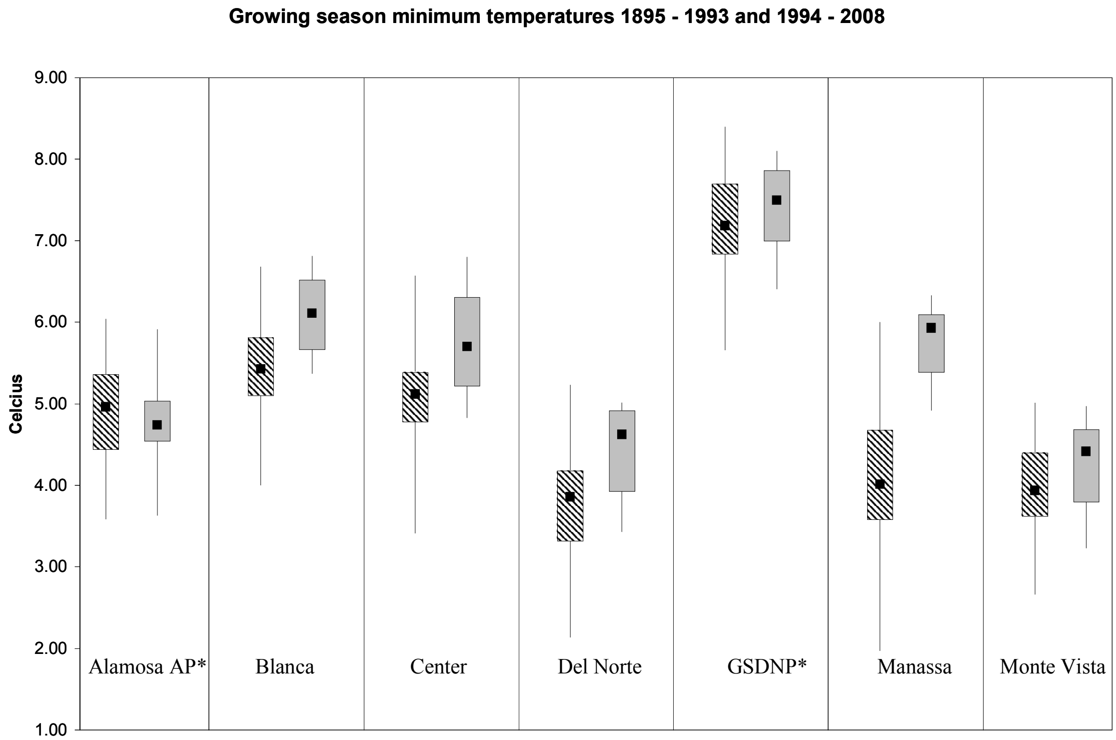


Figure 2.4c.

Figure 2.4 a, b, c. Growing season temperature values during the periods 1895 – 1993 (cross hatch) and 1994 – 2008 (solid grey). Averages of: a) Mean temperature, b) Maximum temperature, c) Minimum temperature. Few 1994 – 2008 temperature values were not significantly higher (* $p > 0.05$) than the 1895 – 1993 period. The box represents the interquartile range, the point in the box is the median, upper and lower lines are the maximum and minimum. From left to right: Alamosa, Blanca, Center, Del Norte, GSDNP, Manassa, Monte Vista.

Table 2.1. Station number, name location and elevation for each station in the San Luis Valley, Colorado. GSDNP = Great Sand Dunes National Park.

| Station Number | Station Name | Location | Elevation in meters |
|---|---|---|---|
| 050130 | Alamosa AP | 37°26'N / 105°52'W | 2296.1 |
| 050776 | Blanca 4NW | 37°29'N / 105°34'W | 2349.7 |
| 051458 | Center 4SSW | 37°42'N / 106°09'W | 2338.7 |
| 052184 | Del Norte 2E | 37°40'N / 106°19'W | 2396.9 |
| 053541 | GSDNP | 37°44'N / 105°31'W | 2475.0 |
| 055322 | Manassa | 37°10'N / 105°56'W | 2343.9 |
| 055706 | Monte Vista 2W | 37°35'N / 106°11'W | 2344.5 |

Table 2.2. Results of change point analysis for weather stations on the floor of the San Luis Valley, Colorado. GSDNP = Great Sand Dune National Park.

| Station | | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|---|
| Alamosa AP | | | | | | |
| | Maximum | 1900 | 1990 | 93 | 15.9 | 17.2 |
| | | 1903 | 1903-1906 | 92 | 17.2 | 14.9 |
| | | 1999 | 1985-2003 | 97 | 14.9 | 16.0 |
| | Minimum | no change | | | | |
| | Mean | 1994 | 1962-2001 | 100 | 5.1 | 5.7 |
| Blanca 4NW | | | | | | |
| | Maximum | 1909 | 1906-1913 | 100 | 14.1 | 13.0 |
| | | 1921 | 1918-1926 | 99 | 13.0 | 14.3 |
| | | 1964 | 1923-1992 | 94 | 14.3 | 14.0 |
| | | 1994 | 1990-1996 | 100 | 14.0 | 15.6 |
| | Minimum | 1994 | 1987-1996 | 99 | -3.2 | -2.3 |
| | Mean | 1908 | 1904-1911 | 100 | 5.6 | 4.8 |
| | | 1921 | 1919-1943 | 93 | 4.8 | 5.5 |
| | | 1994 | 1990-1996 | 100 | 5.5 | 6.7 |
| Center 4SSW | | | | | | |
| | Maximum | 1905 | 1903-1909 | 100 | 15.9 | 14.2 |
| | | 1999 | 1983-2003 | 92 | 14.2 | 15.2 |
| | Minimum | 1994 | 1987-1999 | 100 | -3.8 | -2.8 |
| | Mean | 1911 | 1907-1924 | 93 | 5.9 | 5.2 |
| | | 1994 | 1988-2000 | 98 | 5.2 | 6.1 |
| Del Norte 2E | | | | | | |
| | Maximum | 1903 | 1901-1905 | 100 | 14.4 | 12.9 |
| | | 1933 | 1921-1957 | 98 | 12.9 | 13.5 |
| | | 1960 | 1949-1970 | 98 | 13.5 | 12.7 |
| | | 1994 | 1989-1999 | 100 | 12.7 | 13.9 |
| | Minimum | 1994 | 1989-1999 | 100 | -4.3 | -3.4 |
| | Mean | 1994 | 1986-1999 | 100 | 4.4 | 5.3 |
| GSDNP | | | | | | |
| | Maximum | 1903 | 1901-1906 | 99 | 14.5 | 13.0 |
| | | 1994 | 11987-1997 | 100 | 13.0 | 14.0 |
| | Minimum | 1950 | 1916-1958 | 95 | -1.3 | -1.9 |
| | | 1964 | 1960-1973 | 100 | -1.9 | -1.6 |
| | | 1994 | 1992-1995 | 100 | -1.6 | -0.4 |
| | Mean | 1912 | 1906-1924 | 91 | 6.4 | 5.8 |
| | | 1994 | 1990-1996 | 100 | 5.8 | 6.9 |
| Manassa | | | | | | |
| | Maximum | 1918 | 1916-1920 | 100 | 14.6 | 13.1 |
| | | 1934 | 1932--1945 | 100 | 13.1 | 14.2 |
| | | 1994 | 1979-1999 | 96 | 14.2 | 15.2 |
| | Minimum | 1954 | 1949-1961 | 100 | -5.1 | -4.1 |
| | | 1994 | 1991-1996 | 100 | -4.1 | -2.7 |
| | Mean | 1912 | 1901-1919 | 97 | 4.9 | 4.3 |
| | | 1923 | 1913-1944 | 94 | 4.3 | 4.1 |
| | | 1945 | 1940-1952 | 100 | 4.1 | 5.0 |
| | | 1994 | 1990-1997 | 100 | 5.0 | 6.3 |
| Monte Vista 2W | | | | | | |
| | Maximum | 1911 | 1906-1918 | 98 | 15.0 | 13.7 |
| | | 1994 | 1991-1997 | 100 | 13.7 | 15.4 |
| | Minimum | 1994 | 1984-2001 | 94 | -4.9 | -4.1 |
| | Mean | 1912 | 1906-1924 | 99 | 5.1 | 4.4 |
| | | 1994 | 1990-1998 | 100 | 4.4 | 5.6 |

Table 2.3. Results of GLM analysis for annual temperature data from weather stations on the floor of the San Luis Valley, Colorado. GSDNP = Great Sand Dunes National Park.

| | 1895-1993 | | | | 1994-2008 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| Maximum | 98 | 15.05 | 0.92 | 0.09 | 15 | 15.61 | 0.89 | 0.22 | 0.56 | 0.0125 |
| Minimum | 98 | -4.83 | 0.63 | 0.06 | 15 | -4.37 | 0.58 | 0.14 | 0.45 | 0.0039 |
| Mean | 98 | 5.13 | 0.67 | 0.07 | 15 | 5.63 | 0.66 | 0.17 | 0.50 | 0.0032 |
| Blanca 4NW | | | | | | | | | | |
| Maximum | 98 | 14.03 | 0.84 | 0.09 | 15 | 15.47 | 0.78 | 0.19 | 1.44 | <0.0001 |
| Minimum | 98 | -3.22 | 0.60 | 0.06 | 15 | -2.33 | 0.54 | 0.13 | 0.89 | <0.0001 |
| Mean | 98 | 5.42 | 0.63 | 0.06 | 15 | 6.59 | 0.62 | 0.15 | 1.17 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| Maximum | 98 | 14.33 | 0.97 | 0.10 | 15 | 14.91 | 0.91 | 0.23 | 0.58 | 0.0137 |
| Minimum | 98 | -3.79 | 0.66 | 0.07 | 15 | -2.86 | 0.82 | 0.20 | 0.93 | <0.0001 |
| Mean | 98 | 5.28 | 0.69 | 0.07 | 15 | 6.04 | 0.80 | 0.20 | 0.76 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| Maximum | 98 | 13.16 | 0.89 | 0.09 | 15 | 13.85 | 0.92 | 0.23 | 0.69 | 0.0036 |
| Minimum | 98 | -4.34 | 0.58 | 0.06 | 15 | -3.49 | 0.75 | 0.19 | 0.85 | < 0.0001 |
| Mean | 98 | 4.42 | 0.64 | 0.06 | 15 | 5.18 | 0.80 | 0.20 | 0.75 | < 0.0001 |
| GSDNP | | | | | | | | | | |
| Maximum | 98 | 13.10 | 0.80 | 0.08 | 15 | 13.94 | 0.66 | 0.16 | 0.83 | <0.0001 |
| Minimum | 98 | -1.36 | 0.57 | 0.06 | 15 | -0.46 | 0.51 | 0.13 | 0.91 | <0.0001 |
| Mean | 98 | 5.88 | 0.60 | 0.06 | 15 | 6.76 | 0.56 | 0.14 | 0.87 | <0.0001 |
| Manassa | | | | | | | | | | |
| Maximum | 98 | 14.10 | 0.94 | 0.09 | 15 | 15.06 | 0.94 | 0.23 | 0.96 | <0.0001 |
| Minimum | 98 | -4.71 | 0.86 | 0.09 | 15 | -2.76 | 0.94 | 0.23 | 1.96 | <0.0001 |
| Mean | 98 | 4.71 | 0.76 | 0.77 | 15 | 6.17 | 0.78 | 0.19 | 1.46 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| Maximum | 98 | 13.92 | 0.94 | 0.09 | 15 | 15.25 | 1.05 | 0.26 | 1.32 | <0.0001 |
| Minimum | 98 | -4.85 | 0.57 | 0.06 | 15 | -4.20 | 0.79 | 0.20 | 0.65 | 0.0001 |
| Mean | 98 | 4.55 | 0.67 | 0.07 | 15 | 5.54 | 0.87 | 0.22 | 0.99 | <0.0001 |

Table 2.4. Results of GLM analysis for growing season temperature data from weather stations on the floor of the San Luis Valley, Colorado. GSDNP = Great Sand Dunes National Park.

| | | 1895-1993 | | | | 1994-2008 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| Maximum | 98 | 24.63 | 0.82 | 0.08 | 15 | 25.12 | 0.99 | 0.25 | 0.50 | 0.0325 |
| Minimum | 98 | 4.91 | 0.57 | 0.06 | 15 | 4.75 | 0.56 | 0.14 | -0.16 | 0.2632 |
| Mean | 98 | 14.78 | 0.55 | 0.06 | 15 | 14.95 | 0.54 | 0.13 | 0.17 | 0.2621 |
| Blanca 4NW | | | | | | | | | | |
| Maximum | 98 | 23.45 | 0.90 | 0.09 | 15 | 24.53 | 0.82 | 0.21 | 1.08 | <0.0001 |
| Minimum | 98 | 5.46 | 0.55 | 0.06 | 15 | 6.08 | 0.48 | 0.12 | 0.62 | <0.0001 |
| Mean | 98 | 14.47 | 0.57 | 0.06 | 15 | 15.32 | 0.59 | 0.15 | 0.85 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| Maximum | 98 | 23.78 | 1.04 | 0.11 | 15 | 24.22 | 0.93 | 0.23 | 0.44 | 0.0573 |
| Minimum | 98 | 5.04 | 0.54 | 0.05 | 15 | 5.75 | 0.61 | 0.15 | 0.72 | <0.0001 |
| Mean | 98 | 14.42 | 0.63 | 0.06 | 15 | 15.00 | 0.60 | 0.15 | 0.58 | 0.0008 |
| Del Norte 2E | | | | | | | | | | |
| Maximum | 98 | 21.92 | 1.02 | 0.10 | 15 | 22.61 | 0.75 | 0.19 | 0.69 | 0.0052 |
| Minimum | 98 | 3.77 | 0.57 | 0.06 | 15 | 4.46 | 0.55 | 0.14 | 0.69 | < 0.0001 |
| Mean | 98 | 12.86 | 0.65 | 0.07 | 15 | 13.55 | 0.60 | 0.15 | 0.69 | < 0.0001 |
| GSDNP | | | | | | | | | | |
| Maximum | 98 | 22.66 | 0.83 | 0.08 | 15 | 23.32 | 0.90 | 0.22 | 0.65 | 0.0023 |
| Minimum | 98 | 7.18 | 0.63 | 0.06 | 15 | 7.40 | 0.55 | 0.14 | 0.22 | 0.0999 |
| Mean | 98 | 14.94 | 0.61 | 0.06 | 15 | 15.38 | 0.67 | 0.17 | 0.44 | 0.0048 |
| Manassa | | | | | | | | | | |
| Maximum | 98 | 23.07 | 0.95 | 0.10 | 15 | 24.03 | 0.90 | 0.23 | 0.96 | 0.0001 |
| Minimum | 98 | 4.14 | 0.82 | 0.08 | 15 | 5.78 | 0.45 | 0.11 | 1.64 | <0.0001 |
| Mean | 98 | 13.62 | 0.68 | 0.07 | 15 | 14.92 | 0.61 | 0.15 | 1.29 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| Maximum | 98 | 23.32 | 0.84 | 0.08 | 15 | 24.11 | 1.01 | 0.25 | 0.79 | 0.0004 |
| Minimum | 98 | 3.96 | 0.54 | 0.05 | 15 | 4.27 | 0.54 | 0.14 | 0.32 | 0.0166 |
| Mean | 98 | 13.65 | 0.56 | 0.06 | 15 | 14.21 | 0.70 | 0.18 | 0.56 | 0.0003 |

## CHAPTER 3

# INCREASES IN GROWING DEGREE DAYS IN THE ALPINE DESERT OF THE SAN LUIS VALLEY, COLORADO

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**Abstract.** Most alpine ecosystem climate change studies identify changes in biota and several report abiotic factors and conditions; few report temperature changes and few to none discuss growing degree days (GDD) changes. This study provides results of data analysis on changes in number of GDD in the alpine desert of the San Luis Valley (SLV) whose community is dominated by irrigated agricultural. Analysis indicates significant increases ($p < 0.05$) in annual and growing season $GDD_{10}$, $GDD_{4.4}$ (potato) and $GDD_{5.5}$ (alfalfa) during 1994-2007 compared to 1958-1993. With one exception, all stations experienced significant increases in mean annual daily GDD between 0.12 and 0.50 $day^{-2}$ and growing season GDD $day^{-2}$ 0.21 and 0.81. Higher temperatures increase numbers of GDD, quickening growth of crops and maturity at the cost of reduced yield and quality. Increases in GDD indicate the Valley's agricultural and economy may experience negative impacts as yields decrease and water use increases.

**Keywords:** Growing degree days, climate change, alpine, agriculture, irrigation, Rio Grande

# 1. Introduction

*"Climate is what we expect, weather is what we get." Mark Twain (Samuel Clemens)*

## 1.1. CLIMATE CHANGE

Climate change, as a result of increases in $CO_2$ concentrations, is occurring on a global scale as mean annual temperatures rise (IPCC 2001 and 2007, Hansen et al. 2006). Global temperature increases are considered to be substantial and early findings indicated an increase of global mean temperature of $0.6 \pm 0.2^{\circ}C$ since 1861 (Folland et al. 2001, IPCC 2001). Later studies and data now indicate global temperatures have risen by roughly $0.1^{\circ}C$ per decade (IPCC 2007) over the past century and nearly $0.6^{\circ}C$, in the past 3 decades (Hansen et al. 2006) resulting in a $0.74 \pm 0.2^{\circ}C$ increase in global temperature. Current data analysis indicates the greatest warming period on instrumental record is 1976-2007 (Hansen et al. 2006, IPCC 2001 and 2007). The year 2005 is now considered to be the warmest year on record.

The results of climate change are a rise in both the daily maximum (mostly daytime) and minimum (mostly nighttime) temperatures. Increases in maximum temperature have lagged increases in the minimum temperatures (Karl et al. 1991, IPCC 2001 and 2007). Maximum temperatures have ultimately risen, diurnal asymmetry is evident, as temperature increases have been $0.2^{\circ}C$ and $0.1^{\circ}C$ per decade for mean annual minimum and maximum temperatures (IPCC 2001, Hansen et al. 2006).

Further, climate change is not homogenous (Hansen and Lebedeff 1987, IPCC 2007). Changes in climate have occurred at different rates between latitudes (Hansen and Lebedeff 1987, Giorgi et al. 1994, Hansen et al. 2001) and altitudes (Bucher and Dessens

1991, Weber et al. 1994, Diaz and Bradley 1997). Further, climate change in the U.S. is not necessarily consistent with global warming trends, though it is warming (Giorgi et al. 1994, Hansen et al. 2001). There were cool years in the continental U.S. during the 1990's. Dettinger and Cayan (1995) speculate higher elevations were less sensitive to the increases in temperature that had occurred by 1995. The IPCC (2001) indicates upper altitudes of the atmosphere are increasing more slowly than surface temperatures and Rebetez and Dobbertin (2004) report a possible lag effect of climate change in Alpine regions. Additionally, changes in precipitation in the U.S. are predicted to be variable, according to location, based on the Hadley Centre CM2 and 3 (Arnell 1999 and 2004); while the arid southwest is expected to experience decreases in precipitation, the southeast is expected to experience increases (Arnell 1999).

### 1.2. Agricultural implications of climate change

Increases in the global mean temperature will negatively impact some agricultural ventures. Some projections and models indicate higher temperatures will increase crop water needs, decrease yield volume and quality. Others indicate changes in: pest phenology, distribution and synchrony of crops and beneficial insects, and a few discuss changes in number of growing degree days (GDD).

Increased temperatures are expected to exacerbate the need for irrigation as increases in crop evapotranspiration will occur (Adams 1989, Schimmelpfennig et al. 1996, Fischer et al. 1996, Ramirez and Finnerty 1996). Though, Ramirez and Finnerty (1996) point out crop production will need additional water to reduce the impact of increased temperatures they also indicate increased $CO_2$ concentrations may result in a greater income per hectare as crop production increases, even in light of increasing water needs. Further, higher daily temperatures may affect crop pollination or speed maturation at the cost of yield (weight/volume). Applied climate change scenarios indicate temperature increases will cause worldwide decreases in production, with U.S. production exhibiting variable outcomes based on regional changes in precipitation (Fischer et al. 1996, Reilly et al. 2003). Ultimately, predictions of changes in agricultural production are equivocal (Fischer et al. 1996, Sombroek and Gommes 1996).

Part of the variability is a result of how crops utilize carbon. Plants are generally categorized into 3 types, $C_3$, $C_4$ and CAM, according to their carbon utilization pathways (Sombroek and Gommes 1996). $C_3$ plants are adapted to more mesic and lower light intensity regions, while $C_4$ plants are adapted to higher light more arid regions and utilize $CO_2$ in a manner that reduces water stress under arid conditions. Common $C_3$ agricultural crops include alfalfa, barley, oats, wheat, beans (including soy), sweet and white potatoes and rice. $C_4$ agricultural crops include maize, millet, sorghum and sugarcane and CAM agricultural and horticultural crops include orchids, blue agave, onions and pineapple. Some experimental models indicate climate change will reduce yields of $C_3$ crops and increase yields of $C_4$ and CAM crops (Easterling et al. 1993, Singh et al. 1998); there is still equivocation on the topic. Ultimately, Easterling et al's (1993 and 2001) final comments, when factoring changes in precipitation, temperature, $CO_2$ concentrations, crop adaptations and adaptive technology, indicate most all negative effects of climate change will be offset and a near zero net loss in yield will result, with possible increases.

### 1.3. Changes in Phenology

Just as important to agriculture as temperature change and increases in $CO_2$ concentrations are changes in phenology; the timing of developmental stages in crops, beneficial insects and pests. Several studies report changes in insect, crop and pest plants, and disease distribution, synchrony and emergence, insect fecundity or disease virility (Bradley et al. 1999, Chakraborty et al. 2000, Rosenzweig et al. 2000, Beaubien and Freeland 2000, McCarty 2001, Walther et al. 2002, Thuiller et al. 2005, IPCC 2007). A marker for early insect emergence is phenological changes in bird behavior as evidenced by earlier migration and breeding activity among 20 species of shorebirds and passerines (MacInnes et al. 1990, Crick et al. 1997, Winkle and Hudde 1997, McCleery and Perrins 1998, Dunn and Winkler 1999, Slater 1999, Brown et al. 1999).

Further, in agriculture or forestry there are specific indications of adverse impacts from changes in phenology. Several studies have found increases in insect abundance, distribution, prevalence or voltinism, and changes in synchrony (Manzer and Nelson 1987, Porter et al. 1991, Colbach et al. 1997, Woiwod 1997, Fleming and Candau 1998, Rosenzweig 2000, Losey and Vaughan 2006). The importance of changes in insect phenology should not be underestimated, as insects provide $3 million of beneficial services through pollination, predation and parasitoid activity. Further, without chemical control measures insect pests would account for an additional $26 billion loss annually (Rosenzweig 2000). Therefore the impact of changing phenology could potentially cause large economic losses from loss of beneficial services or increase in chemical control costs.

Lastly, the initiation of florescence in several species is also occurring earlier (Beaubien and Freeland 2000). Bloom onset of several species is occurring earlier by 8.2 – 19.8 days (Bradley et al. 1999, Cayan et al. 2001). These changes in phenology indicate the growing season in the northern hemisphere has increased by 7 – 12 days (Keeling et al. 1996, Myneni et al. 1997, Menzel and Fabian 1999, Walther et al. 2002).

### 1.4. Growing degree days

Changes in temperature induce changes in phenology. The changes can be quantified and used to predict or estimate the development of a particular species. The quantification is conducted by calculating the accumulated heat units necessary for a particular organism to develop. Accumulated heat units are commonly referred to as growing degree days (GDD). As early as 1735, René-Antoine Ferchault de Réaumur (de Reaumur 1735) recognized temperature affected phenology and introduced the concept of growing degree days. He postulated that organisms needed to accumulate a number of heat units unique to that organism in order to initiate growth and to develop or mature. It has since been used extensively in agriculture to estimate days to germination, bloom or maturity (Hartz and Moore 1978, Snyder et al. 1999, Kim et al. 2000) and can be used to predict regional distributions of organisms; i.e. crops, insect and plant pests.

Growing degree days are developed from daily temperature data by taking the mean value of the daily maximum and minimum temperatures and subtracting a base value. The base values are unique to each species and represent the lower temperature threshold for growth (Breazeale et al., Derscheid and Lytle 1981). There is also a maximum temperature threshold, above which the specific organism is dormant. Thus the maximum and minimum temperatures used to derive the GDD are specific for each species and in agriculture specific for certain varietals.

The relationship between GDD and crop production, plant growth and insect development is widely known and understood (Hartz and Moore 1978, Frank and

Hofmann 1989, Power 2002, Ojeda-Bustamante et al. 2004). For example, some plants require a number of accumulated GDD to break thermal dormancy, a period of time when germination, leaf unfurling (bud burst) or bloom set is suspended until triggered by changes in temperature (Cannell and Smith 1983, Snyder et al. 1999, Grundy et al. 2000). These environmental cues also trigger plants to begin initiating changes such as seed/fruit maturation and senescence (Snyder et al. 1999, Aber et al. 1995). Ramankutty et al. (2002) have utilized GDD to predict the sensitivity of agricultural regions to climate change. GDD are also utilized to estimate the emergence of agricultural pests and disease (Pscheidt and Stevenson 1988, Kim et al. 2000).

The principal crops of the San Luis Valley are $C_3$ crops: alfalfa/grass hay, potato, mixed cereals and vegetables. In general, for crops $GDD_{10}$ can be used in most cases; however specific $GDD_{5.5}$ and $GDD_{4.4}$ are used for alfalfa and potato (base refers to the lower temperature threshold in degrees Celsius). Because of the variability between species and crops climate change may not affect each equally, but rather may benefit some while harming others. For instance, base 10 maximum and minimum thresholds are 30$^{\circ}$C and 10$^{\circ}$C, growth is estimated to only occur within those ranges.

Climate change has several aspects which affect agriculture. Changes in temperature alone impact growth and evapotranspiration. Temperature changes also change GDD which in turn affect phenology; maturation of fruit, emergence of pests and disease, synchrony of beneficials and bloom time are all determined by accumulated GDD. Lastly, increases in $CO_2$ concentrations have ameliorating effects that Easterling et al. (1993 and 2001) have indicated may offset any negative impacts of climate change.

## 2. Objectives

Growing degree days determine the phenology of most organisms and are extensively utilized in agriculture to predict the emergence of pests, disease, days from planting to seedling emergence, bloom time and harvest. Few studies have reported changes in GDD resulting from climate change; very few report changes in alpine ecosystems and none have been found reporting changes in GDD in the San Luis Valley. Therefore the objectives of this study were to determine if increases in GDD occurred in the SLV in the mid– to late– 20$^{th}$ and early–21$^{st}$ Centuries. More specifically, the study analyzed the number of annual mean daily $GDD_{10}$, $GDD_{5.5}$, $GDD_{4.4}$ and growing season mean daily $GDD_{10}$, $GDD_{5.5}$, $GDD_{4.4}$. Each of these GDD bases, 10, 5.5 and 4.4, accommodates the chief agricultural products of the Valley: small grains and mixed vegetables – $GDD_{10}$, alfalfa – $GDD_{5.5}$, potatoes – $GDD_{4.4}$. The growing season is defined as May thru September.

### 3. Study area

Located in south central Colorado, the SLV is roughly bisected by the Rio Grande. The river rises in the western San Juan Mountains, which form the western boundary of the SLV and eastern boundary is formed by the Sangre de Cristo Mountains. The elevation of the SLV is approximately 2300 m. The region regularly experiences low wintertime temperatures of less than -20$^{\circ}$ and as low as -40$^{\circ}$C (NCDC a and b). It ranks in the top 20 coldest locations in North America (King 2007). Warm season temperatures reach the 30's C, but the warm season only lasts 90-110 days. The Valley receives less than 20 cm of precipitation annually as it is in the rain shadow of the San Juan Mountains to the west which receive 100-200 cm of precipitation annually.

Even though the Valley is arid, it is a major agricultural region for the state of Colorado, producing the majority of the state's potato crop (14,000 – 30,000 ha) and a large portion of its alfalfa crop (80,000 – 100,000 ha) (CSUa 2003). This results in irrigated agriculture being the dominant industry of the Valley; it accounts for more than 30% of the Valley economy, employs greater than 50% of the local populous (SLVDG 2002) and covers more than 1.4 million ha. The arid conditions of the Valley cause agriculture to be entirely reliant on surface waters of the Rio Grande and groundwater reserves underlying the Valley; virtually all agriculture is irrigated (CSUb 2003) to compensate for aridity of the Valley.

## 4. Methods

Daily climate data from seven valley floor locations were obtained from the National Climate Data Center (NCDC). The stations were selected on the basis of several criteria: location, length of record and period of record common to all stations. Their respective locations and elevation are presented in Table 3.1. The earliest common date for all stations was 1958, with the common period of record being 1958-2007. Three stations are located along the Rio Grande riparian zone: Del Norte 2E (ele. 2396.9 m), Monte Vista 2W (ele. 2344.5 m), and Alamosa AP (ele. 2296.1 m) (in upstream to downstream order). Two stations, Manassa (ele. 2343.9 m) and Center 4SSW (ele. 2338.7 m), are located south and north, respectively, in the interior of the Valley, while two stations, Blanca 4NW (ele. 2349.7 m) and Great Sand Dunes National Monument (GSD) (ele. 2475.0 m), are located north and south, respectively, along the eastern edge of the Valley. A map depicting the locations of the stations within the Valley is shown in Figure 3.1.

Growing degree days were developed for all bases. To convert the daily minimum and maximum temperatures to $GDD_{10}$, used for non-specific crops, the formula $[(T_{max} + T_{min}) / 2] - 10$ was utilized, where $T_{max}$ = maximum temperature, $T_{min}$ = minimum temperature and 10 = the base temperature threshold. For this formula the maximum and minimum temperature thresholds are 30°C and 10°C, all values exceeding the maximum were reduced to 30°C and values below 10°C were raised to 10°C as no growth occurs above or below the threshold values. For $GDD_{4.4}$ commonly used for potatoes the formula $[(T_{max} + T_{min}) / 2] - 4.4$ was used and the maximum and minimum temperature thresholds are 30°C and 4.4°C, with values adjusted to the threshold as above. For $GDD_{5.5}$ commonly used for alfalfa the formula $[(T_{max} + T_{min}) / 2] - 5.5$ was used and the maximum and minimum temperature thresholds are 43.3°C and 5.5°C, with values adjusted to the threshold as above.

In order to quantify time periods within the data where mean values were distinctly different from the previous or following time periods a change point analysis was utilized. This identifies point(s) in the data record where a change in slope of the cumulative sum caused a significant departure from the previous annual mean values. Previous studies indicated changes in means of time series data can be identified via this analysis (Page 1955 and 1957, Pettit 1979, Taylor 2008). Specifically, change point analysis has been used in several climate studies to identify points of departure from mean values (Craddock 1979, Buishand 1981, Salinger and Mullan 1999).

Utilizing the periods identified by the change point analysis, a one-tailed t-test was used to determine if annual and growing season GDD for each base were significantly higher during the latter period than the earlier period at all stations.

The use of daily data is essential for this study, since GDD are predicated on daily accumulated heat units; therefore the use of daily data is the most appropriate means of addressing GDD. Nevertheless, because there is no reliable method for correcting long-term daily data (Menne and Duchon 2000; Alexander et al. 2006), the data set does contain some inhomogeneities. However, the daily data from these stations represents the 'best available' data for this purpose. After reviewing the adjusted monthly and annual data provided by the NCDC, we verified the temperature increase was likely higher than indicated by daily values. As GDD are direct calculations from the temperature data, the results of our calculations represent conservative estimates, with total annual GDD likely being higher by several days on an annual basis. Nonetheless, our results reflect changes in GDD that may have potentially important impacts on the agricultural community of the SLV.

## 5. Results

### 5.1. CHANGE POINT ANALYSIS

Mix et al. (2008) previously utilized change point analysis to identify the years 1993 and 1994 as the point where significant differences in annual mean temperature values occurred in the SLV. The application of change point analysis of annual and growing season GDD indicates there is more variability between, and within, stations for the change point year. Thus the earliest common year identified in the confidence interval, 1994, was utilized as the year when the mean GDD values were significantly different from the previous years. Therefore, the data periods most appropriate for use in the statistical analysis were 1958-1993 and 1994-2007.

The results of the change point analysis of GDD data are presented in Table 3.2. The station location and values tested are presented in column 1. The change point year is the likeliest year that analysis indicates the cumulative sum of the means was significantly different from the previous mean values. The confidence interval indicates the range of years in which this change might have occurred. The confidence level represents the strength of surety the change point is accurate. Lastly, "before" and "after" are the cumulative mean values prior to the change point and after the change point.

5.2. T-TEST ANALYSIS OF ANNUAL DATA

T-test analyses were performed to determine if the period 1994-2007 experienced an increase in the number of mean annual GDD compared to the 1958-1993 period. T-test analyses indicated the annual GDD during the period 1994-2007 were significantly higher ($p < 0.05$) than the period 1958-1993 at nearly all stations, with the exception of Del Norte 2E at which all annual GDD values decreased significantly (Table 3.3). Analysis indicated Del Norte 2E mean values of $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$, were lower during the 1994-2007 period by 0.10, 0.14, 0.13, respectively. The analyses of the mean annual GDD values for Alamosa AP indicated that station experienced significant increase in GDD, however these were the lowest increases with mean values $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$, increasing by 0.17, 0.26 and 0.25, respectively. The highest increases occurred at Manassa with mean values of $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$, significantly higher during the 1994-2007 period by 0.23, 0.50, and 0.44, respectively. The analyses of all annual mean daily GDD values for each time period and station are presented in Table 3.3 and Figures 3.2, 3.3 and 3.4 illustrate the changes $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ at each station.

5.2. T-TEST ANALYSIS OF GROWING SEASON DATA

T-test analyses indicated the growing season GDD during the period 1994-2007 were significantly higher ($p < 0.05$) than the period 1958-1993 at nearly all stations except for Del Norte 2E at which all growing season mean daily GDD values decreased slightly. Analysis indicated Del Norte 2E mean values of GDD decreased for each $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$, by 0.03, 0.10, 0.09, respectively, but were not significantly lower during the latter period. The analysis of the growing season mean daily GDD values for Alamosa AP indicated that station experienced significant increases in GDD, however again these were the lowest increases with mean values with $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ increases of 0.32, 0.32, 0.35, respectively, for 1994-2007. The mean values of GDD for Center 4SSW indicate the greatest increases took place at this location with increases in $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ of 0.38, 0.81, 0.72, respectively, for 1994-2007. The analyses of the growing season mean daily GDD values are presented in Table 3.4 with Figures 3.5, 3.6, and 3.7 for graphs illustrating the changes $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ at each station.

## 6. Discussion

The alpine desert of the San Luis Valley (SLV), Colorado, is located just below the headwaters of the Rio Grande. Irrigated agriculture is the dominant industry of the Valley; it accounts for more than 30% of the Valley economy, employs greater than 50% of the local populous (SLVDG 2002) and covers more than 1.4 million ha. The arid conditions of the Valley cause agriculture to be entirely reliant on surface waters of the Rio Grande and groundwater reserves underlying the Valley for its irrigation needs. These water resources are in turn reliant on mountain precipitation, primarily snowmelt, for recharge. Mix et al. (2008) found climate change is increasing temperature in the Valley, and changing the timing of snowmelt. Research on SLV agriculture indicates climate change will impact agricultural production by increasing irrigation needs (Finnerty and Ramirez 1995, Ramirez and Finnerty 1996). The SLV community's dependence on irrigated agriculture puts it at risk of being highly sensitive to those changes.

As mentioned, increases in temperature, changes in phenology are occurring among several taxa in northern latitudes. These changes can be translated into changes in GDD, and shown to affect the timing of germination, growth and seed/fruit maturity, plant pest and disease distribution, abundance and synchrony (Visser and Both 2005). Increases in GDD may also exacerbate the need for irrigation as increases in growth will have a concomitant increase in crop evapotranspiration (Adams 1989, Schimmelpfennig et al. 1996, Ramirez and Finnerty 1996).

Analysis of the annual and growing season GDD for all bases at the seven valley floor stations indicated all stations, except Del Norte 2E, experienced significantly more GDD during the 1994-2007 period. The increase of GDD would be expected as Mix et al. (2008) revealed an increase in annual mean temperature in the Valley of 0.6 – 1.47$^{\circ}$C and growing season mean temperature increased 0.33 – 1.15$^{\circ}$C, depending on the station. A similar study on Canadian weather stations indicated significant increases in GDD have occurred throughout the major growing regions there (Bonsal et al. 2001).

Growing degree days are an important predictive tool for agriculture. They are used to estimate the timing of emergence of insect pests, germination of crop seedlings, bloom set and maturity. Therefore, changes in GDD have the potential to disrupt the timing of developmental stages in crops and insect (pests or beneficials); thus creating asynchrony in several agricultural milieus (Parmesan 2006). The changes in insect phenology potentially could manifest as increases in number of pest generations, and changes in location or migration (i.e. arrival when the crop is sensitive to herbivory) (Bale et al. 2002). There is evidence that European corn borer will increase the number of generations per growing season with a 1°C increase in mean temperature (Porter et al. 1991), meaning the Valley could experience influxes of pest insects heretofore not present.

Currently, studies of climate change impacts on agriculture are equivocal; this arises from the heterogeneity of climate change (Adams et al. 1990, Schimmelpfennig et al. 1996, Reilly 2003). Within the U.S. there is evidence the plains states will experience greater negative impacts of climate change resulting from increased temperatures and reduced precipitation. The San Luis Valley, however, is an alpine desert and information regarding climate change in these types of ecosystems is scant. Nevertheless, Mix et al. (2008) reported a lagged increase in temperature response using change point analysis. Analysis of climate change in the SLV indicates temperature has risen similarly to global rises and this study indicates GDD are increasing, also. This is similar to IPCC (2001) report of lower increases in temperature higher in the atmosphere indicating altitude may provide ameliorating effects from climate change in the short run.

It has been noted in the later half of the 20th century global mean temperature increased significantly after 1976 (IPCC 2001), and it appears the Valley lagged behind that date by 15 – 20 years (Mix et al. 2008). Change point analysis indicated six stations experienced similar changes in GDD and began to experience those changes around the years 1993 – 1994. There is evidence that upper elevations did experience the onset of warming trends later than lower elevations (IPCC 2001) and Rebetez and Dobbertin (2004) report a possible lag effect of climate change in Alpine regions. One could reasonably expect there to be parallel changes and increases in GDD and the analyses proves this out. It should be noted however, that increases in GDD do not correspond in a linear relationship to increase in temperature as each crop has different bases and threshold temperatures moderating or exacerbating the increase in GDD.

Potato acreage in the SLV in 2005 was 23,400 ha with a yield of 385 cwt and was valued at nearly $200 million, more than 15 times the gross value of any other crop. Increases in potato growing season $GDD_{4.4}$ could possibly reduce the potato yield or quality as an increase in GDD can hasten maturity (Singh et al. 1998). Insect pests of potato like the peach potato aphid (*Myzus persicae*) have been shown to increase their abundance under expected temperature and $CO_2$ increases (Bezemer et al. 1998). Their parasitoids, *Aphidius matricariae*, also responded with increased fecundity. Further, diseases of potato have been shown to benefit from increases in temperature and GDD. Infection of poatoes caused by bacterial ring rot (causal organism *Corynebacterium sepedonicum*) is exacerbated by warmer climatic conditions (Manzer and Nelson 1987) and the advent of more $GDD_{4.4}$ would provide more ideal conditions for the disease to persist in the Valley. Hijmnas et al. (2000) predict a change in distribution and increased incidences of late blight (*Phytophthora infestans*) as northern latitudes warm.

In contrast to potato production in 2005 the SLV had approximately 104,000 ha in hay production, more than half of which is alfalfa. The gross revenue from this crop was $72 million. Growing season $GDD_{5.5}$ significantly increase by 35 – 72 additional GDD. This effectively adds 3 – 7 additional 24 hour periods for growth and could be beneficial for the crop by providing additional warmth and time for growth during the attenuated growing season of the SLV. However, irrigated alfalfa requires 2 to 3 acre feet of water and significant increases in growth would require increased irrigation (Finnerty and Ramirez 1995). The increases in GDD may also indicate insect pests, such as spittle bug and aphid species (Auchenorryncha: Cercopidae) (Whittaker and Tribe 1996), weevils (Coleoptera: Curculionidae) will be able to produce additional generations. Warmer temperatures, i.e. more $GDD_{5.5}$ are expected to increase the incidence of verticillium wilt (*Verticillium albo-atrum*) (Boland et al. 2004). Further, the growth of some fungi is promoted by cool wet conditions whereas other benefit from warm wet conditions. Therefore, fungal infestations by some pathogens may be reduced and others increased.

An increase in $GDD_{10}$ increases the potential for this and other diseases to affect barley, wheat and vegetable crops of the SLV. It has been demonstrated that pathogens like the take-all fungus, *Gaeumannomyces graminis*, increase as heat accumulates throughout the growing season in winter wheat stands (Colbach et al. 1997). However, the present number and execution of studies evaluating the impacts of climate change on crops and their pests are equivocal as well.

Insect pests have been predicted to migrate to new regions as the climate shifts (Brasier and Scott 1994). Porter et al. (1991) has found potential increases in number and distribution to higher latitudes of European corn borer (*Ostrinia nubialis*), a common pest of many crops. Woiwod (1997) and Hassall et al. (2007) found several species of Lepidoptera were flying earlier, hence earlier herbivory by their caterpillars. Fleming and Candau (1998) modeled expected increases in Spruce bud worm outbreaks affecting forestry management in Canada.

Lastly, without additional irrigation, or new varieties, an increase in GDD has potential to hasten maturation at the cost of yield (weight/volume) for $C_3$ plants (alfalfa, wheat, barley oats) which comprise the majority of SLV crops (Singh et al. 1998).

## 7. Conclusion

The San Luis Valley is an important agricultural system both locally and regionally. It employs more than 50% of the Valley's inhabitants and is responsible for producing nearly 100% of the state of Colorado's potatoes. Further, $C_4$ and $C_3$ plants respond differently to increases in $CO_2$ concentrations. And, $CO_2$ concentrations are the leading cause of climate change (IPCC 2001 and 2007). However, more than increases in $CO_2$ will impact agriculture; there are predicted increases in temperature and GDD, as well as changes in precipitation. The major crops in the Valley, alfalfa, potatoes and cereals are all $C_3$ crops and would be expected to have reduced yields from increased GDD forcing early maturity (Singh et al. 1998) and increased evapotranspiration predicted in other analyses (Finnerty and Ramirez 1995).

There is clear evidence the number of GDD have increased significantly in the SLV. Annually, there are approximately 57 more $GDD_{10}$ in the Valley, 120 more $GDD_{4.4}$

(potato) and 108 more $GDD_{5.5}$ (alfalfa). However, when viewing the growing season separately, increases in GDD are even more pronounced, indicating climate is changing disproportionately during the growing season. The approximate increases in growing season $GDD_{10}$, $GDD_{4.4}$, $GDD_{5.5}$ are 118, 213, and 198, respectively. Recognizing this disproportionate increase during the growing season further investigation into changes in temperature, GDD and season length should be conducted to determine where within the season these changes are occurring as increases in GDD may be a result of a lengthened freeze free period rather than daily increases in GDD.

Beneficial impacts of increases in GDD in the SLV have potential to increase opportunities for agriculture by decreasing the number of days per season necessary to produce a crop. Increased GDD may also provide greater opportunities for crop selection or cropping methods. However, negative impacts include increased irrigation needs; investment in newer irrigation methods may be necessary as increases in daily and growing season GDD will increase crop water needs. Lastly, increases in GDD have been shown to increase the presence of pests and disease, and reduce yield and quality as plants are forced to mature.

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**Tables Figures**

Table 3.1. Location and elevation of each station.

| Stations | Location | Elevation in meters |
|---|---|---|
| *Valley floor stations* | | |
| Alamosa AP | 37°26'N / 105°52'W | 2296.1 |
| Blanca 4NW | 37°29'N / 105°34'W | 2349.7 |
| Center 4SSW | 37°42'N / 106°09'W | 2338.7 |
| Del Norte 2E | 37°40'N / 106°19'W | 2396.9 |
| GSDNM | 37°44'N / 105°31'W | 2475.0 |
| Manassa | 37°10'N / 105°56'W | 2343.9 |
| Monte Vista 2W | 37°35'N / 106°11'W | 2344.5 |

Table 3.2. Results of change point analysis for weather stations on the floor of the San Luis Valley, Colorado. Change point year indicates when the change is estimated to have occurred, confidence interval indicates the period when the change occurred and confidence level is the degree of surety the change point year is correct. Before and after indicate the temperature values in Celsius before the change point and after for annual maximum, minimum and mean temperatures.

| *Station* | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| ALAMOSA AP | | | | | |
| $GDD_{10}$ | 2000 | 1994-2000 | 95 | 1365.8 | 1501.0 |
| $GDD_{4.4}$ | 1999 | 1990-2000 | 97 | 2249.9 | 2420.1 |
| $GDD_{5.5}$ | 1999 | 1991-2000 | 98 | 2053.3 | 2222.7 |
| BLANCA 4NW | | | | | |
| $GDD_{10}$ | 2000 | 1988-2000 | 100 | 1342.6 | 1458.7 |
| $GDD_{4.4}$ | 1996 | 1989-1999 | 100 | 2219.2 | 2394.9 |
| $GDD_{5.5}$ | 1999 | 1992-1999 | 100 | 2030.5 | 2213.8 |
| CENTER 4SSW | | | | | |
| $GDD_{10}$ | 1970 | 1967-1972 | 100 | 1377.2 | 1224.0 |
| | 1988 | 1985-1993 | 100 | 1224.0 | 1342.8 |
| $GDD_{4.4}$ | 1971 | 1968-1974 | 100 | 2258.0 | 2054.7 |
| | 1995 | 1992-1997 | 100 | 2054.7 | 2280.0 |
| $GDD_{5.5}$ | 1970 | 1967-1973 | 100 | 2062.9 | 1872.2 |
| | 1995 | 1991-1998 | 100 | 1972.2 | 2069.6 |
| DEL NORTE 2E | | | | | |
| $GDD_{10}$ | 1977 | 1968-1978 | 98 | 1247.4 | 1336.8 |
| | 1990 | 1989-1994 | 92 | 1336.8 | 1242.8 |
| | 2004 | 1991-2005 | 94 | 1242.8 | 1179.5 |
| $GDD_{4.4}$ | 1977 | 1968-1981 | 96 | 2160.1 | 2289.0 |
| | 1990 | 1988-1998 | 96 | 2289.0 | 2131.9 |
| $GDD_{5.5}$ | 1977 | 1967-1981 | 95 | 1950.6 | 2064.0 |
| | 1991 | 1991 | 96 | 2064.0 | 1811.0 |
| | 1994 | 1994-1996 | 92 | 1811.0 | 1992.2 |
| | 2004 | 2001-2004 | 92 | 1992.2 | 1813.4 |
| GSDNM* | | | | | |
| $GDD_{10}$ | No change | | | | |
| $GDD_{4.4}$ | No change | | | | |
| $GDD_{5.5}$ | No change | | | | |
| MANASSA | | | | | |
| $GDD_{10}$ | 1996 | 1987-2001 | 100 | 1339.0 | 1442.5 |
| $GDD_{4.4}$ | 1969 | 1969-1972 | 90 | 2338.9 | 2095.0 |
| | 1980 | 1975-1992 | 97 | 2095.0 | 2214.9 |
| | 1994 | 1989-1997 | 100 | 2214.9 | 2411.9 |
| $GDD_{5.5}$ | 1969 | 1969-1972 | 91 | 2134.9 | 1917.9 |
| | 1980 | 1974-1992 | 95 | 1917.9 | 2014.5 |
| | 1994 | 1989-1997 | 100 | 2014.5 | 2194.9 |
| MONTE VISTA 2W | | | | | |
| $GDD_{10}$ | 1982 | 1973-1982 | 99 | 1343.4 | 1165.3 |
| | 1991 | 1991 | 99 | 1165.3 | 1307.7 |
| | 2000 | 1997-2003 | 92 | 1307.7 | 1422.1 |
| $GDD_{4.4}$ | 1982 | 1971-1982 | 100 | 2226.8 | 2015.5 |
| | 1994 | 1994-1996 | 100 | 2015.5 | 2284.9 |
| $GDD_{5.5}$ | 1982 | 1971-1982 | 100 | 2027.7 | 1824.6 |
| | 1994 | 1994-1995 | 100 | 1824.6 | 2081.6 |

*Great Sand Dunes National Monument

Table 3.3. Results of t-test analysis for annual growing degree days (GDD) occurring in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the GDD base tested.

| | | 1958-1993 | | | | 1994-2007 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| $GDD_{10}$ | 12992 | 3.79 | 3.63 | 0.03 | 5086 | 3.96 | 3.69 | 0.05 | 0.17 | 0.0022 |
| $GDD_{4.4}$ | 12992 | 6.24 | 5.02 | 0.04 | 5086 | 6.49 | 4.98 | 0.07 | 0.26 | 0.0010 |
| $GDD_{5.5}$ | 12992 | 5.69 | 4.74 | 0.04 | 5086 | 5.95 | 4.75 | 0.07 | 0.25 | 0.0006 |
| Blanca 4NW | | | | | | | | | | |
| $GDD_{10}$ | 12081 | 3.74 | 3.62 | 0.03 | 4816 | 3.90 | 3.66 | 0.05 | 0.16 | 0.0041 |
| $GDD_{4.4}$ | 12081 | 6.18 | 5.04 | 0.05 | 4816 | 6.59 | 5.12 | 0.07 | 0.41 | <0.0001 |
| $GDD_{5.5}$ | 12081 | 5.64 | 4.76 | 0.04 | 4816 | 6.00 | 4.86 | 0.07 | 0.36 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| $GDD_{10}$ | 13138 | 3.54 | 3.41 | 0.03 | 4892 | 3.66 | 3.54 | 0.05 | 0.12 | 0.0171 |
| $GDD_{4.4}$ | 13138 | 5.83 | 4.70 | 0.04 | 4892 | 6.17 | 4.97 | 0.07 | 0.34 | <0.0001 |
| $GDD_{5.5}$ | 13138 | 5.30 | 4.42 | 0.04 | 4892 | 5.60 | 4.67 | 0.07 | 0.30 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| $GDD_{10}$ | 13045 | 3.48 | 3.30 | 0.03 | 5034 | 3.38 | 3.27 | 0.05 | *-0.10* | 0.0307 |
| $GDD_{4.4}$ | 13045 | 6.00 | 4.79 | 0.04 | 5034 | 5.87 | 4.72 | 0.07 | *-0.14* | 0.0404 |
| $GDD_{5.5}$ | 13045 | 5.43 | 4.47 | 0.04 | 5034 | 5.29 | 4.41 | 0.06 | *-0.13* | 0.0368 |
| GSDNM* | | | | | | | | | | |
| $GDD_{10}$ | 13031 | 3.41 | 3.57 | 0.03 | 5016 | 3.59 | 3.72 | 0.05 | 0.18 | 0.0017 |
| $GDD_{4.4}$ | 13031 | 5.92 | 5.29 | 0.05 | 5016 | 6.30 | 5.51 | 0.08 | 0.38 | <0.0001 |
| $GDD_{5.5}$ | 13031 | 5.36 | 4.95 | 0.04 | 5016 | 5.70 | 5.17 | 0.07 | 0.34 | <0.0001 |
| Manassa | | | | | | | | | | |
| $GDD_{10}$ | 11700 | 3.75 | 3.51 | 0.03 | 4836 | 3.98 | 3.60 | 0.05 | 0.23 | <0.0001 |
| $GDD_{4.4}$ | 11700 | 6.21 | 4.82 | 0.04 | 4836 | 6.70 | 5.02 | 0.07 | 0.50 | <0.0001 |
| $GDD_{5.5}$ | 11700 | 5.65 | 4.55 | 0.04 | 4836 | 6.10 | 4.74 | 0.07 | 0.44 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| $GDD_{10}$ | 11649 | 3.55 | 3.45 | 0.03 | 4942 | 3.80 | 3.52 | 0.05 | 0.24 | <0.0001 |
| $GDD_{4.4}$ | 11649 | 5.90 | 4.82 | 0.04 | 4942 | 6.33 | 4.81 | 0.07 | 0.43 | <0.0001 |
| $GDD_{5.5}$ | 11649 | 5.37 | 4.53 | 0.04 | 4942 | 5.76 | 4.55 | 0.06 | 0.39 | <0.0001 |

*Great Sand Dunes National Monument

Table 3.4. Results of t-test analysis for growing season growing degree days (GDD) occurring in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the GDD base tested.

| | 1958-1993 | | | | 1994-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| GDD - base 10 | 5496 | 7.29 | 2.20 | 0.03 | 2128 | 7.61 | 2.10 | 0.05 | 0.32 | <0.0001 |
| GDD - base 4.4 | 5496 | 11.02 | 2.88 | 0.04 | 2128 | 11.34 | 2.70 | 0.06 | 0.32 | <0.0001 |
| GDD - base 5.5 | 5496 | 10.22 | 2.75 | 0.04 | 2128 | 10.57 | 2.62 | 0.06 | 0.35 | <0.0001 |
| Blanca 4NW | | | | | | | | | | |
| GDD - base 10 | 5118 | 7.23 | 2.26 | 0.03 | 2032 | 7.43 | 2.26 | 0.05 | 0.21 | 0.0002 |
| GDD - base 4.4 | 5118 | 10.97 | 3.00 | 0.04 | 2032 | 11.49 | 3.08 | 0.07 | 0.52 | <0.0001 |
| GDD - base 5.5 | 5118 | 10.16 | 2.87 | 0.04 | 2032 | 10.63 | 2.98 | 0.07 | 0.47 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| GDD - base 10 | 5503 | 6.84 | 2.07 | 0.03 | 1988 | 7.22 | 2.10 | 0.05 | 0.38 | <0.0001 |
| GDD - base 4.4 | 5503 | 10.31 | 2.61 | 0.04 | 1988 | 11.12 | 2.78 | 0.06 | 0.81 | <0.0001 |
| GDD - base 5.5 | 5503 | 9.53 | 2.46 | 0.03 | 1988 | 10.25 | 2.65 | 0.06 | 0.72 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| GDD - base 10 | 5463 | 6.64 | 2.00 | 0.03 | 2082 | 6.61 | 1.97 | 0.04 | *-0.03* | 0.3009 |
| GDD - base 4.4 | 5463 | 10.56 | 2.76 | 0.04 | 2082 | 10.46 | 2.74 | 0.06 | *-0.10* | 0.0766 |
| GDD - base 5.5 | 5463 | 9.67 | 2.59 | 0.04 | 2082 | 9.58 | 2.55 | 0.06 | *-0.09* | 0.0882 |
| GSDNM* | | | | | | | | | | |
| GDD - base 10 | 5439 | 6.84 | 2.55 | 0.03 | 2110 | 7.22 | 2.55 | 0.06 | 0.37 | <0.0001 |
| GDD - base 4.4 | 5439 | 10.97 | 3.62 | 0.05 | 2110 | 11.69 | 3.52 | 0.08 | 0.72 | <0.0001 |
| GDD - base 5.5 | 5439 | 10.07 | 3.44 | 0.05 | 2110 | 10.73 | 3.39 | 0.07 | 0.66 | <0.0001 |
| Manassa | | | | | | | | | | |
| GDD - base 10 | 4844 | 7.18 | 2.05 | 0.03 | 2012 | 7.54 | 1.97 | 0.04 | 0.37 | <0.0001 |
| GDD - base 4.4 | 4844 | 10.83 | 2.67 | 0.04 | 2012 | 11.60 | 2.73 | 0.06 | 0.78 | <0.0001 |
| GDD - base 5.5 | 4844 | 10.02 | 2.53 | 0.04 | 2012 | 10.72 | 2.60 | 0.06 | 0.70 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| GDD - base 10 | 4780 | 6.97 | 2.05 | 0.03 | 2055 | 7.25 | 2.03 | 0.04 | 0.29 | <0.0001 |
| GDD - base 4.4 | 4780 | 10.59 | 2.71 | 0.04 | 2055 | 10.97 | 2.70 | 0.06 | 0.38 | <0.0001 |
| GDD - base 5.5 | 4780 | 9.78 | 2.56 | 0.04 | 2055 | 10.15 | 2.55 | 0.06 | 0.36 | <0.0001 |

*Great Sand Dunes National Monument

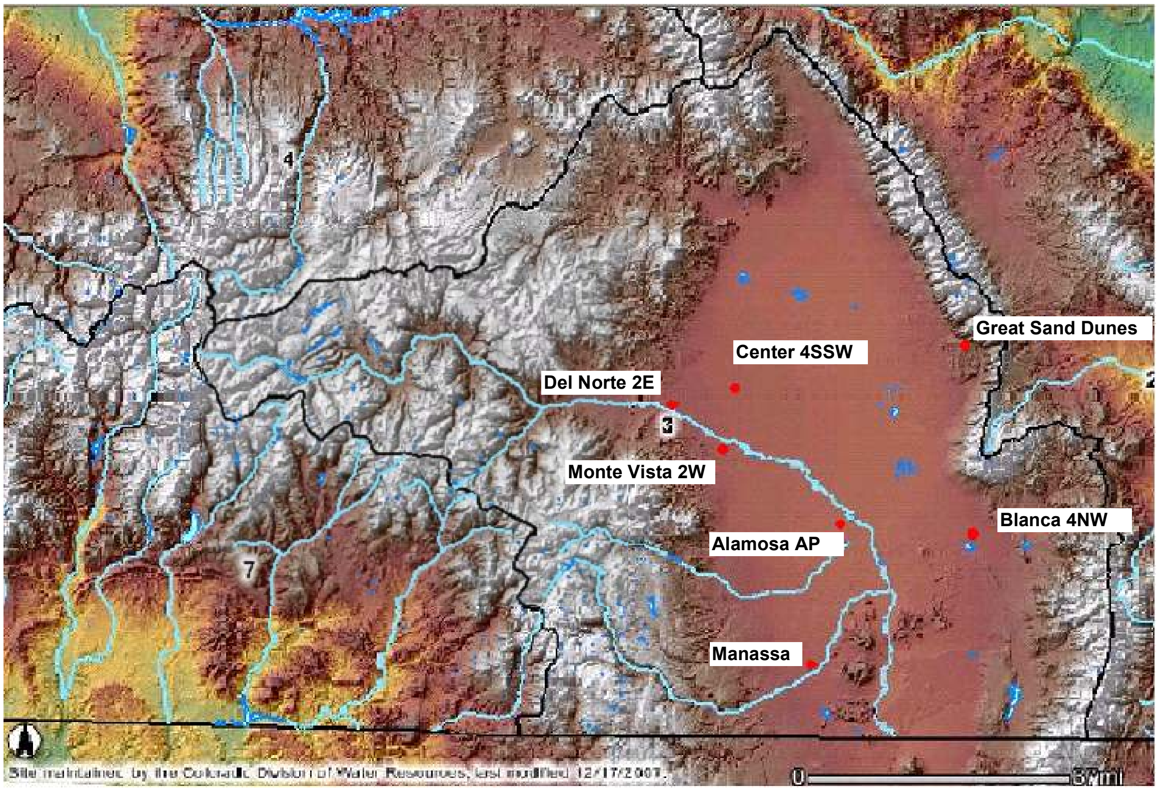


Figure 3.1. Map depicting the locations of each station in the San Luis valley, Colorado. Map source: Colorado Decision Support System

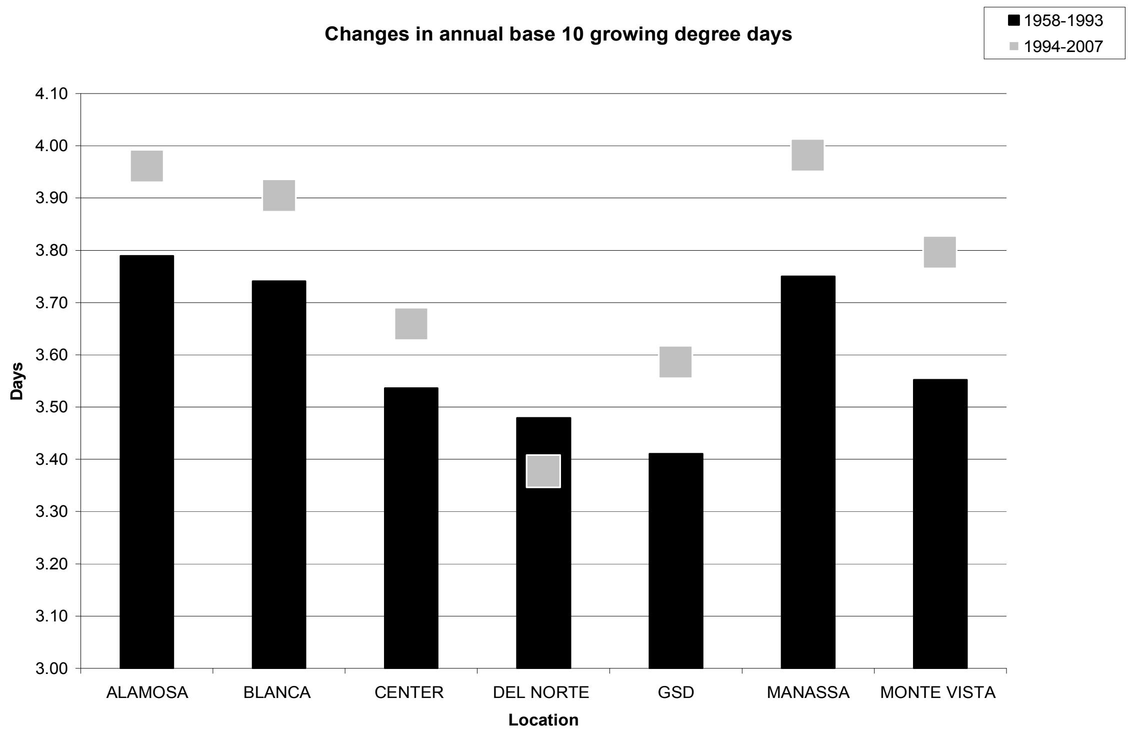


Figure 3.2. Comparison of 1958-1993 (bar) average annual $GDD_{10}$ to 1994-2007 (square) average annual $GDD_{10}$ for each valley floor station in the San Luis Valley, Colorado.

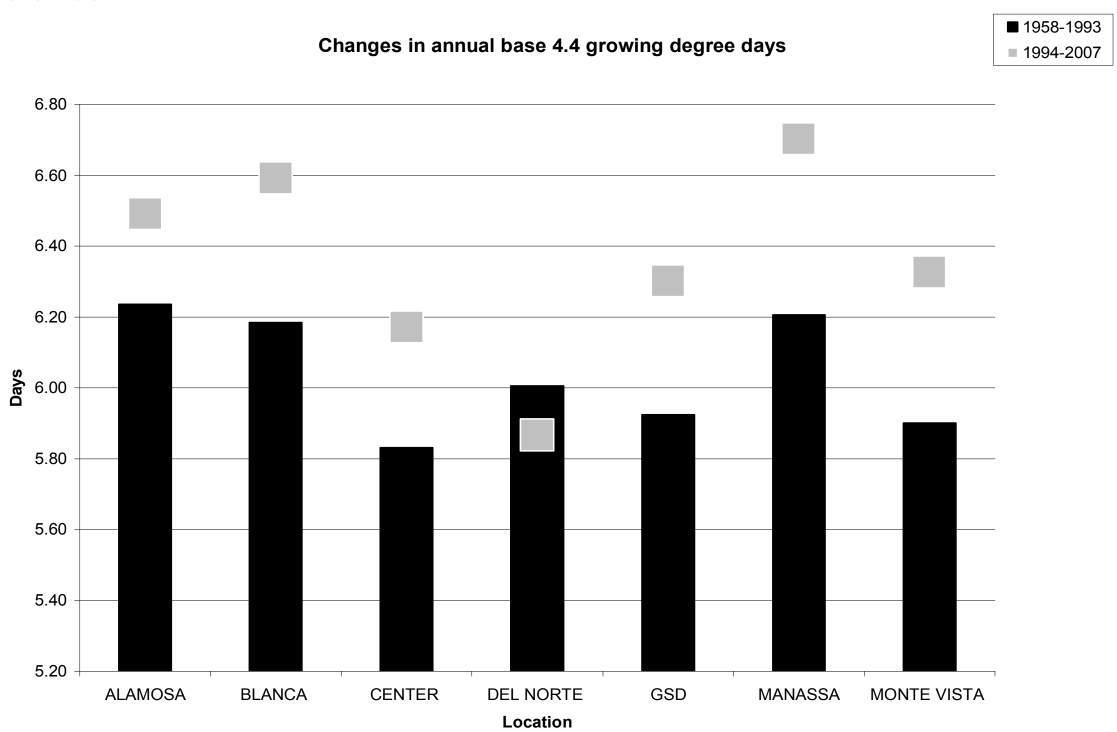


Figure 3.3. Comparison of 1958-1993 (bar) average annual $GDD_{4.4}$ to 1994-2007 (square) average annual $GDD_{4.4}$ for each valley floor station in the San Luis Valley, Colorado.

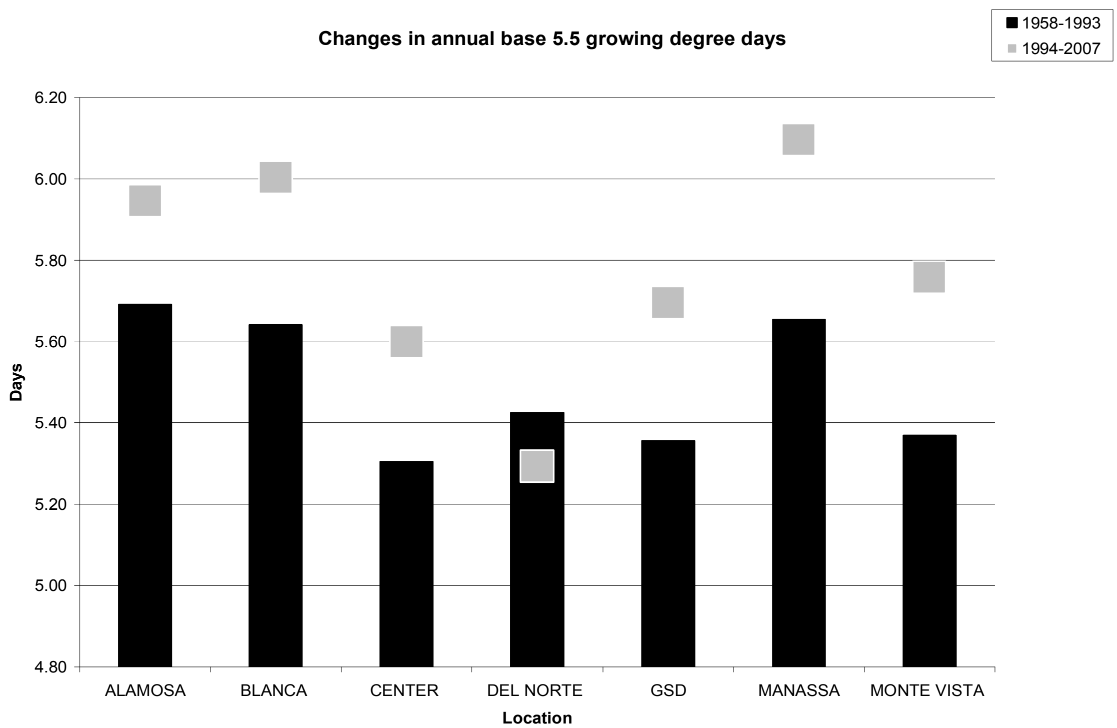


Figure 3.4. Comparison of 1958-1993 (bar) average annual $GDD_{5.5}$ to 1994-2007 (square) average annual $GDD_{5.5}$ for each valley floor station in the San Luis Valley, Colorado.

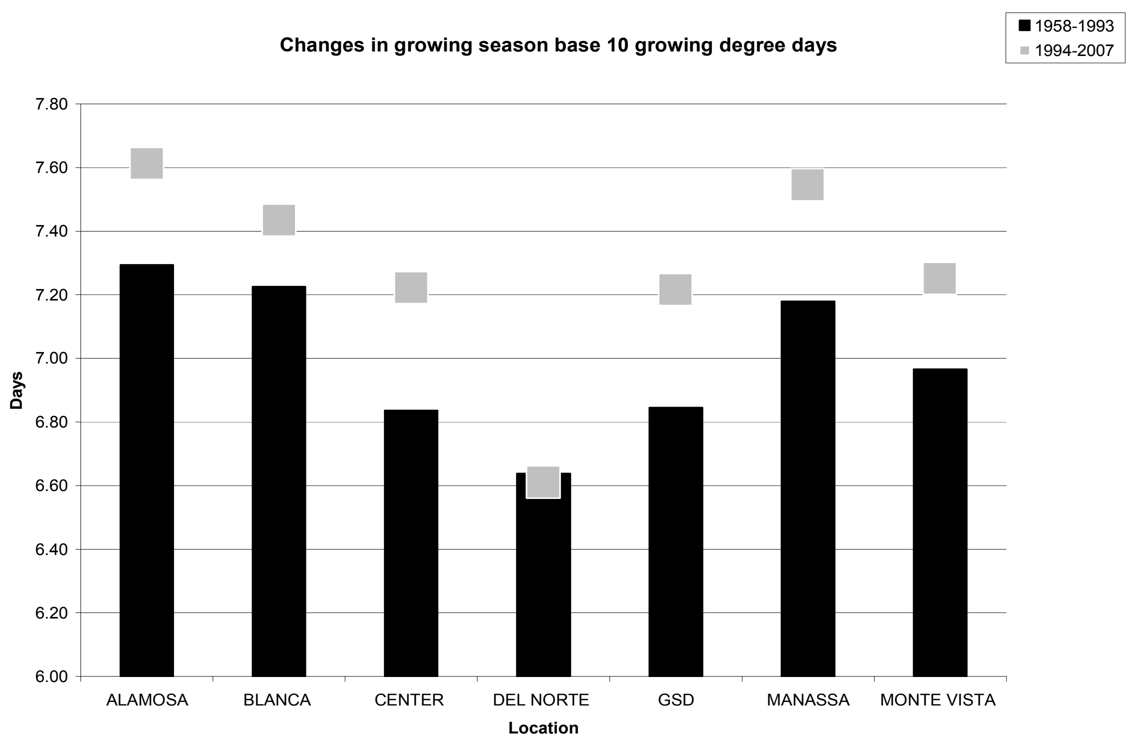


Figure 3.5. Comparison of 1958-1993 (bar) average growing season $GDD_{10}$ to 1994-2007 (square) average growing season $GDD_{10}$ for each valley floor station in the San Luis Valley, Colorado.

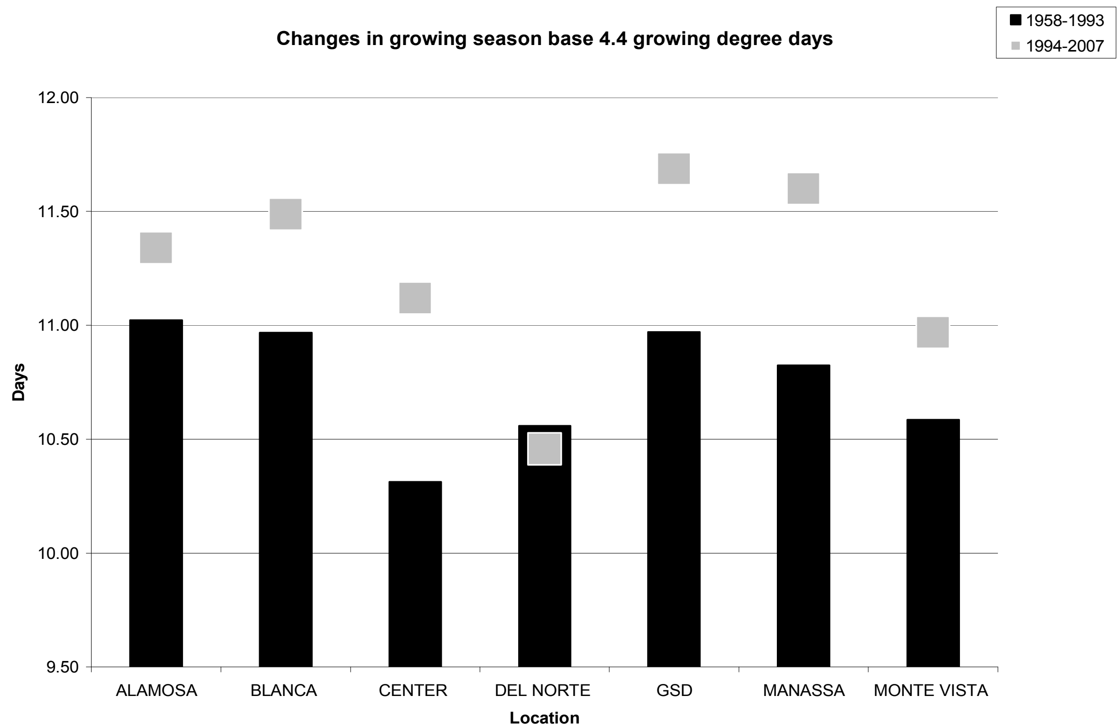


Figure 3.6. Comparison of 1958-1993 (bar) average growing season $GDD_{4.4}$ to 1994-2007 (square) average growing season $GDD_{4.4}$ for each valley floor station in the San Luis Valley, Colorado.

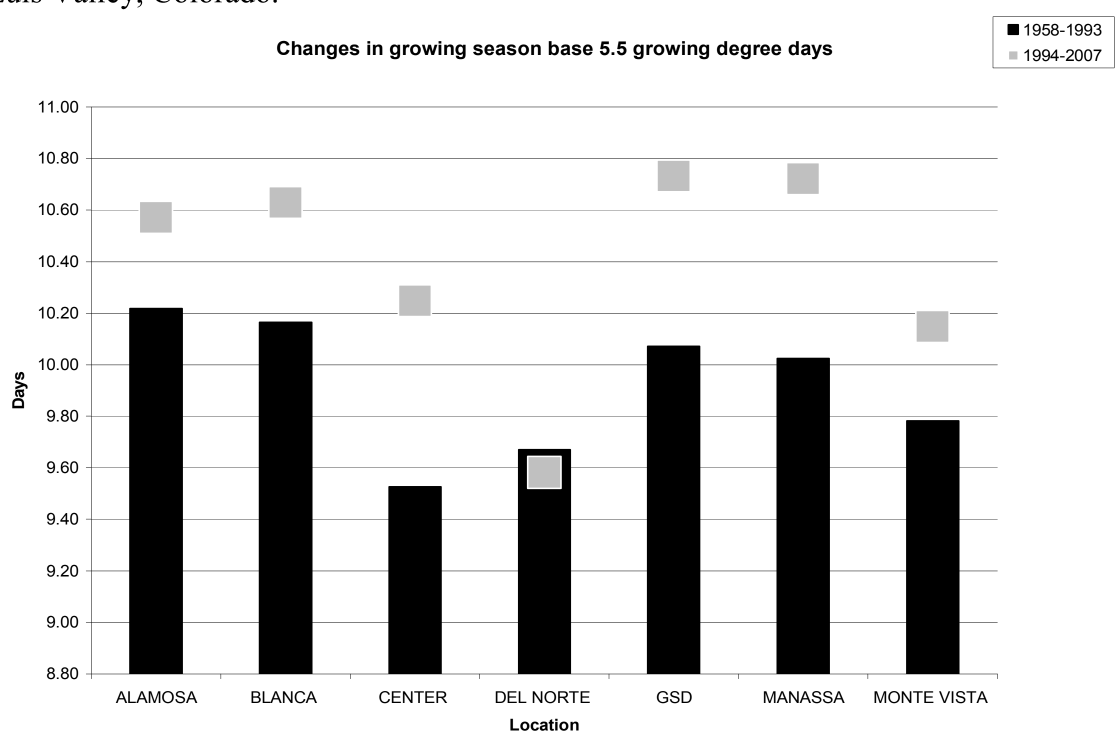


Figure 3.7. Comparison of 1958-1993 (bar) average growing season $GDD_{5.5}$ to 1994-2007 (square) average growing season $GDD_{5.5}$ for each valley floor station in the San Luis Valley, Colorado.

## CHAPTER 4

# GROWING SEASON EXPANSION AND RELATED CHANGES IN MONTHLY TEMPERATURE AND GROWING DEGREE DAYS IN THE ALPINE DESERT OF THE SAN LUIS VALLEY, COLORADO

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**Abstract.** Most alpine ecosystems climate change studies identify changes in biota, several report abiotic factors; few to none report expansion of the freeze-free period or discuss monthly changes of temperature and growing degree days (GDD) during the growing season. This study provides initial data on agriculturally related aspects of climate change during the growing season (M-J-J-A-S) in the alpine desert of the San Luis Valley (SLV). Temperature data were gathered from weather stations within the SLV. Based on Julian dates the last vernal freeze is occurring ($p < 0.05$) earlier by 5.52 to 11.86 days, at 3 stations during 1981-2007. Significantly later autumnal freezes are occurring at 5 stations by 5.95 to 18.10 days and expansion of the freeze-free period was significantly longer at all stations by 7.20 to 24.21 days. Prior to the 1980's the freeze-free period averaged about 93 days and now averages about 107 days. Increases ($p < 0.05$) in daily mean, maximum, minimum temperature occurred at nearly all stations for each month. Increases in $GDD_{10}$, $GDD_{4.4}$ (potato) and $GDD_{5.5}$ (alfalfa) also occurred at nearly all stations for all months, during 1994-2007. Higher temperatures increase numbers of GDD, quickening growth of crops and maturity, and potentially reduce yield and quality.

***Keywords:*** *Growing degree days, climate change, alpine, agriculture, freeze-free period, growing season*

## 1. Introduction

The most important element determining the suitability and type of agricultural production in a given area is the prevailing annual climatic conditions present at that location. The freeze-free period, growing season length, mean minimum and maximum daily temperature, number of growing degree days (GDD), precipitation and even soil type are all determined, in part or in total, by the climate. Of those only precipitation can be totally augmented by the farmer through irrigation.

Climate change, therefore, has potential to impact local growing conditions by changing the date of the last vernal and first autumnal freeze, the length of the growing season, daily temperature and number of GDD. The leading theory explaining the cause of climate change and global mean temperature rise is the evolution of anthropogenic $CO_2$ as a result of fossil fuel combustion. Accordingly, increases in $CO_2$ concentrations in the troposphere are trapping heat in the lower few kilometers of the atmosphere. Historical data indicate $CO_2$ concentrations have risen from approximately 280 ppm in the 1800's to about 360 ppm today (IPCC 2001). This has resulted in a global increase of mean annual temperature of approximately $0.74 \pm 0.2^{\circ}C$ and decreased daily temperature asymmetry (IPCC 2007, Hansen et al. 2006). This can be seen in a mean annual maximum temperature rise of about $0.1^{\circ}C$ per decade compared to $0.2^{\circ}C$ per decade for mean annual minimum temperature (IPCC 2001, Hansen et al. 2006).

The aforementioned changes are global; however climate change is not homogenous (Hansen and Lebedeff 1987, IPCC 2007). Changes in climate have occurred at different rates between latitudes (Hansen and Lebedeff 1987, Giorgi et al. 1994, Hansen et al. 2001) and altitudes (Bucher and Dessens 1991, Weber et al. 1994, Diaz and Bradley 1997, Rebetez and Dobbertin 2004). Dettinger and Cayan (1995) speculate there was less sensitivity to climate change prior to 1995 at higher elevations. This concurs with IPCC (2001) data which indicate a slower increase of temperature at upper altitudes of the atmosphere than surface temperatures. Rebetez and Dobbertin (2004) also report a possible lag effect of climate change in Alpine regions as climate related die offs of Scots pine (*Pinus sylvestris*) lagged global trends.

### 1.1. AGRICULTURAL IMPLICATIONS OF CLIMATE CHANGE

The negative and positive impacts of climate change on agriculture are variable according to location and topic. The potential beneficial impacts include atmospheric fertilization by higher $CO^2$ concentrations. Higher $CO^2$ concentrations have been shown to increase photosynthetic activity, growth and water use efficiency (Bowes 1993; Drake, González Meier and Long 1997; Wand et al. 1999). Increased temperatures can lengthen the growing season and reduce the risks of late freezes. Increases in the number of GDD can reduce the production time frame and possibly allow for double cropping.

Negative impacts include increased crop water needs from increased rate of growth and reduced soil moisture content from increased temperature (Rosenzweig et al. 2000). Pollen death from high temperatures can result in low yields from poor pollination. Reduction of yield also occurs from forced early maturation as GDD increases reduce the length of time between germination and senescence (Singh et al. 1998). Further negative impacts include climate change induced changes synchrony of beneficial insects and pests, which include timing of pollination, distribution and range and voltinism of insect pests and disease distribution and emergence.

Agricultural crops are generally categorized into 3 types, $C_3$, $C_4$ and CAM, according to their carbon utilization pathways (Sombroek and Gommes 1996). $C_3$ plants are adapted to more mesic and lower light intensity regions, while $C_4$ plants are adapted to higher light more arid regions and utilize $CO_2$ in a manner that reduces water stress under arid conditions. Common $C_3$ agricultural crops include alfalfa, barley, oats, wheat, beans (including soy), sweet and white potatoes and rice. $C_4$ agricultural crops include maize, millet, sorghum and sugarcane and CAM agricultural and horticultural crops include orchids, blue agave, onions and pineapple. Some experimental models indicate climate change will reduce yields of $C_3$ crops and increase yields of $C_4$ and CAM crops (Easterling et al. 1993, Singh et al. 1998); there is still equivocation on the topic.

Increased temperatures are expected to exacerbate the need for irrigation as increases in crop evapotranspiration will occur (Adams 1989, Schimmelpfennig et al. 1996, Fischer et al. 1996, Ramirez and Finnerty 1996). Though, Ramirez and Finnerty (1996) point out crop production will need additional water to reduce the impact of increased temperatures they also indicate increased $CO_2$ concentrations may result in a greater income per hectare as crop production increases, even in light of increasing water needs. Further, higher daily temperatures may affect crop pollination or speed maturation at the cost of yield (weight/volume). Applied climate change scenarios indicate temperature increases will cause worldwide decreases in production, with U.S. production exhibiting variable outcomes based on regional changes in precipitation (Fischer et al. 1996, Reilly et al. 2003). It should be noted predictions of changes in agricultural production are equivocal (Fischer et al. 1996, Sombroek and Gommes 1996). Ultimately, Easterling et al's (1993 and 2001) final comments, when factoring changes in precipitation, temperature, $CO_2$ concentrations, crop adaptations and adaptive technology, indicate most all negative effects of climate change will be offset and a near zero net loss in yield will result, with possible increases.

## 1.2. CHANGES IN PHENOLOGY

Temperature changes are important to agriculture as temperature triggers changes in phenology; the timing of developmental stages in crops, beneficial insects and pests. Many studies have reported climate change related shifts in phenology of insects, crop and pest plants, and disease distributions, synchrony and emergence, insect fecundity or disease virility (Bradley et al. 1999, Chakraborty et al. 2000, Rosenzweig et al. 2000, Beaubien and Freeland 2000, McCarty 2001, Walther et al. 2002, Thuiller et al. 2005, IPCC 2007). Phenological shifts have been recorded in birds as well as evidenced by earlier migration and breeding activity among 20 species of shorebirds and passerines (MacInnes et al. 1990, Crick et al. 1997, Winkle and Hudde 1997, McCleery and Perrins 1998, Dunn and Winkler 1999, Slater 1999, Brown et al. 1999). This may possibly be related to phenological shifts in invertebrates as birds rely heavily upon that taxon for food.

Changes in phenology have been implicated to adversely impact agriculture or forestry. These adverse impacts manifest themselves as increases in insect abundance, distribution, prevalence, voltinism, and changes in synchrony (Manzer and Nelson 1987, Porter et al. 1991, Colbach et al. 1997, Woiwod 1997, Fleming and Candau 1998, Rosenzweig 2000, Losey and Vaughan 2006). Changes in insect prey/predator synchrony relationships have potential for severe economic losses. Insects provide $3 billion worth of beneficial services through pollination, predation and parasitoid activity. In the U.S. insect predators as pest control measure for crops currently account for an additional $26 billion in natural capital (Rosenzweig 2000). Therefore the impact of changes in phenology could potentially cause large economic losses.

Observations of plant phenology indicate changes in this taxon as well. Early inflorescence is occurring in several species (Beaubien and Freeland 2000) with bloom time earlier by 8.2 – 19.8 days in several species (Bradley et al. 1999, Cayan et al. 2001). These changes in phenology indicate the growing season in the northern hemisphere has increased by 7 – 12 days (Keeling et al. 1996, Myneni et al. 1997, Menzel and Fabian 1999, Walther et al. 2002).

### 1.3. GROWING DEGREE DAYS

Phenological advancement can be numerically quantified. This can then be used to predict or estimate the timing of developmental stages of a particular species. It is calculated by summing the accumulated heat units necessary for a particular organism to develop. These heat units are commonly referred to as growing degree days (GDD). As early as 1735, René-Antoine Ferchault de Réaumur (de Reaumur 1735) recognized temperature affected phenology and introduced the concept of growing degree days. He postulated that in order to initiate growth and to develop or mature organisms needed to accumulate a number of heat units unique to that organism. It is extensively used in agriculture to estimate days to germination, bloom or maturity (Hartz and Moore 1978, Snyder et al. 1999, Kim et al. 2000). Further, it can be used to predict regional distributions of organisms; i.e. crops, insect and plant pests.

Growing degree days are calculated from daily temperature data. The mean value of the daily maximum and minimum temperatures is defined and base value is subtracted. The base values are unique to each species and represent the lower temperature threshold for growth (Breazeale et al., Derscheid and Lytle 1981). There is also a maximum temperature threshold, above which the specific organism is dormant. Thus the maximum and minimum temperature thresholds used to derive the GDD are specific for each species and in agriculture specific for certain varietals.

The principal crops of the San Luis Valley are $C_3$ crops: alfalfa/grass hay, potato, mixed cereals and vegetables. In general, for crops $GDD_{10}$ can be used in most cases; however specifically $GDD_{5.5}$ is used for alfalfa and $GDD_{4.4}$ for potato and cereals (base refers to the lower temperature threshold in degrees Celcius). Because of the variability between species and crops climate change may not affect each equally, but rather may benefit some while harming others. For instance, base 10 maximum and minimum thresholds are 30°C and 10°C, growth is estimated to only occur within those ranges.

There is a well known and understood relationship between GDD and crop production, plant growth and insect development (Hartz and Moore 1978, Frank and Hofmann 1989, Power 2002, Ojeda-Bustamante et al. 2004). Many developmental stages in plants are triggered by accumulated GDD. Thermal dormancy is controlled by GDD; this is a period of time when germination, leaf unfurling (bud burst) or bloom set is suspended until triggered by changes in temperature (Cannell and Smith 1983, Snyder et al. 1999, Grundy et al. 2000). Accumulation of GDD also triggers plants to begin initiating changes such as seed/fruit maturation and senescence (Snyder et al. 1999, Aber et al. 1995). Ramankutty et al. (2002) have utilized GDD to predict the sensitivity of agricultural regions to climate change. GDD are also utilized to estimate the emergence of agricultural pests and disease (Pscheidt and Stevenson 1988, Kim et al. 2000).

Climate change has several aspects which affect agriculture. Changes in temperature alone impact growth and evapotranspiration. Temperature changes also change GDD which in turn affect phenology; maturation of fruit, emergence of pests and disease, synchrony of beneficials and bloom time are all determined by accumulated GDD. Lastly, increases in $CO_2$ concentrations have ameliorating effects that Easterling et al. (1993, 2001) have indicated may offset any negative impacts of climate change.

## 2. Objectives

This study addresses climate variables and potential effects on agriculture in the SLV, which can be considered a region of international importance as it is located just below the headwaters of the Rio Grande. Climate change has the potential to manifest itself as an expanded freeze-free period, higher monthly temperatures and increased number of GDD during the growing season. All of these factors influence agricultural practices and yield. Few studies have reported an expansion of the freeze-free period, changes in growing season monthly temperature and GDD resulting from climate change; very few report changes in alpine ecosystems and none have been found reporting these changes in the San Luis Valley. Therefore the objectives of this study were to determine in the length of the growing season, increases in monthly temperature and GDD occurred in the SLV in the mid– to late– 20$^{th}$ and early–21$^{st}$ Centuries. The growing season is defined as May thru September as these are the primary months for heat accumulation, however some crops may be planted in late March and April. The freeze-free period is defined as that which occurs between the last vernal freeze and first fall freeze.

### 3. Study area

Located in south central Colorado, the SLV is roughly bisected by the Rio Grande. The river rises in the western San Juan Mountains, which form the western boundary of the SLV and the eastern boundary is formed by the Sangre de Cristo Mountains. The elevation of the SLV is approximately 2300 m. The region regularly experiences low wintertime temperatures of less than -20$^{\circ}$ and as low as -40$^{\circ}$C (NCDCa, b). It ranks in the top 20 coldest locations in North America (King 2007). Warm season temperatures reach the 30’s C, but the warm season only lasts 90-110 days. The Valley receives less than 20 cm of precipitation annually as it is in the rain shadow of the San Juan Mountains to the west which receive 100-200 cm of precipitation annually.

Even though the Valley is arid, it is a major agricultural region for the state of Colorado, producing the majority of the state’s potato crop (14,000 – 30,000 ha) and a large portion of its alfalfa crop (80,000 – 100,000 ha) (CSUa 2003). This results in irrigated agriculture being the dominant industry of the Valley; it accounts for more than 30% of the Valley economy, employs greater than 50% of the local populous (SLVDG 2002) and covers more than 1.4 million ha. The arid conditions of the Valley cause agriculture to be entirely reliant on surface waters of the Rio Grande and groundwater reserves underlying the Valley; virtually all agriculture is irrigated (CSUb 2003) to compensate for aridity of the Valley.

Weather stations in the SLV were selected on the basis of several criteria: location, length of record and period of record common to all stations. Their respective locations and elevation are presented in Table 4.1. The earliest common date for all stations was 1958, with the common period of record being 1958-2007. Three stations are located along the Rio Grande riparian zone: Del Norte 2E (ele. 2396.9 m), Monte

Vista 2W (ele. 2344.5 m), and Alamosa AP (ele. 2296.1 m) (in upstream to downstream order). Two stations, Manassa (ele. 2343.9 m) and Center 4SSW (ele. 2338.7 m), are located south and north, respectively, in the interior of the Valley, while two stations, Blanca 4NW (ele. 2349.7 m) and Great Sand Dunes National Monument (GSDNM) (ele. 2475.0 m), are located north and south, respectively, along the eastern edge of the Valley. A map depicting the locations of the stations within the Valley is shown in Figure 4.1.

## 4. Methods

Daily maximum, minimum and mean temperature data were gathered from the NCDC for the years 1958-2007. To determine changes in the freeze-free period Julian dates for the last vernal freeze (minimum temperature at or below 0°C) and first autumnal freeze of each year were identified. Growing degree days were developed for 3 bases: 10 4.4 and 5.5. To convert the daily minimum and maximum temperatures to $GDD_{10}$, used for non-specific crops, the formula $[(T_{max} + T_{min}) / 2] – 10$ was utilized, where $T_{max}$ = maximum temperature, $T_{min}$ = minimum temperature and 10 = the base temperature threshold. For this formula the maximum and minimum temperature thresholds are 30°C and 10°C, all values exceeding the maximum were reduced to 30°C and values below 10°C were raised to 10°C as no growth occurs above or below the threshold values. For $GDD_{4.4}$ commonly used for potatoes the formula $[(T_{max} + T_{min}) / 2] – 4.4$ was used and the maximum and minimum temperature thresholds are 30°C and 4.4°C, with values adjusted to the threshold as above. For $GDD_{5.5}$ commonly used for alfalfa the formula $[(T_{max} + T_{min}) / 2] – 5.5$ was used and the maximum and minimum temperature thresholds are 43.3°C and 5.5°C, with values adjusted to the threshold as above.

In order to quantify time periods within the data where mean values were distinctly different from the previous or following time periods a change point analysis was utilized. This identifies point(s) in the data record where a change in slope of the cumulative sum caused a significant departure from the previous annual mean values. Previous studies indicated changes in means of time series data can be identified via this analysis (Page 1955 and 1957, Pettit 1979, Taylor 2008). Specifically, change point analysis has been used in several climate studies to identify points of departure from mean values (Craddock 1979, Buishand 1981, Salinger and Mullan 1999).

Utilizing the periods identified by the change point analysis, a one-tailed t-test was used to determine if the Julian date of the last vernal and first autumnal freeze was significantly earlier or later during the period 1994-2007. Similarly, the numbers of days of the freeze-free period were tested to determine if that period had extended significantly during 1994-2007. Further, the mean monthly temperature values and GDD for each base were tested to determine if they were significantly higher during the latter period than the earlier period at all stations.

## 5. Results

### 5.1. CHANGE POINT ANALYSIS

A change point analysis was utilized to identify the periods having significantly different Julian dates for the freeze-free period. The most inclusive periods in this analysis were 1958 – 1980 and 1981 – 2007. Previously, Mix et al. (2008a) utilized the same analysis to identify the periods 1958 – 1993 and 1994 – 2007 as having significantly different annual mean temperature values. The application of change point analysis of annual and growing season GDD indicates there is more variability between, and within, stations for the change point year. Thus the earliest common year identified in the confidence interval, 1994, was utilized as the year when the mean GDD values were significantly different from the previous years. Therefore, the data periods most appropriate for use in the statistical analysis were 1958-1993 and 1994-2007.

The results of the change point analysis for the freeze-free period, temperature values and GDD are presented in Tables 4.2, 4.3 and 4.4. The station location and values tested are presented in the column headed “Station”. The column “Change point year” is the likeliest year that analysis indicates the cumulative sum of the means was significantly different from the previous mean values. The column “Confidence interval” indicates the range of years in which this change might have occurred. The column “Confidence level” represents the strength of surety the change point is accurate. Lastly, columns “Before” and “After” are the cumulative mean values prior to the change point and after the change point.

## 5.2. T-TEST ANALYSIS

Julian dates of the last vernal freeze and first autumnal freeze were analyzed to determine if the 1981-2007 period had significantly earlier last vernal and first autumnal freezes (Table 4.5 and Figure 4.2). The last vernal freeze occurred significantly ($p < 0.05$) earlier at only 2 stations, Center 4SSW and GSDNM with each occurring 7.75 and 11.86 days earlier, respectively. First autumnal freezes occurred significantly ($p < 0.05$) later at all stations, except Del Norte 2E and GSDNM, by 5.95 and 18.1 days later. Additionally, the number of days occurring during the freeze-free period was analyzed to determine if the freeze-free period had gotten longer during the 1981-2007 period. The freeze-free period significantly ($p < 0.05$) expanded at all stations, except Del Norte 2E, by 7.3 to 24.2 days (Figure 4.3).

T-test analyses were performed to determine if the growing season months of May, June, July, August and September in the period 1994-2007 experienced an increase in the number of mean temperature values compared to those of 1958-1993. Data analysis of maximum temperature indicates 3 stations, Blanca 4NW, Del Norte 2E and GSDNM experienced no significant ($p < 0.05$) increase in most months during 1994-2008 over that of 1958-1993 (Table 4.6 and Figure 4.4). With little exception all other stations experienced significant ($p < 0.05$) increases in maximum monthly mean temperature of 0.30 – 1.4$^{\circ}$C (Table 4.6 and Figure 4.4). Analysis of mean monthly minimum temperature indicated all stations with limited exception experienced significant ($p < 0.05$) increases in all months of 0.34 – 2.12$^{\circ}$C (Table 4.7 and Figure 4.5). The notable exception was Del Norte 2E, which experienced significant ($p < 0.05$) decreases in minimum temperature in all months except May. Analysis of monthly mean temperature indicates 5 of 7 stations experienced increases in all months of 0.30 – 1.64$^{\circ}$C (Table 4.8 and Figure 4.6). The two exceptions were Alamosa AP and Del Norte 2E, the former indicating no changes in June, July and September while Del Norte 2E experiencing no change in May, July and August, and data from June and September indicate significant ($p < 0.05$) decrease in monthly mean temperature.

Analyses were performed to determine if GDD had increased during the growing season months of May, June, July, August and September in the period 1994-2007 compared to those of 1958-1993. The analysis of $GDD_{10}$ indicates all stations, experienced significant ($p < 0.05$) increases, between 0.13 – 0.68 $GDD_{10}$ in nearly every month during the period 1994-2007 compared to 1958-1993 (Table 4.9 and Figure 4.7). Notable exceptions to this include no change in all months for Del Norte 2E, and no change in June, July and September for Blanca 4NW. The analysis of $GDD_{4.4}$ indicates significant ($p$ < 0.05) increases at all stations and all months from 0.23 – 1.08 (Table 4.10 and Figure 4.8). Exceptions to this include no change in July at Alamosa AP and no changes in May, July, August and September at Del Norte 2E, with significant ($p$ < 0.05) decrease in $GDD_{4.4}$ for June. The analysis of $GDD_{5.5}$ indicates all stations in all months experienced significant ($p$ < 0.05) increases of 0.19 – 0.97, with the exception of Blanca 4NW in June and Del Norte 2E which had no change except a significant decrease in June (Table 4.11 and Figure 4.9).

## 6. Discussion

The major crops of the SLV include alfalfa and other hays, small grains of barley and spring wheat, potatoes, spinach, lettuce and carrots (CAS 2006). All of these crops are freeze resistant, that is they can tolerate short periods of below $0^{\circ}$C without mortality. For this reason, these crops are typically planted prior to the last freeze (SLVDG 2003). This maximizes the growing season as they are germinated and growing by the time the freeze-free period arrives, thereby taking full advantage of warmer temperatures.

Within the arid alpine desert of the SLV the freeze-free period has expanded, GDD and temperature variables have increased in most months of the growing season and most stations. These are not homogeneous increases in time or location. A review of monthly climate variables indicates where within the growing season change is occurring. Changes in the length of the freeze-free period have occurred most significantly in the first autumnal freeze date with little significant change in earliness of the last vernal freeze date. Similarly, increases in temperature variables and GDD do not indicate homogeneous increases throughout the season.

The freeze period in the SLV is significantly longer now, by about 7 – 20 days, than between 1958-1993. Similarly, Menzel and Fabian (1999) reported an increase in the growing season of Europe by about 10 days over a 30 year period since the early 1960's. Further, their study reveals 1980 as the date after which the greatest expansion took place. Analysis of the changes in the last vernal and first autumnal freezes indicates the last vernal freezes are arriving earlier at Center 4SSW and GSDNM marginally so at Blanca 4NW, by about 8 days $\pm$ 3. The autumnal freeze dates, however, are later at all but Del Norte 2E and GSDNM stations by 6 – 18 days. When these changes in freeze dates are combined it produces the significantly longer growing season noted above. Typically the last vernal freeze date occurred around June 9th, in the latter period it now occurs around June 5th and the first autumnal freeze typically occurred near September 10th, is now occurring much later, around September 18th. In contrast to Menzel and Fabian (1999), the greater expansion of the growing season in the SLV is occurring during the autumnal phase. Their data on European changes only extended to the early 1990's whereas data on the SLV extends to 2007, 10 – 15 years longer.

Expansion of the freeze-free period has a potential to benefit agricultural endeavors. A longer freeze-free period allows for longer uninterrupted growth. Depending on the amount of lengthening, it may provide enough time to grow new crops that require a longer season or possibly allow for the planting of a second crop. Further, it can reduce planting and harvest time pressures by reducing the threat of late and early freezes. With only a few extra days in the spring are occurring at 2 or 3 locations and an increase of several days in the fall at all locations the SLV agricultural community is not likely experiencing a reduction of timing pressures except at the end of the season.

The analysis of temperature data indicates increases during the growing season months was highest in May and June. Mean daily maximum and mean temperature increases were highest in May at 5 of 7 stations, similarly mean daily minimum temperature increased in May but with 4 stations also reporting increases in August and September. The mean daily minimum temperature increased in May by about 1°C at 4 stations, 0.6°C at Monte Vista 2W, with no change at Alamosa AP and Del Norte 2E. The increase in mean daily minimum temperature potentially indicates a trend toward earlier last vernal freezes, though not significantly every station did report an earlier mean date for the last vernal freeze. In contrast, the increases in the minimum temperatures for September were not as great, though the first autumnal freeze is significantly later at most stations. It has been noted in the later half of the 20th century global mean temperature increased significantly after 1976 (IPCC 2001), and it appears the Valley lagged behind that date by 15 – 20 years (Mix et al. 2008).

Increases in temperature have been shown to cause changes in phenology and these changes are evident in several taxa in northern latitudes (see McCarty 2001). Temperature changes can be translated into changes in GDD, which are known to affect the timing of germination, growth and seed/fruit maturity, plant pest and disease distribution, abundance and synchrony (Visser and Both 2005). Data analyses of the GDD in the SLV, with few exceptions, indicate all stations and all months have a greater number of GDD during the 1994-2007 period than prior. This is similar to a Canadian study which indicated significant increases in GDD have occurred throughout the major growing regions there (Bonsal et al. 2001).

In the SLV the highest increases in $GDD_{10}$ occurred in May at 5 of 7 stations. This might be expected as $GDD_{10}$ has a minimum threshold of 10$^{\circ}$C and maximum of 30$^{\circ}$C making it the most sensitive to increases in maximum temperatures. It also coincides with increases in mean maximum temperature at the same stations. $GDD_{4.4}$ and $GDD_{5.5}$ have lower minimum temperature thresholds and therefore responded with increases at all stations and months with the exception of July at Alamosa AP and June at Blanca. At most stations the greater increases temperature and GDD occurred in the early months of the growing season with lesser increases occurring later.

Growing degree days are an important tool in agricultural to predict developmental stages of crops, pests and beneficials. They are used to estimate the timing of emergence of insect pests, germination of crop seedlings, bloom set and maturity. Therefore, the timing of developmental stages in crops and insect (pests or beneficials) has potential to change as GDD increase. This could lead to asynchrony of pest/prey relationships in several agricultural milieus (Parmesan 2006). Further, an increase in number of pest generations, and changes in location or migration (i.e. arrival when the crop is sensitive to herbivory) could manifest as changes in insect phenology occur (Bale et al. 2002).

Early onset of increased temperature or GDD in the Valley potentially includes changes in several parameters: irrigation, planting dates, pest prevalence and yield. The results here indicate about a 1$^{\circ}$C increase in daily mean temperature and 15 – 20 additional GDD in both May and June, depending on location. A reduction in quality or yield has been shown to result from increases in $GDD_{4.4}$ as increases in GDD can hasten maturity (Singh et al. 1998).

Studies of potato insect pests, like the peach potato aphid (*Myzus persicae*), indicate an increase in their abundance with temperature increases (Bezemer et al. 1998). Further, their parasitoid, *Aphidius matricariae*, also responded with increased fecundity. Diseases of potato also have been shown to benefit from increases in temperature and GDD. Infection of potatoes caused by bacterial ring rot (causal organism *Corynebacterium sepedonicum*) is exacerbated by warmer climatic conditions (Manzer and Nelson 1987) and the advent of more $GDD_{4.4}$ would provide more ideal conditions for the disease to persist in the Valley. It is predicted late blight (*Phytophthora infestans*) will change distribution and increase virility as northern latitudes warm (Hijmnas et al. 2000). Early blight (*Alternaria solani*) spores become present in the Valley at about 360 GDD, roughly mid-July (Franc et al. 1988). With the increases in $GDD_{4.4}$ found here, this effectively moves the presence of early blight to late-June. It also has been demonstrated that winter wheat pathogen take-all fungus, *Gaeumannomyces graminis*, begins appearing around 800 GDD (Colbach et al. 1997) which now accumulate about 15-20 days earlier.

In contrast to potato production in 2005 the SLV had approximately 104,000 ha in hay production, more than half of which is alfalfa. The gross revenue from this crop was $72 million. At most stations May and June $GDD_{5.5}$ show significant increases of about a 0.5 $GDD_{5.5}$ per 24 hours. This effectively adds about 15 additional GDD in those months. This could be beneficial for the crop by providing additional warmth and time for growth during the attenuated growing season of the SLV. However, it potentially increases the need for irrigation. Irrigated alfalfa requires 2 to 3 acre feet of water and significant increases in growth would require increased irrigation (Finnerty and Ramirez 1995). The increases in GDD may also indicate insect pests, such as spittle bug and aphid species (Auchenorryncha: Cercopidae) (Whittaker and Tribe 1996), weevils (Coleoptera: Curculionidae) will be able to produce additional generations. Additional $GDD_{5.5}$ are also expected to increase the incidence of verticillium wilt (*Verticillium albo-atrum*) (Boland et al. 2004). Further, the growth of some fungi is promoted by warm wet conditions. As temperatures rise more irrigation water will be applied potentially improving the conditions for these pathogens.

Similar changes occurred in $GDD_{10}$ potentially increasing the time for diseases to infect other crops of the SLV. However, the present number and execution of studies evaluating the impacts of climate change on crops and their pests are equivocal as well. With early increases in GDD the appearance of these diseases and pests may appear earlier, increasing the length of time for crop damage and changing the timing of crop applications.

Climate change models indicate insect pests will have greater abundance, new distribution or range and increased voltinism and can be expected to migrate to new regions as the climate shifts (Porter et al. 1991, Brasier and Scott 1994, Woiwod 1997, Hassall et al. 2007). Studies indicate higher temperatures will increase abundance and distribution to higher latitudes of European corn borer (*Ostrinia nubialis*), a common pest of many crops. Lepidopterans are flying earlier under the current increase in temperature, hence earlier herbivory by their caterpillars. The Fleming and Candau

(1998) model of climate change insect interactions predicts increases in Spruce bud worm outbreaks affecting forestry management in Canada.

Information regarding climate change in the San Luis Valley is scant, as are studies on other alpine deserts and ecosystems. Nevertheless, Mix et al. (2008) reported a lagged increase in temperature response using change point analysis. This is similar to IPCC (2001) report of lower increases in temperature higher in the atmosphere indicating altitude may provide ameliorating effects from climate change in the short run. Analysis of climate change in the SLV indicates the freeze-free period has expanded, temperature has risen similarly to global rises and GDD are increasing.

The greatest negative impact likely experienced at this time is increases in irrigation. Several studies confirm increases in GDD exacerbate the need for irrigation as increases in growth will have a concomitant increase in crop evapotranspiration (Adams 1989, Schimmelpfennig et al. 1996, Ramirez and Finnerty 1996). Herrington (1996) predicts a 12 percent increase in irrigation demands for every 1.1$^{\circ}$C increase in temperature. The Valley utilizes an average of 500,000 acre feet annually this results in additional 60,000 acre feet irrigation requirement.

The economic importance of the risks climate change poses to agriculture by reduced yields from forced maturity, changes in pest presence or increased irrigation cost can be observed easily when viewing the SLV production statistics. Potato acreage in the SLV in 2005 covered 23,400 ha and yielded 22.2 million cwt, valued at nearly $200 million, more than 15 times the gross value of any other SLV crop. Hays, including alfalfa, covered 100,000 ha, valued at nearly $75 million. Small grains and vegetables generate an additional $45 million on the remaining acreage. A small percentage change in volume or quality as a result of climate changes has the potential to cause several million dollar loss. However, it should not be left unsaid that agriculture is constantly adapting with new varietals and hybrids and there is considerable potential for the ongoing adaptive process to ameliorate any negative impacts of climate change.

## 7. Conclusion

The San Luis Valley is an important agricultural system both locally and regionally. It employs more than 50% of the Valley's inhabitants and is responsible for producing nearly 100% of the state of Colorado's potatoes. Since the early 1980's the growing season has expanded significantly at all stations by about 7 – 24 days. The last vernal freeze is occurring significantly earlier at 3 stations by approximately 5 – 12 days and the first autumnal freeze is occurring significantly later at 5 stations by approximately 6 – 18 days. Though, the last vernal freeze is not occurring significantly earlier 6 stations report the months of May and June have significantly higher mean temperatures. If this is a trend toward warmer spring then it potentially indicates the last vernal freeze will continue to occur earlier. Analysis also indicates that at nearly every station daily maximum, minimum and mean temperatures in most months of the growing season has increased by about 0.3 – 1.4$^{\circ}$C, 0.3 – 1.7$^{\circ}$C and 0.5 – 1.6$^{\circ}$C, respectively. Further, nearly all stations report significant increases in $GDD_{10,}$ $GDD_{4.4,}$ $GDD_{5.5}$ in most months of 0.15 – 0.7, 0.2 – 1.0, and 0.2 – 0.95, respectively.

The benefits of earlier last vernal freeze include longer growing periods for crops and reduced risk of freeze injury for late plantings. Additionally, higher temperatures at the onset of the growing season have a potential beneficial impact of increasing the growth rate of young plants or plants breaking dormancy. Negative impacts of higher temperature and more GDD include bolting in lettuce and spinach crops prior to harvest, longer irrigation periods, potential earlier and increased disease presence. Increases in pest insect generations, abundance and potential asynchrony with parasitoid insects can also occur. Further, increases in GDD can cause reduced crop yield from forced maturation, quality can be reduced and early senescence may be induced.

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**Tables Figures**

Table 4.1. Location and elevation of each station.

| Stations | Location | Elevation in meters |
|---|---|---|
| *Valley floor stations* | | |
| Alamosa AP | 37°26'N / 105°52'W | 2296.1 |
| Blanca 4NW | 37°29'N / 105°34'W | 2349.7 |
| Center 4SSW | 37°42'N / 106°09'W | 2338.7 |
| Del Norte 2E | 37°40'N / 106°19'W | 2396.9 |
| GSDNM | 37°44'N / 105°31'W | 2475.0 |
| Manassa | 37°10'N / 105°56'W | 2343.9 |
| Monte Vista 2W | 37°35'N / 106°11'W | 2344.5 |

Table 4.2. Results of change point analysis of vernal and autumnal freeze dates and freeze-free period for weather stations on the floor of the San Luis Valley, Colorado. Change point year indicates when the change is estimated to have occurred, confidence interval indicates the period when the change occurred and confidence level is the degree of surety the change point year is correct. Before and After indicate the mean Julian date before and after the change point year for the last vernal and first autumnal freeze and mean number of days during the freeze-free period before and after the change point year.

| Station | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Alamosa AP | | | | | |
| Last vernal freeze | No change | - | - | - | - |
| First autumnal freeze | No change | - | - | - | - |
| Freeze free period | 1982 | 1962-2002 | 92 | 91.8 | 99.2 |
| Blanca 4NW | | | | | |
| Last vernal freeze | 1991 | 1979-1999 | 98 | 161.2 | 150.0 |
| First autumnal freeze | 1974 | 1967-1983 | 95 | 249.7 | 261.3 |
| Freeze free period | 1993 | 1979-1998 | 93 | 95.0 | 114.2 |
| Center 4SSW | | | | | |
| Last vernal freeze | 1985 | 1974-1993 | 99 | 163.8 | 152.0 |
| First autumnal freeze | 1981 | 1973-1985 | 100 | 248.1 | 261.7 |
| Freeze free period | 1983 | 1977-1988 | 100 | 85.3 | 109.0 |
| Del Norte 2E | | | | | |
| Last vernal freeze | 1963 | 1962-1975 | 99 | 144.2 | 156.7 |
| | 1985 | 1980-1992 | 99 | 156.6 | 143.6 |
| | 2001 | 1996-2003 | 93 | 143.6 | 160.3 |
| First autumnal freeze | 1973 | 1959-2001 | 93 | 256.1 | 263.6 |
| Freeze free period | 1978 | 1973-1986 | 99 | 104.5 | 119.0 |
| | 2001 | 1999-2001 | 94 | 119.0 | 90.2 |
| GSDNM | | | | | |
| Last vernal freeze | 1967 | 1965-1967 | 100 | 145.3 | 170.2 |
| | 1977 | 1977-1979 | 100 | 170.2 | 143.3 |
| First autumnal freeze | No change | - | - | - | - |
| Freeze free period | 1978 | 1968-1992 | 97 | 100.3 | 120.7 |
| Manassa | | | | | |
| Last vernal freeze | 1988 | 1974-1996 | 97 | 164.0 | 152.5 |
| First autumnal freeze | 1981 | 1977-1984 | 100 | 242.1 | 260.2 |
| Freeze free period | 1988 | 1984-1991 | 100 | 81.7 | 109.0 |
| Monte Vista 2W | | | | | |
| Last vernal freeze | 1965 | 1962-1971 | 91 | 163.4 | 151.0 |
| | 1977 | 1975-1977 | 99 | 151.0 | 168.4 |
| | 1986 | 1986-1995 | 99 | 168.4 | 153.5 |
| First autumnal freeze | 1982 | 1964-1991 | 99 | 250.2 | 260.9 |
| Freeze free period | 1965 | 1960-1985 | 96 | 82.6 | 102.5 |

Table 4.3. Results of change point analysis for weather stations on the floor of the San Luis Valley, Colorado. Change point year indicates when the change is estimated to have occurred, confidence interval indicates the period when the change occurred and confidence level is the degree of surety the change point year is correct. Before and after indicate the temperature values in Celsius before and after the change point year for annual maximum, minimum and mean temperatures.

| Station | | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|---|
| Alamosa AP | | | | | | |
| | Maximum | 1999 | 1989-2001 | 96 | 14.9 | 16.2 |
| | Minimum | 1990 | 1966-2000 | 95 | -4.7 | -4.0 |
| | Mean | 1989 | 1976-1994 | 99 | 5.2 | 6.0 |
| Blanca 4NW | | | | | | |
| | Maximum | 1999 | 1993-2006 | 99 | 14.9 | 16.2 |
| | Minimum | 1995 | 1992-1995 | 100 | -3.9 | -2.5 |
| | Mean | 1995 | 1992-1997 | 100 | 5.6 | 6.8 |
| Center 4SSW | | | | | | |
| | Maximum | 1971 | 1968-1975 | 98 | 15.2 | 13.6 |
| | | 1995 | 1988-1998 | 95 | 13.6 | 15.1 |
| | Minimum | 1972 | 1971-1972 | 100 | -4.2 | -6.0 |
| | | 1980 | 1977-1987 | 100 | -6.0 | -4.7 |
| | | 1995 | 1992-1995 | 100 | -5.3 | -2.7 |
| | Mean | 1971 | 1969-1971 | 100 | 5.7 | 4.0 |
| | | 1980 | 1974-1994 | 98 | 4.0 | 4.8 |
| | | 1995 | 1991-1996 | 100 | 4.8 | 6.4 |
| Del Norte 2E | | | | | | |
| | Maximum | No Change | | | | |
| | Minimum | 1977 | 1969-1999 | 98 | -2.3 | -1.7 |
| | | 1999 | 1996-1999 | 99 | -1.7 | -3.3 |
| | Mean | No Change | | | | |
| GSDNM | | | | | | |
| | Maximum | No Change | | | | |
| | Minimum | 1977 | 1960-1993 | 97 | -1.6 | -1.1 |
| | | 1995 | 1990-1997 | 10 | -1.1 | -0.2 |
| | Mean | 1999 | 1985-2000 | 97 | 6.5 | 7.5 |
| Manassa | | | | | | |
| | Maximum | 1991 | 1960-1991 | 91 | 15.3 | 13.3 |
| | | 1994 | 1994-1995 | 90 | 13.3 | 16.3 |
| | Minimum | 1994 | 1990-1994 | 98 | -4.1 | -2.0 |
| | Mean | 1994 | 1975-1995 | 94 | 5.6 | 7.2 |
| Monte Vista 2W | | | | | | |
| | Maximum | 1982 | 1968-1984 | 95 | 14.6 | 13.7 |
| | | 1994 | 1994-1997 | 99 | 13.7 | 15.6 |
| | Minimum | 1965 | 1965 | 99 | -5.1 | -2.9 |
| | | 1982 | 1982 | 99 | -2.9 | -4.9 |
| | | 1993 | 1986-2001 | 97 | -4.9 | -3.7 |
| | Mean | 1965 | 1961-1967 | 96 | 4.9 | 6.1 |
| | | 1982 | 1980-1982 | 99 | 6.1 | 4.5 |
| | | 1994 | 1993-1996 | 99 | 4.5 | 6.0 |

Table 4.4. Results of change point analysis for weather stations on the floor of the San Luis Valley, Colorado. Change point year indicates when the change is estimated to have occurred, confidence interval indicates the period when the change occurred and confidence level is the degree of surety the change point year is correct. Before and after indicate the number of GDD for each base before and after change point year.

| Station | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Alamosa AP | | | | | |
| $GDD_{10}$ | 2000 | 1994-2000 | 95 | 1365.8 | 1501.0 |
| $GDD_{4.4}$ | 1999 | 1990-2000 | 97 | 2249.9 | 2420.1 |
| $GDD_{5.5}$ | 1999 | 1991-2000 | 98 | 2053.3 | 2222.7 |
| Blanca 4NW | | | | | |
| $GDD_{10}$ | 2000 | 1988-2000 | 100 | 1342.6 | 1458.7 |
| $GDD_{4.4}$ | 1996 | 1989-1999 | 100 | 2219.2 | 2394.9 |
| $GDD_{5.5}$ | 1999 | 1992-1999 | 100 | 2030.5 | 2213.8 |
| Center 4SSW | | | | | |
| $GDD_{10}$ | 1970 | 1967-1972 | 100 | 1377.2 | 1224.0 |
| | 1988 | 1985-1993 | 100 | 1224.0 | 1342.8 |
| $GDD_{4.4}$ | 1971 | 1968-1974 | 100 | 2258.0 | 2054.7 |
| | 1995 | 1992-1997 | 100 | 2054.7 | 2280.0 |
| $GDD_{5.5}$ | 1970 | 1967-1973 | 100 | 2062.9 | 1872.2 |
| | 1995 | 1991-1998 | 100 | 1972.2 | 2069.6 |
| Del Norte 2E | | | | | |
| $GDD_{10}$ | 1977 | 1968-1978 | 98 | 1247.4 | 1336.8 |
| | 1990 | 1989-1994 | 92 | 1336.8 | 1242.8 |
| | 2004 | 1991-2005 | 94 | 1242.8 | 1179.5 |
| $GDD_{4.4}$ | 1977 | 1968-1981 | 96 | 2160.1 | 2289.0 |
| | 1990 | 1988-1998 | 96 | 2289.0 | 2131.9 |
| $GDD_{5.5}$ | 1977 | 1967-1981 | 95 | 1950.6 | 2064.0 |
| | 1991 | 1991 | 96 | 2064.0 | 1811.0 |
| | 1994 | 1994-1996 | 92 | 1811.0 | 1992.2 |
| | 2004 | 2001-2004 | 92 | 1992.2 | 1813.4 |
| GSDNM* | | | | | |
| $GDD_{10}$ | No change | | | | |
| $GDD_{4.4}$ | No change | | | | |
| $GDD_{5.5}$ | No change | | | | |
| Manassa | | | | | |
| $GDD_{10}$ | 1996 | 1987-2001 | 100 | 1339.0 | 1442.5 |
| $GDD_{4.4}$ | 1969 | 1969-1972 | 90 | 2338.9 | 2095.0 |
| | 1980 | 1975-1992 | 97 | 2095.0 | 2214.9 |
| | 1994 | 1989-1997 | 100 | 2214.9 | 2411.9 |
| $GDD_{5.5}$ | 1969 | 1969-1972 | 91 | 2134.9 | 1917.9 |
| | 1980 | 1974-1992 | 95 | 1917.9 | 2014.5 |
| | 1994 | 1989-1997 | 100 | 2014.5 | 2194.9 |
| Monte Vista 2W | | | | | |
| $GDD_{10}$ | 1982 | 1973-1982 | 99 | 1343.4 | 1165.3 |
| | 1991 | 1991 | 99 | 1165.3 | 1307.7 |
| | 2000 | 1997-2003 | 92 | 1307.7 | 1422.1 |
| $GDD_{4.4}$ | 1982 | 1971-1982 | 100 | 2226.8 | 2015.5 |
| | 1994 | 1994-1996 | 100 | 2015.5 | 2284.9 |
| $GDD_{5.5}$ | 1982 | 1971-1982 | 100 | 2027.7 | 1824.6 |
| | 1994 | 1994-1995 | 100 | 1824.6 | 2081.6 |

Table 4.5. Results of t-test analyses for the Julian dates of the last vernal and first autumnal freezes and length of the freeze-free period in the San Luis Valley, Colorado. Negative values in the difference column for the vernal dates indicates an earlier last freeze.

| | 1958-1980 | | | | 1981-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| Last vernal freeze | 22 | 160.18 | 11.19 | 2.39 | 27 | 158.74 | 9.61 | 1.85 | -1.44 | 0.3149 |
| First autumnal freeze | 22 | 251.86 | 10.78 | 2.30 | 27 | 257.81 | 10.04 | 1.93 | 5.95 | 0.0258 |
| Freeze free period | 22 | 91.68 | 16.94 | **3.61** | 27 | 99.07 | 13.06 | 2.51 | 7.39 | 0.0455 |
| Blanca 4NW | | | | | | | | | | |
| Last vernal freeze | 21 | 160.33 | 10.66 | 2.33 | 27 | 154.81 | 12.17 | 2.34 | -5.52 | 0.0535 |
| First autumnal freeze | 21 | 253.52 | 10.25 | 2.24 | 23 | 261.43 | 9.58 | 2.00 | 7.91 | 0.0057 |
| Freeze free period | 21 | 93.19 | 15.90 | 3.47 | 23 | 106.61 | 16.44 | 3.43 | 13.42 | 0.0044 |
| Center 4SSW | | | | | | | | | | |
| Last vernal freeze | 22 | 162.59 | 11.26 | 2.40 | 25 | 154.84 | 12.08 | 2.42 | -7.75 | 0.0142 |
| First autumnal freeze | 22 | 248.14 | 11.71 | 2.50 | 25 | 261.68 | 9.01 | 1.80 | 13.54 | <0.0001 |
| Freeze free period | 22 | 85.55 | 17.51 | 3.73 | 25 | 106.84 | 16.02 | 3.20 | 21.30 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| Last vernal freeze | 19 | 153.26 | 8.92 | 2.05 | 26 | 149.50 | 11.74 | 2.30 | -3.76 | 0.1241 |
| First autumnal freeze | 18 | 260.11 | 11.70 | 2.76 | 26 | 263.12 | 9.63 | 1.89 | 3.01 | 0.1453 |
| Freeze free period | 18 | 106.44 | 10.74 | 2.53 | 25 | 113.64 | 16.74 | 3.35 | 7.20 | 0.0587 |
| GSDNM | | | | | | | | | | |
| Last vernal freeze | 23 | 155.48 | 17.23 | 3.59 | 26 | 143.62 | 10.84 | 2.13 | -11.86 | 0.0027 |
| First autumnal freeze | 17 | 260.35 | 7.65 | 1.85 | 19 | 264.21 | 12.63 | 2.90 | 3.86 | 0.1412 |
| Freeze free period | 17 | 103.18 | 19.72 | 4.78 | 19 | 120.21 | 19.45 | 4.46 | 17.03 | 0.0067 |
| Manassa | | | | | | | | | | |
| Last vernal freeze | 18 | 161.94 | 11.45 | 2.70 | 25 | 157.12 | 13.62 | 2.72 | -4.82 | 0.1142 |
| First autumnal freeze | 15 | 242.07 | 12.46 | 3.22 | 23 | 260.17 | 9.89 | 2.06 | 18.10 | <0.0001 |
| Freeze free period | 15 | 78.53 | 14.75 | 3.81 | 23 | 102.74 | 18.77 | 3.91 | 24.21 | 0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| Last vernal freeze | 19 | 158.26 | 9.76 | 2.24 | 23 | 156.13 | 11.01 | 2.30 | -2.13 | 0.2574 |
| First autumnal freeze | 17 | 250.24 | 13.03 | 3.16 | 23 | 260.35 | 9.56 | 1.99 | 10.11 | 0.0036 |
| Freeze free period | 17 | 91.65 | 19.00 | 4.61 | 21 | 104.62 | 15.45 | 3.37 | 12.97 | 0.0129 |

Table 4.6. Results of t-test analyses for average maximum temperature for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average maximum temperature.

| | | 1958-1993 | | | | 1994-2007 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1116 | 20.08 | 4.48 | 0.13 | 434 | 21.49 | 4.65 | 0.22 | 1.41 | <0.0001 |
| June | 1080 | 25.52 | 3.72 | 0.11 | 419 | 26.41 | 3.36 | 0.16 | 0.89 | <0.0001 |
| July | 1116 | 27.76 | 2.48 | 0.07 | 433 | 28.35 | 2.85 | 0.14 | 0.58 | <0.0001 |
| August | 1116 | 26.28 | 2.70 | 0.08 | 434 | 26.85 | 2.48 | 0.12 | 0.57 | <0.0001 |
| September | 1080 | 22.73 | 3.69 | 0.11 | 420 | 22.97 | 3.73 | 0.18 | 0.24 | 0.1321 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 19.80 | 4.52 | 0.14 | 403 | 20.71 | 4.77 | 0.24 | 0.90 | 0.0004 |
| June | 1003 | 25.35 | 3.83 | 0.12 | 420 | 25.20 | 4.07 | 0.20 | -0.16 | 0.2418 |
| July | 1048 | 27.82 | 2.68 | 0.08 | 426 | 27.93 | 2.96 | 0.14 | 0.11 | 0.2438 |
| August | 1042 | 26.22 | 2.86 | 0.09 | 415 | 26.44 | 2.62 | 0.13 | 0.23 | 0.0821 |
| September | 978 | 22.65 | 3.61 | 0.12 | 369 | 22.98 | 3.89 | 0.20 | 0.33 | 0.0703 |
| Center 4SSW | | | | | | | | | | |
| May | 1115 | 19.55 | 4.41 | 0.13 | 402 | 20.54 | 4.59 | 0.23 | 0.99 | <0.0001 |
| June | 1080 | 24.42 | 3.55 | 0.11 | 390 | 25.12 | 3.47 | 0.18 | 0.70 | 0.0004 |
| July | 1115 | 26.43 | 2.48 | 0.07 | 403 | 27.15 | 2.93 | 0.15 | 0.72 | <0.0001 |
| August | 1116 | 25.36 | 2.64 | 0.08 | 404 | 26.08 | 2.96 | 0.15 | 0.73 | <0.0001 |
| September | 1078 | 22.32 | 3.57 | 0.11 | 420 | 20.84 | 7.97 | 0.39 | -1.48 | 0.0001 |
| Del Norte 2E | | | | | | | | | | |
| May | 1113 | 19.64 | 4.14 | 0.12 | 434 | 19.58 | 4.26 | 0.20 | -0.06 | 0.4001 |
| June | 1079 | 24.07 | 3.32 | 0.10 | 390 | 23.85 | 3.24 | 0.16 | -0.22 | 0.1330 |
| July | 1116 | 25.77 | 2.53 | 0.08 | 434 | 25.83 | 2.54 | 0.12 | 0.06 | 0.3314 |
| August | 1084 | 24.56 | 2.67 | 0.08 | 434 | 24.68 | 2.37 | 0.11 | 0.12 | 0.2099 |
| September | 1073 | 21.58 | 3.33 | 0.10 | 390 | 21.55 | 3.36 | 0.17 | -0.03 | 0.4474 |
| GSDNM | | | | | | | | | | |
| May | 1081 | 19.10 | 4.52 | 0.14 | 434 | 19.35 | 5.00 | 0.24 | 0.25 | 0.1755 |
| June | 1074 | 24.70 | 3.88 | 0.12 | 420 | 25.00 | 3.60 | 0.18 | 0.30 | 0.0840 |
| July | 1079 | 27.01 | 2.71 | 0.08 | 434 | 27.16 | 3.06 | 0.15 | 0.15 | 0.1677 |
| August | 1080 | 25.42 | 2.71 | 0.08 | 434 | 25.76 | 2.67 | 0.13 | 0.35 | 0.0121 |
| September | 1045 | 21.71 | 3.77 | 0.12 | 389 | 21.98 | 3.89 | 0.20 | 0.27 | 0.1160 |
| Manassa | | | | | | | | | | |
| May | 1022 | 20.24 | 4.14 | 0.13 | 428 | 21.38 | 4.05 | 0.20 | 1.15 | <0.0001 |
| June | 934 | 25.06 | 3.34 | 0.11 | 387 | 25.93 | 3.01 | 0.15 | 0.87 | <0.0001 |
| July | 979 | 27.20 | 2.49 | 0.08 | 419 | 27.61 | 2.60 | 0.13 | 0.41 | 0.0002 |
| August | 1003 | 26.01 | 2.58 | 0.08 | 417 | 26.41 | 2.22 | 0.11 | 0.40 | 0.0029 |
| September | 960 | 22.95 | 3.45 | 0.11 | 385 | 23.20 | 3.20 | 0.16 | 0.25 | 0.1117 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 20.01 | 4.25 | 0.14 | 434 | 20.71 | 4.52 | 0.22 | 0.70 | 0.0025 |
| June | 966 | 24.67 | 3.48 | 0.11 | 420 | 25.21 | 3.40 | 0.17 | 0.54 | 0.0039 |
| July | 974 | 26.73 | 2.57 | 0.08 | 434 | 27.29 | 2.77 | 0.13 | 0.56 | 0.0001 |
| August | 928 | 25.58 | 2.58 | 0.08 | 434 | 25.88 | 2.40 | 0.12 | 0.30 | 0.0211 |
| September | 955 | 22.31 | 3.34 | 0.11 | 360 | 22.79 | 3.35 | 0.18 | 0.48 | 0.0104 |

Table 4.7. Results of t-test analyses for average minimum temperature for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average minimum temperature.

| | 1958-1993 | | | | 1994-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1109 | 0.56 | 3.51 | 0.11 | 432 | 0.72 | 3.54 | 0.17 | 0.17 | 0.2025 |
| June | 1078 | 5.11 | 3.01 | 0.09 | 418 | 4.49 | 2.90 | 0.14 | -0.62 | 0.0001 |
| July | 1113 | 8.58 | 2.52 | 0.08 | 431 | 8.29 | 2.61 | 0.13 | -0.29 | 0.0234 |
| August | 1116 | 7.53 | 2.89 | 0.09 | 429 | 7.87 | 2.69 | 0.13 | 0.34 | 0.0171 |
| September | 1080 | 2.60 | 3.55 | 0.11 | 419 | 2.73 | 3.98 | 0.19 | 0.13 | 0.2689 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 0.72 | 3.68 | 0.11 | 403 | 1.98 | 3.35 | 0.17 | 1.26 | <0.0001 |
| June | 1013 | 5.23 | 3.14 | 0.10 | 420 | 6.35 | 2.88 | 0.14 | 1.12 | <0.0001 |
| July | 1048 | 8.54 | 2.43 | 0.08 | 425 | 9.42 | 2.30 | 0.11 | 0.88 | <0.0001 |
| August | 1042 | 7.35 | 2.77 | 0.09 | 415 | 8.59 | 2.28 | 0.11 | 1.25 | <0.0001 |
| September | 982 | 2.84 | 3.59 | 0.11 | 369 | 4.03 | 3.79 | 0.20 | 1.19 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| May | 1116 | 0.77 | 3.20 | 0.10 | 403 | 2.43 | 3.35 | 0.17 | 1.67 | <0.0001 |
| June | 1079 | 4.40 | 2.77 | 0.08 | 390 | 5.58 | 2.46 | 0.12 | 1.19 | <0.0001 |
| July | 1115 | 7.32 | 2.45 | 0.07 | 403 | 8.73 | 2.18 | 0.11 | 1.41 | <0.0001 |
| August | 1116 | 6.33 | 2.73 | 0.08 | 404 | 8.01 | 2.42 | 0.12 | 1.68 | <0.0001 |
| September | 1079 | 2.26 | 3.09 | 0.09 | 420 | 2.85 | 5.97 | 0.29 | 0.59 | 0.0063 |
| Del Norte 2E | | | | | | | | | | |
| May | 1114 | 1.88 | 3.04 | 0.09 | 434 | 1.63 | 3.33 | 0.16 | -0.25 | 0.0750 |
| June | 1080 | 5.82 | 2.68 | 0.08 | 390 | 5.34 | 2.67 | 0.14 | -0.48 | 0.0012 |
| July | 1116 | 9.06 | 2.01 | 0.06 | 434 | 8.72 | 1.92 | 0.09 | -0.34 | 0.0012 |
| August | 1084 | 8.27 | 2.23 | 0.07 | 434 | 7.99 | 2.22 | 0.11 | -0.28 | 0.0129 |
| September | 1077 | 4.39 | 2.91 | 0.09 | 390 | 3.52 | 3.35 | 0.17 | -0.86 | <0.0001 |
| GSDNM | | | | | | | | | | |
| May | 1075 | 2.44 | 3.62 | 0.11 | 434 | 3.62 | 3.76 | 0.18 | 1.18 | <0.0001 |
| June | 1076 | 7.08 | 3.19 | 0.10 | 420 | 8.13 | 2.82 | 0.14 | 1.05 | <0.0001 |
| July | 1083 | 10.05 | 2.20 | 0.07 | 433 | 10.87 | 2.21 | 0.11 | 0.82 | <0.0001 |
| August | 1080 | 9.03 | 2.30 | 0.07 | 434 | 9.83 | 2.43 | 0.12 | 0.81 | <0.0001 |
| September | 1043 | 5.21 | 3.20 | 0.10 | 390 | 6.22 | 3.43 | 0.17 | 1.01 | <0.0001 |
| Manassa | | | | | | | | | | |
| May | 1016 | 0.46 | 3.90 | 0.12 | 428 | 2.58 | 3.73 | 0.18 | 2.12 | <0.0001 |
| June | 916 | 4.93 | 3.20 | 0.11 | 380 | 6.28 | 2.93 | 0.15 | 1.35 | <0.0001 |
| July | 979 | 7.89 | 2.69 | 0.09 | 416 | 9.24 | 2.41 | 0.12 | 1.36 | <0.0001 |
| August | 1000 | 6.93 | 3.05 | 0.10 | 413 | 8.59 | 2.47 | 0.12 | 1.66 | <0.0001 |
| September | 954 | 2.71 | 3.89 | 0.13 | 381 | 4.43 | 3.82 | 0.20 | 1.73 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 0.67 | 3.38 | 0.11 | 425 | 1.26 | 3.17 | 0.15 | 0.59 | 0.0011 |
| June | 968 | 4.56 | 2.83 | 0.09 | 414 | 4.64 | 2.77 | 0.14 | 0.08 | 0.3172 |
| July | 974 | 8.06 | 2.58 | 0.08 | 432 | 8.18 | 2.33 | 0.11 | 0.12 | 0.2081 |
| August | 928 | 7.27 | 2.80 | 0.09 | 425 | 7.67 | 2.41 | 0.12 | 0.40 | 0.0056 |
| September | 954 | 2.64 | 3.19 | 0.10 | 359 | 2.81 | 3.53 | 0.19 | 0.17 | 0.2089 |

Table 4.8. Results of t-test analyses for average mean temperature for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average mean temperature.

| | | | 1958-1993 | | | | 1994-2007 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1109 | 10.45 | 3.33 | 0.10 | 432 | 11.22 | 3.42 | 0.16 | 0.77 | <0.0001 |
| June | 1078 | 15.45 | 2.78 | 0.08 | 417 | 15.59 | 2.40 | 0.12 | 0.13 | 0.1975 |
| July | 1113 | 18.31 | 1.66 | 0.05 | 431 | 18.45 | 1.82 | 0.09 | 0.14 | 0.0694 |
| August | 1116 | 17.04 | 1.91 | 0.06 | 429 | 17.50 | 1.67 | 0.08 | 0.47 | <0.0001 |
| September | 1080 | 12.79 | 2.79 | 0.08 | 419 | 12.99 | 3.03 | 0.15 | 0.19 | 0.1219 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 10.39 | 3.58 | 0.11 | 403 | 11.47 | 3.66 | 0.18 | 1.08 | <0.0001 |
| June | 1000 | 15.44 | 3.05 | 0.10 | 420 | 15.92 | 2.91 | 0.14 | 0.48 | 0.0030 |
| July | 1047 | 18.33 | 1.95 | 0.06 | 425 | 18.82 | 2.06 | 0.10 | 0.49 | <0.0001 |
| August | 1042 | 16.92 | 2.16 | 0.07 | 415 | 17.66 | 1.88 | 0.09 | 0.73 | <0.0001 |
| September | 977 | 12.91 | 2.97 | 0.10 | 369 | 13.63 | 3.33 | 0.17 | 0.72 | <0.0001 |
| Center 4SSW | | | | | | | | | | |
| May | 1115 | 10.29 | 3.29 | 0.10 | 402 | 11.62 | 3.54 | 0.18 | 1.33 | <0.0001 |
| June | 1079 | 14.55 | 2.69 | 0.08 | 390 | 15.49 | 2.52 | 0.13 | 0.95 | <0.0001 |
| July | 1115 | 17.01 | 1.76 | 0.05 | 403 | 18.08 | 1.85 | 0.09 | 1.07 | <0.0001 |
| August | 1116 | 15.99 | 1.96 | 0.06 | 404 | 17.19 | 1.98 | 0.10 | 1.20 | <0.0001 |
| September | 1078 | 12.43 | 2.66 | 0.08 | 420 | 11.97 | 6.72 | 0.33 | -0.46 | 0.0283 |
| Del Norte 2E | | | | | | | | | | |
| May | 1112 | 10.90 | 3.11 | 0.09 | 434 | 10.74 | 3.52 | 0.17 | -0.16 | 0.1387 |
| June | 1079 | 15.09 | 2.63 | 0.08 | 390 | 14.73 | 2.56 | 0.13 | -0.35 | 0.0115 |
| July | 1116 | 17.56 | 1.70 | 0.05 | 434 | 17.41 | 1.72 | 0.08 | -0.15 | 0.0617 |
| August | 1084 | 16.56 | 1.86 | 0.06 | 434 | 16.46 | 1.76 | 0.08 | -0.09 | 0.1856 |
| September | 1072 | 13.13 | 2.61 | 0.08 | 390 | 12.67 | 2.86 | 0.15 | -0.46 | 0.0020 |
| GSDNM | | | | | | | | | | |
| May | 1075 | 10.90 | 3.69 | 0.11 | 434 | 11.61 | 4.12 | 0.20 | 0.72 | 0.0005 |
| June | 1073 | 16.03 | 3.24 | 0.10 | 420 | 16.70 | 2.97 | 0.15 | 0.67 | 0.0001 |
| July | 1078 | 18.67 | 2.07 | 0.06 | 433 | 19.14 | 2.35 | 0.11 | 0.47 | <0.0001 |
| August | 1078 | 17.35 | 2.10 | 0.06 | 434 | 17.93 | 2.16 | 0.10 | 0.58 | <0.0001 |
| September | 1043 | 13.60 | 3.12 | 0.10 | 389 | 14.24 | 3.39 | 0.17 | 0.63 | 0.0004 |
| Manassa | | | | | | | | | | |
| May | 1013 | 10.49 | 3.34 | 0.11 | 427 | 12.13 | 3.39 | 0.16 | 1.64 | <0.0001 |
| June | 912 | 15.12 | 2.72 | 0.09 | 378 | 16.24 | 2.39 | 0.12 | 1.12 | <0.0001 |
| July | 974 | 17.68 | 1.80 | 0.06 | 416 | 18.57 | 1.85 | 0.09 | 0.90 | <0.0001 |
| August | 996 | 16.61 | 1.95 | 0.06 | 410 | 17.64 | 1.68 | 0.08 | 1.04 | <0.0001 |
| September | 949 | 12.96 | 2.82 | 0.09 | 381 | 13.95 | 2.79 | 0.14 | 0.98 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 10.48 | 3.29 | 0.11 | 425 | 11.13 | 3.45 | 0.17 | 0.65 | 0.0004 |
| June | 963 | 14.75 | 2.70 | 0.09 | 414 | 15.08 | 2.61 | 0.13 | 0.33 | 0.0175 |
| July | 970 | 17.52 | 1.96 | 0.06 | 432 | 17.88 | 1.79 | 0.09 | 0.35 | 0.0006 |
| August | 925 | 16.56 | 1.95 | 0.06 | 425 | 16.93 | 1.78 | 0.09 | 0.37 | 0.0004 |
| September | 950 | 12.62 | 2.64 | 0.09 | 359 | 12.92 | 2.89 | 0.15 | 0.30 | 0.0382 |

Table 4.9. Results of t-test analyses for $GDD_{10}$ for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average mean temperature.

| | 1958-1993 | | | | 1994-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1109 | 5.07 | 2.15 | 0.06 | 432 | 5.74 | 2.24 | 0.11 | 0.68 | <0.0001 |
| June | 1078 | 7.74 | 1.81 | 0.06 | 417 | 8.15 | 1.60 | 0.08 | 0.41 | <0.0001 |
| July | 1113 | 9.01 | 1.13 | 0.03 | 431 | 9.13 | 1.14 | 0.05 | 0.13 | 0.0238 |
| August | 1116 | 8.26 | 1.33 | 0.04 | 429 | 8.54 | 1.20 | 0.06 | 0.28 | 0.0001 |
| September | 1080 | 6.37 | 1.83 | 0.06 | 419 | 6.50 | 1.86 | 0.09 | 0.13 | 0.1148 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 4.94 | 2.15 | 0.07 | 403 | 5.39 | 2.28 | 0.11 | 0.45 | 0.0002 |
| June | 1000 | 7.66 | 1.88 | 0.06 | 420 | 7.59 | 2.00 | 0.10 | -0.07 | 0.2735 |
| July | 1047 | 8.99 | 1.30 | 0.04 | 425 | 9.12 | 1.41 | 0.07 | 0.12 | 0.1102 |
| August | 1042 | 8.18 | 1.44 | 0.04 | 415 | 8.36 | 1.34 | 0.07 | 0.19 | 0.0104 |
| September | 977 | 6.33 | 1.79 | 0.06 | 369 | 6.50 | 1.95 | 0.10 | 0.17 | 0.0652 |
| Center 4SSW | | | | | | | | | | |
| May | 1115 | 4.81 | 2.11 | 0.06 | 402 | 5.31 | 2.22 | 0.11 | 0.50 | <0.0001 |
| June | 1079 | 7.20 | 1.75 | 0.05 | 390 | 7.55 | 1.72 | 0.09 | 0.35 | 0.0004 |
| July | 1115 | 8.27 | 1.21 | 0.04 | 403 | 8.66 | 1.35 | 0.07 | 0.39 | <0.0001 |
| August | 1116 | 7.72 | 1.32 | 0.04 | 403 | 8.16 | 1.26 | 0.06 | 0.43 | <0.0001 |
| September | 1078 | 6.17 | 1.77 | 0.05 | 390 | 6.41 | 1.81 | 0.09 | 0.25 | 0.0093 |
| Del Norte 2E | | | | | | | | | | |
| May | 1112 | 4.85 | 2.00 | 0.06 | 434 | 4.83 | 2.03 | 0.10 | *-0.02* | 0.4449 |
| June | 1079 | 7.05 | 1.67 | 0.05 | 390 | 6.93 | 1.61 | 0.08 | *-0.12* | 0.1040 |
| July | 1116 | 8.07 | 1.31 | 0.04 | 434 | 8.04 | 1.28 | 0.06 | *-0.04* | 0.3136 |
| August | 1084 | 7.41 | 1.39 | 0.04 | 434 | 7.43 | 1.23 | 0.06 | *0.01* | 0.4230 |
| September | 1072 | 5.80 | 1.66 | 0.05 | 390 | 5.78 | 1.68 | 0.09 | *-0.02* | 0.4083 |
| GSDNM | | | | | | | | | | |
| May | 1075 | 4.61 | 2.14 | 0.07 | 434 | 4.76 | 2.33 | 0.11 | 0.15 | 0.1136 |
| June | 1073 | 7.45 | 2.05 | 0.06 | 420 | 7.66 | 1.98 | 0.10 | 0.21 | 0.0342 |
| July | 1109 | 8.63 | 2.15 | 0.06 | 433 | 9.19 | 1.91 | 0.09 | 0.56 | <0.0001 |
| August | 1109 | 7.72 | 2.00 | 0.06 | 434 | 8.30 | 1.69 | 0.08 | 0.58 | <0.0001 |
| September | 1073 | 5.73 | 2.12 | 0.06 | 389 | 6.07 | 2.01 | 0.10 | 0.34 | 0.0031 |
| Manassa | | | | | | | | | | |
| May | 1013 | 5.14 | 1.99 | 0.06 | 427 | 5.71 | 2.00 | 0.10 | 0.57 | <0.0001 |
| June | 912 | 7.54 | 1.68 | 0.06 | 378 | 7.99 | 1.49 | 0.08 | 0.45 | <0.0001 |
| July | 974 | 8.70 | 1.20 | 0.04 | 416 | 9.02 | 1.26 | 0.06 | 0.32 | <0.0001 |
| August | 996 | 8.11 | 1.29 | 0.04 | 410 | 8.41 | 1.17 | 0.06 | 0.30 | <0.0001 |
| September | 949 | 6.48 | 1.73 | 0.06 | 381 | 6.62 | 1.62 | 0.08 | 0.15 | 0.0780 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 5.03 | 2.06 | 0.07 | 425 | 5.38 | 2.18 | 0.11 | 0.35 | 0.0018 |
| June | 963 | 7.32 | 1.71 | 0.06 | 414 | 7.61 | 1.66 | 0.08 | 0.29 | 0.0017 |
| July | 970 | 8.47 | 1.28 | 0.04 | 432 | 8.69 | 1.27 | 0.06 | 0.22 | 0.0012 |
| August | 925 | 7.88 | 1.32 | 0.04 | 425 | 8.02 | 1.21 | 0.06 | 0.14 | 0.0307 |
| September | 950 | 6.16 | 1.65 | 0.05 | 359 | 6.40 | 1.67 | 0.09 | 0.24 | 0.0110 |

Table 4.10. Results of t-test analyses for $GDD_{4.4}$ for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average mean temperature.

| | 1958-1993 | | | | 1994-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1109 | 7.94 | 2.33 | 0.07 | 432 | 8.64 | 2.38 | 0.11 | 0.70 | <0.0001 |
| June | 1078 | 11.31 | 2.27 | 0.07 | 417 | 11.54 | 1.82 | 0.09 | 0.23 | 0.0322 |
| July | 1113 | 13.71 | 1.52 | 0.05 | 431 | 13.75 | 1.54 | 0.07 | 0.04 | 0.3082 |
| August | 1116 | 12.60 | 1.74 | 0.05 | 429 | 13.00 | 1.54 | 0.07 | 0.40 | <0.0001 |
| September | 1080 | 9.51 | 2.00 | 0.06 | 419 | 9.74 | 2.07 | 0.10 | 0.24 | 0.0214 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 7.82 | 2.37 | 0.07 | 403 | 8.38 | 2.61 | 0.13 | 0.56 | <0.0001 |
| June | 1000 | 11.30 | 2.46 | 0.08 | 420 | 11.56 | 2.55 | 0.12 | 0.26 | 0.0283 |
| July | 1047 | 13.69 | 1.77 | 0.05 | 425 | 14.13 | 1.84 | 0.09 | 0.44 | <0.0001 |
| August | 1042 | 12.47 | 1.94 | 0.06 | 415 | 13.11 | 1.82 | 0.09 | 0.64 | <0.0001 |
| September | 977 | 9.50 | 2.09 | 0.07 | 369 | 9.92 | 2.42 | 0.13 | 0.42 | 0.0009 |
| Center 4SSW | | | | | | | | | | |
| May | 1115 | 7.67 | 2.28 | 0.07 | 402 | 8.35 | 2.60 | 0.13 | 0.68 | <0.0001 |
| June | 1079 | 10.55 | 2.15 | 0.07 | 390 | 11.19 | 2.16 | 0.11 | 0.64 | <0.0001 |
| July | 1115 | 12.51 | 1.63 | 0.05 | 403 | 13.47 | 1.71 | 0.09 | 0.96 | <0.0001 |
| August | 1116 | 11.64 | 1.72 | 0.05 | 403 | 12.71 | 1.50 | 0.07 | 1.08 | <0.0001 |
| September | 1078 | 9.17 | 1.88 | 0.06 | 390 | 9.83 | 2.16 | 0.11 | 0.66 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| May | 1112 | 7.77 | 2.19 | 0.07 | 434 | 7.76 | 2.36 | 0.11 | *-0.01* | 0.4824 |
| June | 1079 | 10.80 | 2.26 | 0.07 | 390 | 10.52 | 2.09 | 0.11 | *-0.28* | 0.0257 |
| July | 1116 | 13.01 | 1.66 | 0.05 | 434 | 12.88 | 1.68 | 0.08 | *-0.13* | 0.0776 |
| August | 1084 | 12.03 | 1.81 | 0.06 | 434 | 11.97 | 1.71 | 0.08 | *-0.07* | 0.2586 |
| September | 1072 | 9.17 | 2.01 | 0.06 | 390 | 9.03 | 1.98 | 0.10 | *-0.14* | 0.1127 |
| GSDNM | | | | | | | | | | |
| May | 1075 | 7.66 | 2.61 | 0.08 | 434 | 8.05 | 3.08 | 0.15 | 0.40 | 0.0059 |
| June | 1073 | 11.67 | 2.90 | 0.09 | 420 | 12.23 | 2.76 | 0.13 | 0.57 | 0.0003 |
| July | 1109 | 13.68 | 3.02 | 0.09 | 433 | 14.54 | 2.23 | 0.11 | 0.86 | <0.0001 |
| August | 1109 | 12.48 | 2.90 | 0.09 | 434 | 13.40 | 2.10 | 0.10 | 0.93 | <0.0001 |
| September | 1073 | 9.24 | 2.95 | 0.09 | 389 | 10.06 | 2.83 | 0.14 | 0.82 | <0.0001 |
| Manassa | | | | | | | | | | |
| May | 1013 | 8.06 | 2.20 | 0.07 | 427 | 8.87 | 2.40 | 0.12 | 0.82 | <0.0001 |
| June | 912 | 11.08 | 2.18 | 0.07 | 378 | 11.91 | 2.02 | 0.10 | 0.83 | <0.0001 |
| July | 974 | 13.13 | 1.65 | 0.05 | 416 | 13.94 | 1.68 | 0.08 | 0.81 | <0.0001 |
| August | 996 | 12.23 | 1.70 | 0.05 | 410 | 13.09 | 1.61 | 0.08 | 0.86 | <0.0001 |
| September | 949 | 9.70 | 1.96 | 0.06 | 381 | 10.19 | 2.02 | 0.10 | 0.49 | <0.0001 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 7.91 | 2.22 | 0.07 | 425 | 8.28 | 2.40 | 0.12 | 0.37 | 0.0025 |
| June | 963 | 10.71 | 2.17 | 0.07 | 414 | 11.01 | 2.06 | 0.10 | 0.31 | 0.0075 |
| July | 970 | 12.99 | 1.81 | 0.06 | 432 | 13.29 | 1.64 | 0.08 | 0.30 | 0.0019 |
| August | 925 | 12.14 | 1.76 | 0.06 | 425 | 12.44 | 1.69 | 0.08 | 0.30 | 0.0018 |
| September | 950 | 9.23 | 1.82 | 0.06 | 359 | 9.57 | 1.93 | 0.10 | 0.34 | 0.0017 |

Table 4.11. Results of t-test analyses for $GDD_{5.5}$ for each month of the growing season in the San Luis Valley, Colorado. Difference represents the daily mean increase or decrease in the average mean temperature.

| | 1958-1993 | | | | 1994-2007 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | n | Mean | Std Dev | Std Error | n | Mean | Std Dev | Std Error | Difference | *p*-Value |
| Alamosa AP | | | | | | | | | | |
| May | 1109 | 7.34 | 2.27 | 0.07 | 432 | 8.04 | 2.35 | 0.11 | 0.71 | <0.0001 |
| June | 1078 | 10.51 | 2.20 | 0.07 | 417 | 10.82 | 1.81 | 0.09 | 0.31 | 0.0059 |
| July | 1113 | 12.75 | 1.55 | 0.05 | 431 | 12.93 | 1.63 | 0.08 | 0.19 | 0.0173 |
| August | 1116 | 11.63 | 1.67 | 0.05 | 429 | 12.02 | 1.51 | 0.07 | 0.39 | <0.0001 |
| September | 1080 | 8.82 | 1.93 | 0.06 | 419 | 9.02 | 1.97 | 0.10 | 0.20 | 0.0370 |
| Blanca 4NW | | | | | | | | | | |
| May | 1052 | 7.21 | 2.29 | 0.07 | 403 | 7.73 | 2.52 | 0.13 | 0.51 | 0.0001 |
| June | 1000 | 10.50 | 2.37 | 0.08 | 420 | 10.66 | 2.49 | 0.12 | 0.17 | 0.1165 |
| July | 1047 | 12.75 | 1.84 | 0.06 | 425 | 13.23 | 1.99 | 0.10 | 0.48 | <0.0001 |
| August | 1042 | 11.51 | 1.89 | 0.06 | 415 | 12.07 | 1.79 | 0.09 | 0.57 | <0.0001 |
| September | 977 | 8.80 | 1.99 | 0.06 | 369 | 9.15 | 2.27 | 0.12 | 0.35 | 0.0029 |
| Center 4SSW | | | | | | | | | | |
| May | 1115 | 7.07 | 2.22 | 0.07 | 402 | 7.68 | 2.48 | 0.12 | 0.61 | <0.0001 |
| June | 1079 | 9.78 | 2.03 | 0.06 | 390 | 10.32 | 2.06 | 0.10 | 0.54 | <0.0001 |
| July | 1115 | 11.54 | 1.59 | 0.05 | 403 | 12.49 | 1.76 | 0.09 | 0.95 | <0.0001 |
| August | 1116 | 10.71 | 1.61 | 0.05 | 403 | 11.67 | 1.49 | 0.07 | 0.97 | <0.0001 |
| September | 1078 | 8.52 | 1.83 | 0.06 | 390 | 9.04 | 2.02 | 0.10 | 0.52 | <0.0001 |
| Del Norte 2E | | | | | | | | | | |
| May | 1112 | 7.14 | 2.13 | 0.06 | 434 | 7.13 | 2.25 | 0.11 | *-0.01* | 0.4598 |
| June | 1079 | 9.91 | 2.12 | 0.06 | 390 | 9.65 | 1.97 | 0.10 | *-0.26* | 0.0274 |
| July | 1116 | 11.94 | 1.66 | 0.05 | 434 | 11.80 | 1.65 | 0.08 | *-0.13* | 0.0779 |
| August | 1084 | 10.98 | 1.77 | 0.05 | 434 | 10.92 | 1.65 | 0.08 | *-0.06* | 0.2850 |
| September | 1072 | 8.38 | 1.87 | 0.06 | 390 | 8.28 | 1.85 | 0.09 | *-0.10* | 0.1854 |
| GSDNM | | | | | | | | | | |
| May | 1075 | 6.97 | 2.47 | 0.08 | 434 | 7.29 | 2.88 | 0.14 | 0.32 | 0.0263 |
| June | 1073 | 10.73 | 2.79 | 0.09 | 420 | 11.23 | 2.69 | 0.13 | 0.49 | 0.0009 |
| July | 1109 | 12.68 | 2.94 | 0.09 | 433 | 13.53 | 2.32 | 0.11 | 0.85 | <0.0001 |
| August | 1109 | 11.44 | 2.76 | 0.08 | 434 | 12.34 | 2.09 | 0.10 | 0.90 | <0.0001 |
| September | 1073 | 8.41 | 2.74 | 0.08 | 389 | 9.14 | 2.65 | 0.13 | 0.73 | <0.0001 |
| Manassa | | | | | | | | | | |
| May | 1013 | 7.45 | 2.14 | 0.07 | 427 | 8.18 | 2.29 | 0.11 | 0.73 | <0.0001 |
| June | 912 | 10.28 | 2.07 | 0.07 | 378 | 11.02 | 1.94 | 0.10 | 0.74 | <0.0001 |
| July | 974 | 12.17 | 1.65 | 0.05 | 416 | 12.97 | 1.76 | 0.09 | 0.80 | <0.0001 |
| August | 996 | 11.30 | 1.63 | 0.05 | 410 | 12.05 | 1.60 | 0.08 | 0.76 | <0.0001 |
| September | 949 | 8.99 | 1.89 | 0.06 | 381 | 9.38 | 1.88 | 0.10 | 0.39 | 0.0003 |
| Monte Vista 2W | | | | | | | | | | |
| May | 972 | 7.31 | 2.17 | 0.07 | 425 | 7.66 | 2.32 | 0.11 | 0.36 | 0.0027 |
| June | 963 | 9.94 | 2.07 | 0.07 | 414 | 10.23 | 1.97 | 0.10 | 0.29 | 0.0077 |
| July | 970 | 12.01 | 1.80 | 0.06 | 432 | 12.32 | 1.65 | 0.08 | 0.31 | 0.0010 |
| August | 925 | 11.15 | 1.69 | 0.06 | 425 | 11.43 | 1.62 | 0.08 | 0.28 | 0.0020 |
| September | 950 | 8.55 | 1.74 | 0.06 | 359 | 8.86 | 1.82 | 0.10 | 0.30 | 0.0028 |

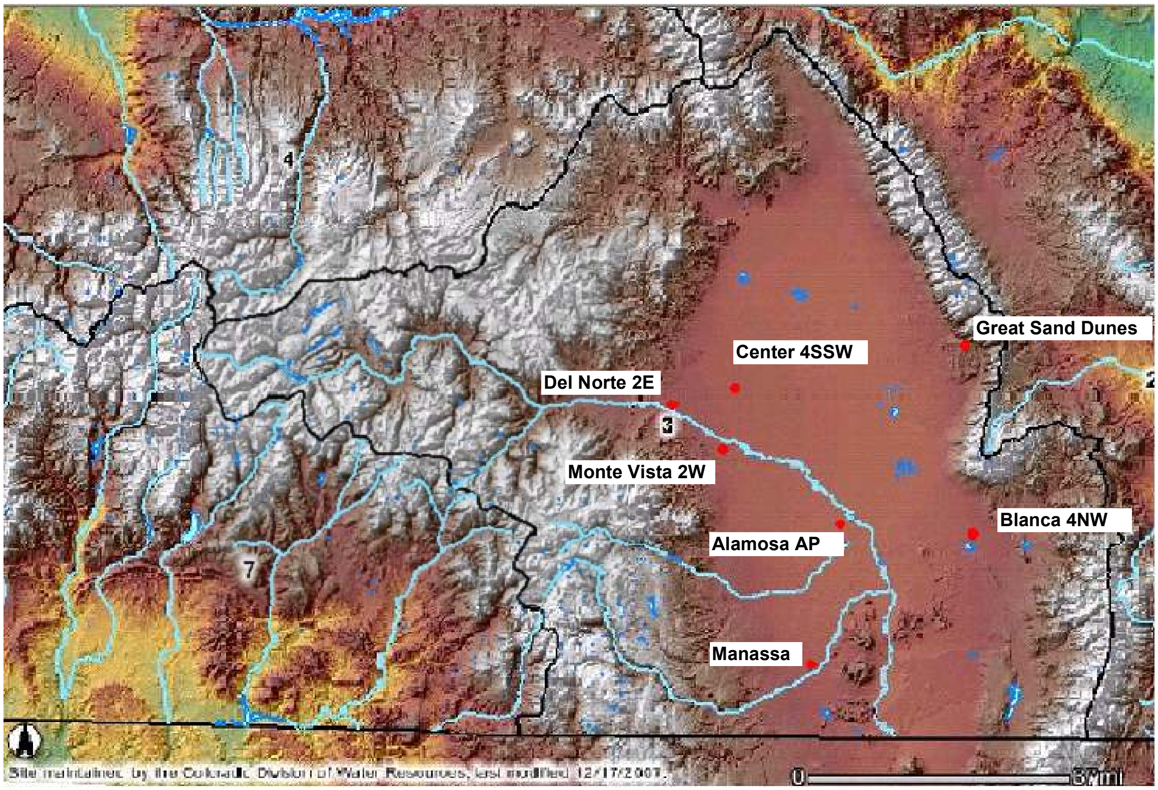


Figure 4.1. Map depicting the locations of each station in the San Luis valley, Colorado. Map source: Colorado Decision Support System

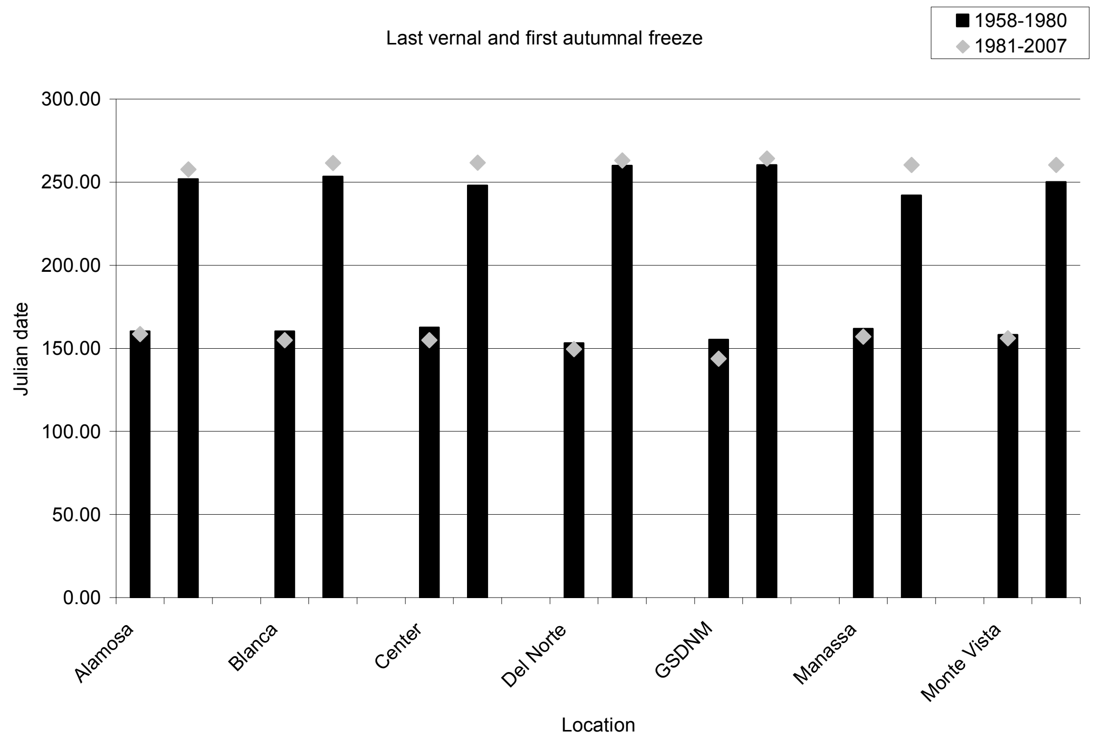


Figure 4.2. Comparison of 1958-1993 (bar) mean annual freeze dates to 1994-2007 (diamond) mean annual freeze dates for each valley floor station in the San Luis Valley, Colorado. The first bar and diamond for each station represents the vernal freeze and the second the autumnal freeze.

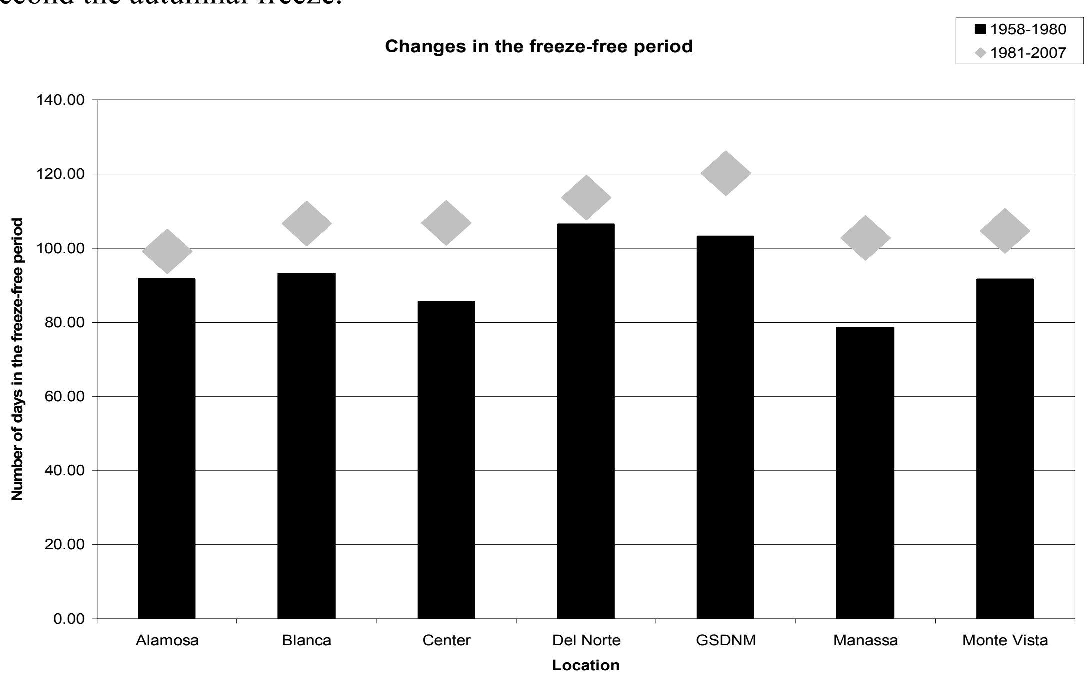


Figure 4.3. Comparison of 1958-1993 (bar) mean length of the freeze-free period to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

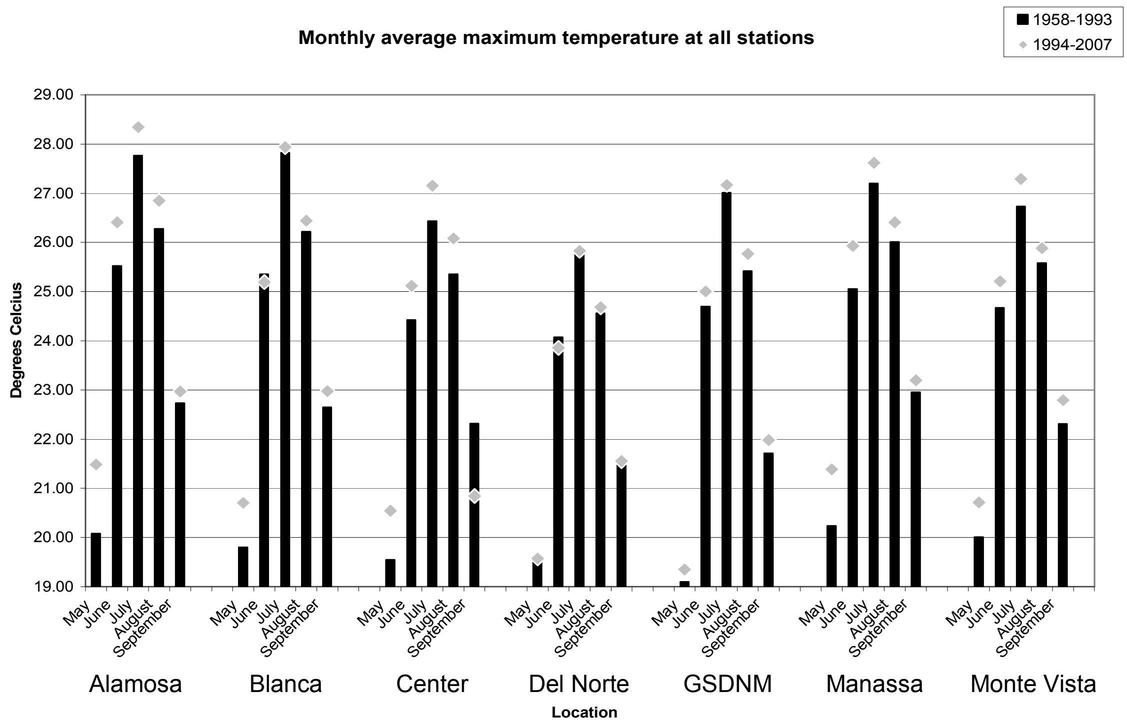


Figure 4.4. Comparison of 1958-1993 (bar) monthly average maximum temperature to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

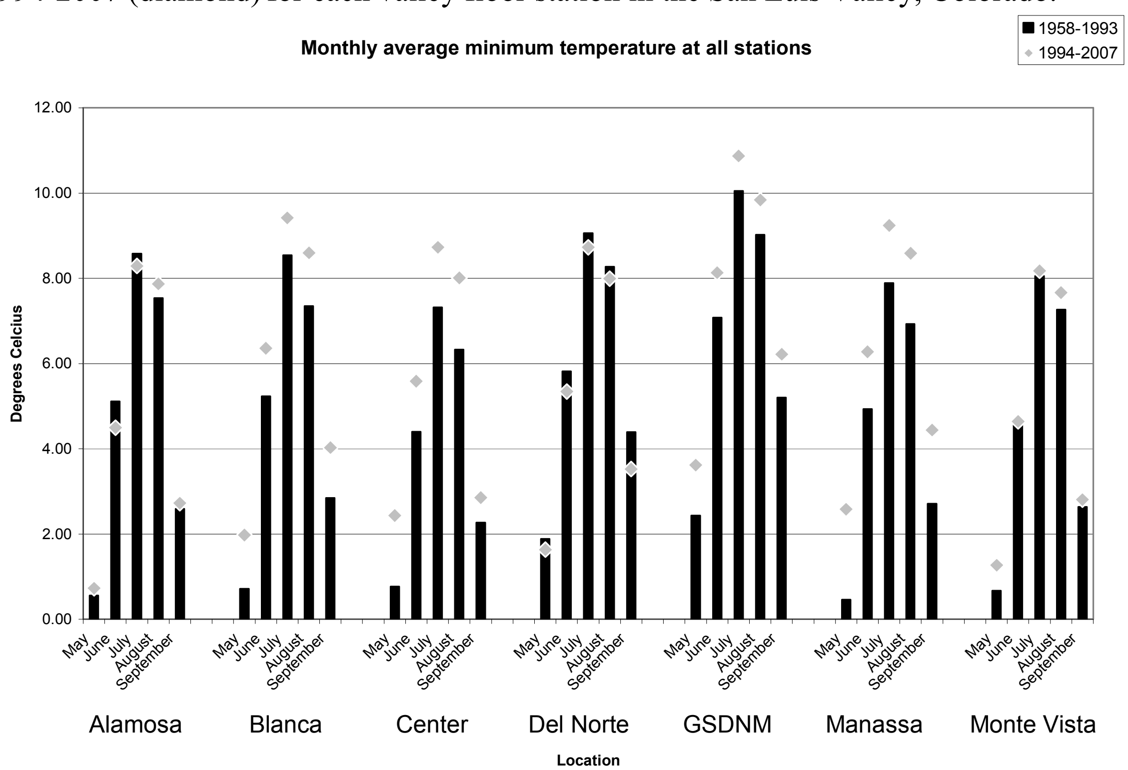


Figure 4.5. Comparison of 1958-1993 (bar) monthly average minimum temperature to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

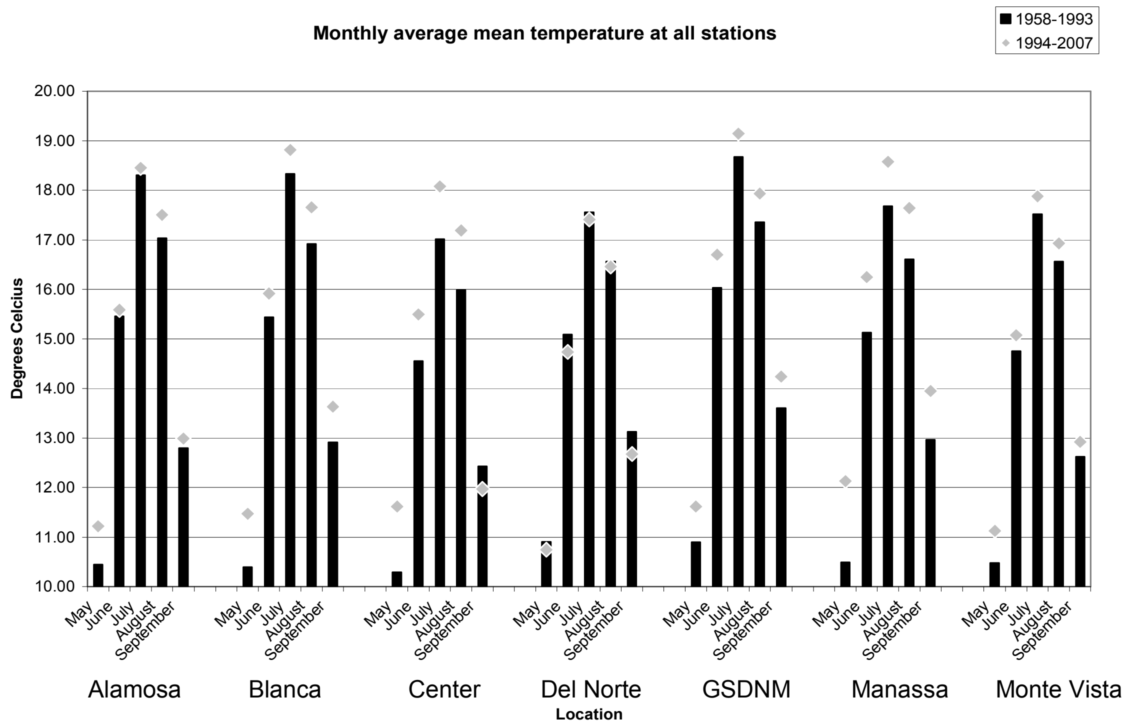


Figure 4.6. Comparison of 1958-1993 (bar) monthly average mean temperature to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

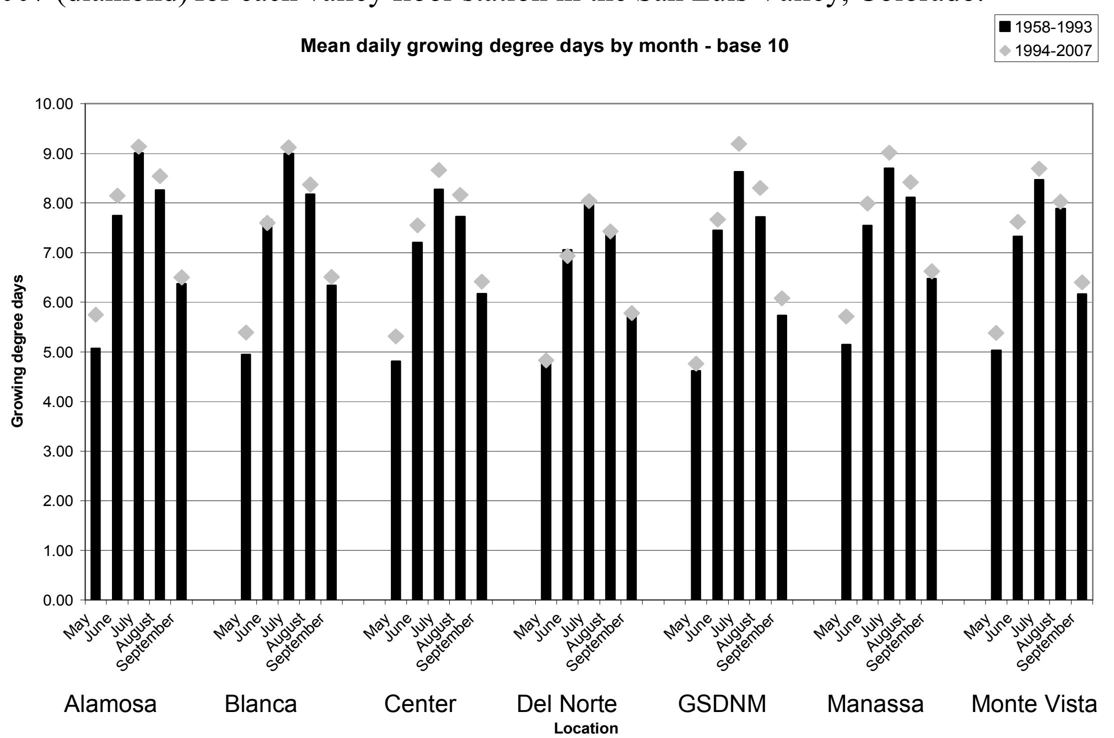


Figure 4.7. Comparison of 1958-1993 (bar) mean daily $GDD_{10}$ in each month to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

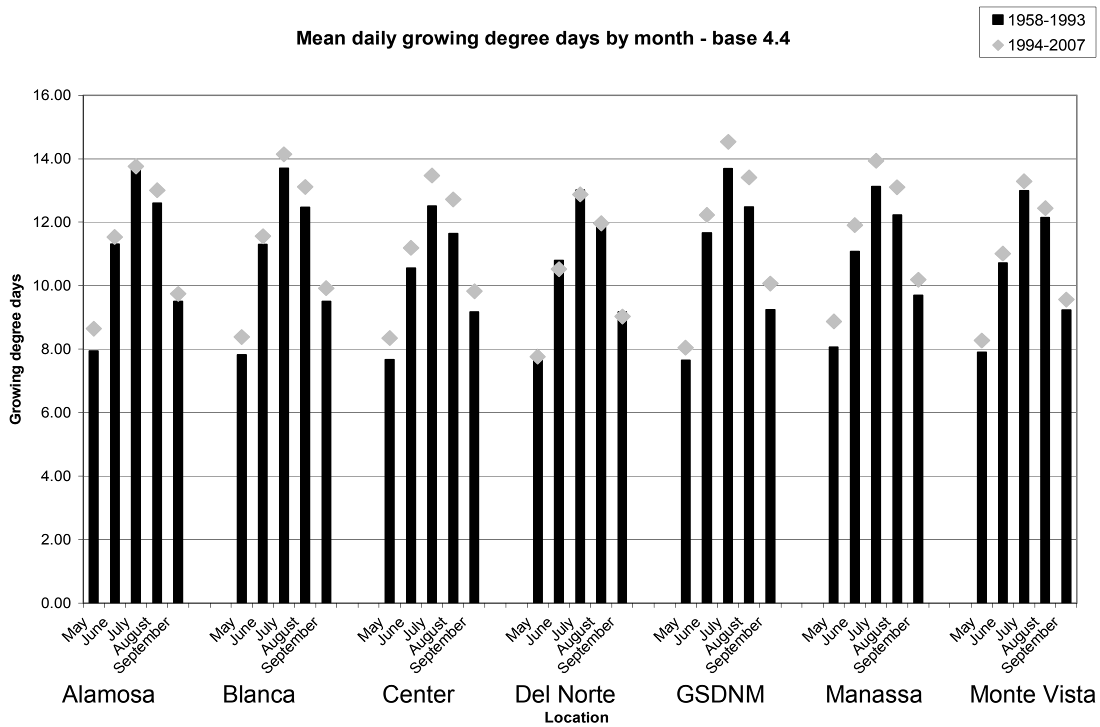


Figure 4.8. Comparison of 1958-1993 (bar) mean daily $GDD_{4.4}$ in each month to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

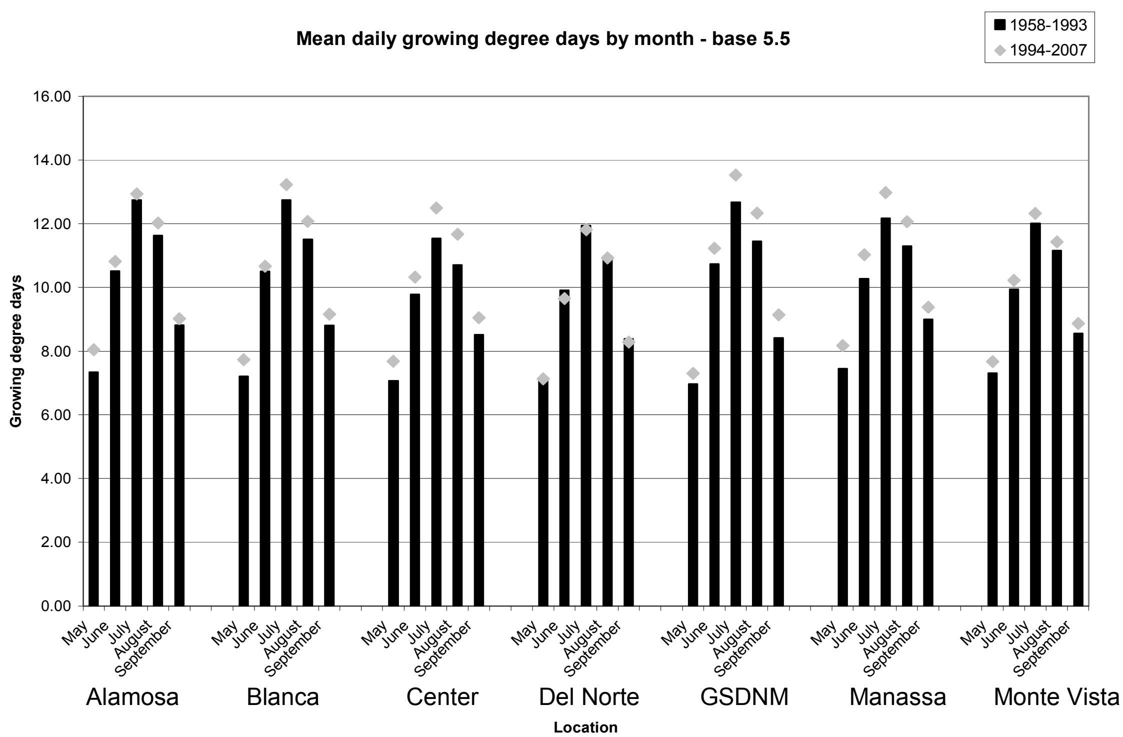


Figure 4.9. Comparison of 1958-1993 (bar) mean daily $GDD_{5.5}$ in each month to 1994-2007 (diamond) for each valley floor station in the San Luis Valley, Colorado.

**CHAPTER 5**

# WATER RIGHTS IN THE UPPER RIO GRANDE: THE EFFECTS OF WATER APPROPRIATIONS AND ALLOCATIONS

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***Abstract:*** *This study assesses changes in water rights appropriations and allocations in the Upper Rio Grande (URG). It also explores the causes and effects of the changes on collateral elements in the URG agriculture system, namely the San Luis Valley (SLV), Colorado. Population increases, after the acquisition of the territory from 1854 to 1900, were the major cause of increased acquisitions of surface water rights. By 1912 surface waters were nearly 100% appropriated. The population continued to increase until 1930 after which it remained stable. Water users began making large increases in the number of appropriations of groundwater around 1925, with the majority of increases starting around 1935. As a result, moratoriums were placed on well development in the 1970s and 80s. Individual 'spikes' in water rights acquisitions of surface and groundwater were associated with periodic droughts and high crop prices. A change point analysis identified major periods of acquisition of waters rights, including 1881-1911 for surface water, 1935-1981 for the unconfined aquifer and 1945-1967 for the confined aquifer. Collateral effects on stream flows and agricultural acreage also were evident. The annual stream outflows from the SLV declined by 400 $hm^3$ after 1924, being attributed to surface water extractions. An additional reduction in outflow of 60 $hm^3$ 1925-1963 was attributed to groundwater extraction. An increase in agricultural acreage by 80,000 ha from 1948-1978 fostered the increase in groundwater rights acquisition from 1935-1981.*

Keywords: Upper Rio Grande, San Luis Valley, stream flow, appropriation, allocation, groundwater, surface water, water rights

## Introduction

Food and water security are two critical issues facing society today.[1] They are of even greater concern in arid regions, such as the western U.S., where the aridity has prompted the development of large irrigated agriculture enterprises. Water rights must be acquired in order for western U.S. agriculture operations to secure the water necessary for agricultural irrigation. The timing of when water rights appropriations and allocations occurred may be tied to changes in other regional factors such as drought, agricultural economics, policy change or population growth. Further, the extraction of water from the hydrologic system influences stream flow and possibly agricultural expansion. This report provides a historical analysis of water appropriations and allocations in the Upper Rio Grande (URG) which, for the purpose of this study, is defined as the region north of the New Mexico state line. Of primary concern are changes in policy and water law, population growth and development, and climate and agricultural economics as potential causes for the timing of those activities and their influences on other regional elements.

### *Western water law and Colorado water law*

Water laws of the U.S. are historically bimodal, with water laws in the western U.S. being based on prior appropriation, as opposed to riparian rights in the eastern U.S. This situation arose because of the evolution of U.S. water laws in different climatic settings, with different settlement patterns, uses and different access to developing water law and property rights precedents. Eastern states receive much more precipitation than the western states and, therefore, adequate supplies of water for agricultural irrigation were not a major concern in their water law development. In-stream uses were most important in the developing industrial period of the early-1800s, particularly for mill operation.[2]

In contrast to eastern water instream uses, western water use is largely consumptive or extractive in nature, typically extracted for mining applications or irrigation.[3] Western water laws were developed in response to these needs and interests in an arid climatic setting, and during the rush for western expansion. Further, western water laws were developed in a relative communication vacuum in the western frontier, thereby not being significantly influenced by water law precedents of the eastern U.S.[4, 5, 3, 6]

As a result of the above circumstances, the only law governing water acquisition and rights in Colorado is prior appropriation. Although many other states utilize prior appropriation as part of their water laws, Colorado is unique in that prior appropriation is the only state water law.[7] As early as 1879, however, the state created water districts, using watershed boundaries to define their limits. Colorado was the first western state to enact state control of water resources.[7] The state constitution also called for all water not previously apportioned to be considered public property and, therefore, available for appropriation.

As the URG was settled and developed, irrigated agriculture became the major economic activity, and comprises more than 30% of its present local economy.[8] Within a few years of settlement, nearly 240,000 hectares were under irrigated cultivation. So much surface water had been appropriated by the late 1880s, that water shortages began to appear in the El Paso (Texas) and Cuidad Juarez (Mexico) reaches of the Rio Grande.[9] These shortages were the impetus for treaties between Mexico and U.S. to govern the shared waters of the Rio Grande and resulted in the 1906 and 1944 Treaties with Mexico. It also led to the Interstate Compact of 1938 with New Mexico (NM) and Texas (TX), and all contained requirement for Colorado to deliver a portion of Rio Grande water to its state border.

The law of prior appropriation, however, was originally applied to only surface waters, ignoring groundwater resources. Although Colorado now has a Water Conservation Board to create Groundwater Management Districts, the San Luis Valley (SLV) was denied a request for the designation of a groundwater district for the Valley.[10] The apparent rationale for this denial was the complex hydrologic connection of the aquifers with surface water, and the impact that groundwater development could have on the Interstate Compact.[10] Potential negative impacts from these un-metered groundwater withdrawals include withdrawals from the aquifers greater than the rate of annual recharge, or unauthorized lateral withdrawals from the hydrologically-connected streams.

Since the settlement of the SLV in 1850, the development of local agriculture has been strongly linked to the availability of irrigation water. The historical activity of water rights acquisitions and their sources reflect increases in irrigated acreage, changes in irrigation practices, or shifts to different water sources. A water right imparts both a singular right to water, dating from the time and location for which it was appropriated, and carrying with it an allocation (i.e., the quantity of water allotted to the right).

*The San Luis Valley*

The San Luis Valley portion of the URG is located in south-central Colorado (Figure 5.1). The San Juan Mountains form the western boundary of the SLV, which contain the headwaters of the Rio Grande, an important international transboundary river between the U.S. and Mexico. The eastern boundary of the SLV is formed by the Sangre de Cristo Mountains. The drainage area, approximately 20,719 sq km., was created from the Rio Grande Rift, formed as the two mountain ranges began moving apart from each other approximately 300 mya. The elevation of the SLV valley floor is approximately 2200 m, making it one of the highest inhabited and developed montane deserts in the world, with the surrounding mountain peaks rising to greater than 4200 m. Approximately 200,000 hectares are under cultivation on the valley floor.

Much of the moisture in the prevailing westerly winds precipitates out in the San Juan Mountains as orographic events, while the moisture in the easterly winds is precipitated in the Sangre de Cristo Mountains. Thus, each range effectively creates a rainshadow for the valley floor, resulting in less than 20 cm of precipitation annually in the SLV itself.[11, 12, 13] The area also is characterized by periodic droughts, some being intermittently severe and long-lasting.[14]

Snowmelt from winter snowpacks in the western San Juan Mountains and eastern Sangre de Cristo Mountains, sustain the spring flow in the Upper Rio Grande, and its local tributaries and streams. The river and its local tributaries are essentially the lifeblood of the SLV, facilitating the development of irrigated agriculture in the alpine desert of the valley floor. The appropriation and allocation of these waters for irrigated agriculture has resulted in the development of a linked social-ecological system, with the agricultural system heavily reliant on local surface and ground water for irrigation.

The habitation of the SLV has changed considerably over the last millennium. There is evidence the SLV was periodically settled by members of the Ute nation and other native peoples of the southwest during pre-Columbian times.[12, 15] During the 1500s and into the early-1800s, Spanish missionaries entered the SLV and built missions that were temporarily occupied. Spain held title to the territory at that time, as a portion of northern Mexico, known as New Mexico Territory.[16] Following Mexican independence in 1821, the territory containing the SLV became part of Mexico.

After the secession of Texas from Mexico in 1836, the Republic of Texas claimed all or most of the land in the SLV east and north of the Rio Grande.[16] When Texas was annexed by the U.S. in 1845, the boundaries remained relatively unchanged. During discussion of the annexation, there was a dispute as to whether or not the western-most regions, including the SLV, would be a part of Texas or the United States, notwithstanding the dispute with Mexico over the same region.[17] Following the annexation of Texas and the Mexican-American War, which concluded with the Treaty of Guadalupe in 1848, all of the SLV became U.S. territory.[17] The SLV officially became a part of the territory of the future state of Colorado in 1854.

During this period of changing political boundaries, ownerships of several large tracts of land in Colorado were deeded by Mexico as land grants to petitioners, with three being located in the SLV. The largest claimed colony grant was the Conejos/Guadalupe Grant, covering about 1.01 million ha., including all of present day Conejos and Rio Grande counties and large portions of Alamosa and Saguache counties.[18] The next largest was the colony grant of Sangre de Cristo/Lee-Beaubien, being approximately 400,000 ha, comprising all of present day Costilla County, Colorado. Colony grants stipulated that colonization of the land was to occur. The Luis Maria Baca No. 4/Vegas Grande Grant, located in present day Saguache County, Colorado was the smallest

(40,000 ha). Only the Baca and Sangre de Cristo grants were formally confirmed by Congress after U.S. annexation.[18]

In 1891, the Federal Court of Private Land Claims began taking appeals to settle land ownership disputes arising from the Mexican land grants.[19] The largest claim of the Conejos/Guadelupe in the SLV was ultimately denied by the Court of Private Land Claims in 1900.[20] The denial was based on a lack of evidence that colonization, as stipulated in the deed, actually had occurred in the granted territory.[18]

Permanent European settlement was not established in the SLV until the local Hispanic population founded the town of San Luis in 1851, within the Sangre de Cristo grant.[21] Shortly after the town of San Luis was founded, the first major water right was claimed in 1852.[22] This first right was a community right, in the form of a ditch, "San Luis People's Ditch," which was collectively dug and maintained by members of the community. It diverted water from the Culebra Creek, a Rio Grande tributary, for agricultural use, marking the beginning of irrigated agriculture in the SLV. Many other ditches and additional water rights appropriations and allocations have been granted in the SLV for irrigated agriculture since this first ditch was dug.

The Denver and Rio Grande Railroad was constructed in the 1870s, traversing the SLV east/west and north/south.[15] Gold discoveries in the San Juan Mountains also precipitated a major influx of settlers seeking their fortunes.[16] This influx was concurrent with the arrival of Midwesterners and Mormons, marking the beginning of agrarian settlement of the SLV.[15] Both groups brought a farming style typical of the eastern plains (small grains and vegetables, with some livestock). As a consequence, most settlement took place on the alluvial fan of the Rio Grande, where irrigation water was readily available. In the 1920s and 1930's, a contingent of Nisei Japanese-Americans moved into the SLV, initiating a further change in the Valley's agricultural system by introducing vegetable production operations. This change resulted in development of a large truck farming enterprise of more than 1600 ha within a few years.[15, 22]

Frank Zybach, a Nebraskan farmer, invented center pivot irrigation in 1948.[23, 24] This revolutionary, self-propelled irrigation system is now the primary irrigation method for nearly a third of all irrigated lands in the U.S.[23] Although the water source for center pivot systems can be groundwater or surface water, these systems are not constrained by proximity to surface water, making it possible to utilize them on landlocked acreage. They were dependent, therefore, on groundwater, with most systems utilizing the unconfined aquifer as a water source.[25] Center pivot irrigation is a prominent irrigation system in the arid western U.S., particularly where surface water is unavailable. In this region irrigation is a requirement for crop production and as an insurance against the occurrence of droughts. The southwestern U.S. frequently experiences periods of drought, which appears to be part of an ongoing climatic cycle.[26] Being located in this region, the SLV has also experienced several droughts since recent settlement.[26] Snowmelt runoff from snowpack on these mountains provides the water for spring streamflows in the Rio Grande, its local tributaries and groundwater recharge and therefore irrigation waters for the SLV.[12]

Objectives

Surface and ground water rights in the Upper Rio Grande's San Luis Valley have had a major influence on international and interstate water availability. In regard to this background, the objective of this study is to identify: (1) specific time periods between

1850 and 2003 when high and low periods of water appropriations and allocations occurred for different water sources; (2) the potential causes for increases and decreases in that activity; and (3) collateral impacts on stream flows and agriculture in the Upper Rio Grande.

Methods

Relevant data were identified from the Colorado Water Division 3, Water Rights Tabulation for 2006. The earliest documented water rights are 1852, while this tabulation's most recent rights occurred in 2003. Because more than 95% (by volume) of all water use in the SLV is related to irrigation, the data were not separated into irrigation related and non-irrigation related. However, the data were separated by water source (surface water; reservoirs; groundwater in confined and unconfined aquifers). Further, each type of water source was separated into categories of appropriation (count) and allocation (volume or pumping rate).

Change point analysis was conducted to identify the distinct periods of activity for each category (count and volume) within each type of water source. Change point analysis utilizes an iterative cumulative sum (CUSUM) procedure in combination with the bootstrapping method of analysis.[27] The CUSUM chart starts and ends at zero with the maximum distance the CUSUM chart deviates from zero being the measure of change. It then compares the CUSUM chart of the original data with the CUSUM charts of random reordering of the data (called bootstraps) to determine if there is a significant difference indicating a significant change. Because of this bootstrapping approach, the method is distribution free. If a change is detected, the time of the change is estimated and the data split at the change point. The analysis is then repeated on each segment to detect further changes. As a result, more than one set of data is identified as being statistically separate from other sets. Each set or sequence has a statistical distribution more similar to the data within than to data in other sets of the same series. One or more points are estimated that define the moment of change or shift in distribution and a range of points is provided as the likeliest period for change, along with the previous and new mean value. Previous studies indicated changes in the means of time series data can be identified via this analysis.[28, 29, 30, 27] A correlation analysis was also performed to determine the presence of any positive or negative correlation between the appropriation and allocation activity of surface and ground waters.

The Closed Basin Project was not included in the analysis. It is a singular large volume event designed to augment water deliveries to downstream states and Mexico in order to comply with the Interstate Compact of 1938 and the treaties with Mexico. It was authorized by Congress in 1972 and completed in the 1990's.

Results

Change point analysis of surface water appropriations identified 8 distinct periods of appropriations. The periods were identified as 1852-1869, 1870-1875, 1876-1890, 1891-1907, 1908-1911, 1912-1926, 1927-1982 and 1983-2001, with respective annual mean appropriations of 11.61, 102.33, 65.73, 18.82, 38.00, 9.47, 2.43 and 5.74 (Table 5.1). There were 6 periods identified for allocations: 1852-1969, 1870-1880, 1881-1891, 1892-1906, 1907-1911 and 1912-2001 with respective mean annual allocations of 95.44, 298.91, 692.09, 172.47, 871.20 and 52.12 cubic feet second$^{-1}$ (cfs). Change point analysis of the unconfined aquifer identified 5 distinct periods for the number of well appropriations (Table 5.2): 1852-1893, 1894-1909, 1910-1934, 1935-1980 and 1981-

2001 with respective annual mean appropriations of 2.77, 1.06, 5.76, 62.87 and 1.00. There were 6 periods identified for allocations: 1852-1900, 1901-1924, 1925-1933, 1934-1949, 1950-1980 and 1981-2001 with respective total mean annual pumping rate of 3.58, 0.33, 14.62, 90.93, 160.37, 17.82 cfs. Change point analysis of confined aquifer appropriation identified 4 distinct periods: 1852-1889, 1890-1899, 1900-1968, 1969-2001 with respective mean annual appropriations of 2.92, 21.10, 88.22 and 5.75. Ten distinct periods were identified for confined aquifers allocations (Table 5.3): 1852-1900, 1901-1935, 1936-1944, 1945-1950, 1951-1956, 1957-1962, 1963-1967, 1968-1972, 1973 and 1974-2001, with respective total mean annual pumping rate of 0.51, 7.61, 43.05, 92.76, 255.29, 74.72, 214.28, 53.93, 17.44 and 0.88 cfs. Change point analysis of appropriations related to reservoir building identified 5 periods as 1852-1878, 1879-1911, 1912-1961, 1962-1977 and 1978-2001 with mean annual reservoir construction of 2.17, 5.36, 1.70, 7.19 and 2.17 respectively. Change point analysis of the reservoirs construction based on volume identified 3 periods (Table 5.4): 1852-1901, 1902-1911 and 1910-2001 with mean annual volumes of 556.16, 38603.00 and 539.97 acre feet, respectively. Correlation analysis (Table 5.5) indicated a strong negative correlation ($p<0.05$) between surface water appropriations and increases in groundwater appropriations.

Discussion

Change point analysis indicated there were several different periods of activity for all types of water sources, as well as within each type, based on water appropriations and allocations. To identify more meaningful periods of activity for discussion, the data were combined into 3-5 periods of high or low rates of activity, based on the boundaries defined by the analysis. This was achieved by combining contiguous periods of similarly high or low values into longer time periods. Surface water appropriations and allocations were combined into 4 periods of activity each: 1852-1870, 1871-91, 1892-1912, 1913-2001 and 1852-1870, 1871-92, 1893-1912, 1913-2001 respectively (Figures 5.2 and 5.3). Appropriations and allocations from the unconfined aquifer were combined into 3 periods of activity: 1885-1935, 1936-1981 and 1982-2001 for each (Figures 5.4 and 5.5). Appropriations and allocations from the confined aquifer were combined into 3 and 4 periods of activity: 1865-1900, 1901-1969, 1970-2001 and 1865-1936, 1937-1952, 1953-1969, 1970-2001 respectively (Figures 5.6 and 5.7).

Nearly all surface water rights were acquired prior to 1911. Water rights for groundwater began a steep increase by 1935 (Figures 5.8 and 5.9). For groundwater rights, appropriation activity is similar for both aquifers with each beginning steep increases after about 1935; however there are some differences. One difference is the confined aquifer offers the advantage of artesian flows. It is deeper, and therefore more costly to access. Major activity in the number of wells developed in the confined aquifer began after 1900 and continued until about 1969, but allocation volumes increased much later, starting around 1936 (Figure 5.8). Appropriations of well development in the unconfined aquifer largely took place between 1935 and 1981 (Figure 5.9).

Within the dates identified by change point analysis, several different events occurred with the potential to influence changes in water rights; including settlement, high crop prices, drought, and policy changes in regard to moratoriums on well development.[22, 31, 32, 33] These periods also correspond to other change points in stream flow and agriculture (Figure 5.10 and 5.11).

*The influence of population*

As the population of the SLV increased, surface waters were the first appropriated and most easily-accessed waters in the SLV. Further, as the population increased, so did agriculture acreage and the need for irrigation. The San Luis Peoples Ditch was the first diversion of appropriated surface waters in the SLV, being granted in 1852. Following the Homestead Act of 1862, permanent settlement of the SLV during the first 20 years after the Act when into effect was slow. Early appropriations were relatively few, at a rate of about 11 per year until 1871 (Table 5.1). The greatest influx of settlers to the area was during 1871-1891. By this time a newly-dug 225 kilometer complex of canals, including the Rio Grande, San Luis Valley, Citizens Ditch and Empire, made the water readily available to new settlers, allowing the irrigation of more than 200,000 hectares.[22] In the same time period the railroad was completed in the SLV, increasing access to settlers and opportunities for shipping agriculture commodities. Additionally, the land grants were being broken up, land speculators arrived, gold was discovered in the San Juan Mountains and a large contingent of settlers arrived.[15, 34] These factors undoubtedly contributed to increases in surface water appropriations with mean annual appropriations increasing by six to ten times that of the previous period's rate. After 1891 the opportunity for appropriating surface waters diminished as indicated by the drop in appropriations from an annual mean of 76 appropriations to 22 during the period 1891-1911 (Figure 5.2). Mean annual appropriations diminished to less than 5 after 1911, further indicating the lack of availability of surface water rights.

Surface water allocation rates decreased considerably after 1891, from a prior annual mean allocation rate of 315 cfs to 172 cfs during the 1892-1906 period (Figure

5.3). The reduction in water allocations is likely attributable to both the lack of available surface water for allocation purposes, and the 1906 Treaty with Mexico that guaranteed delivery of 60,000 acre-feet of water to Ciudad Juarez (Chihuahua, Mexico). However, the population of the SLV continued to increase after the 1906 Treaty, putting additional pressure on the local water resources.

Population increases also affected groundwater extraction between 1900 and 1940. The population was stable at about 20,000 until 1940, increasing to about 40,000 between 1930 and 1940, after which it stabilized (Figure 5.12). This rise in population from 1900 to 1940 coincides with the increase in groundwater exploitation around 1936. At that point, surface water was no longer easily available, meaning that, as the population increased, so did the groundwater exploitation. Groundwater rights mean annual appropriation increased by more than 90 with mean annual allocation rates increasing by more than 50 cfs. There is no evidence of drought in the early 1930s nor were increases in agricultural acreage responsible for increases in groundwater rights. Since surface water was no longer available, the population increase seems to be the only other proximal cause for increased groundwater exploitation. The effect of the declining availability of surface water rights on the increasing groundwater rights, illustrated in Figures 5.13 and 5.14, indicate a shift from surface waters rights to groundwater rights. These figures compare a reducing sum of total surface appropriations and allocations to an increasing sum of all well appropriations and pumping rates.

*The influence of drought*

Drought is another cause of the increased surface water allocation rates in the late 1800s. Increases in surface water appropriations and allocation rates would have served as a hedge against future droughts. Reconstructed data indicates a severe drought of about -1.5 on the Palmer Drought Severity Index between 1870 and 1885, and another from 1890 to about 1905.[14] Surface water appropriation and allocation increased greatly between 1870 and 1891, with some minor increases thereafter until 1912. Several spikes in both surface appropriation and allocations that correspond to drought are evident in Figures 5.2 and 5.3, respectively.

Other droughts occurred around 1925 and 1950-1960, resulting in a pattern of groundwater allocations in response to drought, similar to surface water rights. Groundwater allocations are similar for both aquifers. Allocations were highest for both during 1952-1968, with 1955 and 1964 being greater than in any other years. In those years the total mean annual allocation rate of nearly 350-450 cfs was almost 3 times that of previous years. This period is most likely a response to the severe drought of the 1950s. It is common for farmers to utilize groundwater as a supplemental resource for agricultural irrigation during droughts.[32] Moreover, government officials have recommended increased well development as a preventative measure against drought conditions.[35] There is a tendency for groundwater extractions to increase following droughts.[32, 36] This tendency was observed in the SLV. Additionally, concurrent with the droughts there was an expansion of irrigated agriculture in the SLV, concomitant with population increases.[22, 37]

*The influence of crop prices*

One other factor that might have caused increases in the number of wells and pumping volumes was the emergence of high crop prices. Several periods of increased well development appear after high price years for potato crops. Potatoes are high value crops, roughly 10 times the value of alfalfa. Reasonably high potato prices occurred for many of the years between 1910 and 1960; relative to the years previous. Notably record high potato prices occurred in the period between World War I and 1940. Government price supports were enacted during World War II until 1950, to reduce price volatility and created a period of consistent prices higher than following years. Occasional high price years also occurred in the 1950s and 1960s.[38, 39] Post war high prices encouraged additional well developments, with spikes in groundwater rights occurring concurrently or following closely within one or two years (Figures 5.4, 5.5 and 5.6). Water appropriations nearly doubled from a few years earlier in each case, from an annual mean of 60 to more than 150 in both 1955 and 1964. This corresponds approximately to the same period in which potato prices peaked. On-farm capital reinvestment is a common practice following high crop price years. This was substantiated in research in Devon, England that indicated reinvestment in farm machinery increases with net revenue.[31] Further, the personal experiences in agriculture of the lead author of this report, coupled with that of other anecdotal accounts, indicates that, in years following periods of high net return, capital re-investment in infrastructure or machinery is typical. Specifically, the research found “cash on hand” to be a good indicator of capital re-investment on farms.[21]

*Influence of policy*

Some policies influenced water rights in the SLV. As mentioned earlier, the initial and current water law of Colorado is the rights of prior appropriation, meaning the first claimant had rights to water before later claimants. As the population of the SLV increased, there was a diminishing opportunity for new water rights claimants to appropriate and allocate surface waters. This obviously led to increased well development in both the confined and unconfined aquifer, starting around 1920, as groundwater was the least appropriated water resource at the time. However, groundwater rights came into question when it was discovered that groundwater was a water source of surface water systems in some cases. Further, extraction of groundwater could adversely impact senior surface water rights holders. In 1965, the Colorado State Legislature ruled all tributary groundwater fell under the law of prior appropriation. This was subsequently challenged in the state Supreme Court in 1968, with the challenge being over-ruled. The resulting effect was the passing of the Water Rights Determination and Administration Act of 1969 to codify the state Supreme Court decision. In particular, this led to the development of moratoriums on wells in the SLV. The first was instituted in 1972, wherein no new wells could be placed in the confined aquifer and unconfined aquifer outside the Closed Basin without special permits, with few being granted. The second occurred in 1981, when no new wells could be placed in the unconfined aquifer of the Closed Basin, thereby effectively ending further well development in the SLV as clearly shown in Figures 5.4 and 5.6.[33]

*Collateral issues*

The effects of surface water and groundwater extraction can be seen in changes in stream outflow volumes at Lobatos gauge. Outflow volumes decreased by more than half after 1925, to 400 $hm^3$, compared to 1912-1924 volumes (Table 5.6). During this period, water extraction was mostly confined to surface water. It was not until after the 1920s that groundwater extraction began increasing. Further, the pumping rate increased by 2-3 times the previous rates after 1950, which also corresponds to the advent of center pivot irrigation. Center pivot irrigation appeared in the SLV around the mid-late 1960s, facilitating the expansion of irrigated agriculture into areas that did not have readily-available surface water.[22, 25] Roughly 120,000 hectares were being irrigated with center pivot systems by 1981, when a moratorium on well placement in the unconfined aquifer was enacted.[25]

However, during the period between the 1920s and 1960s when the groundwater allocations peaked, the water output volume at the Lobatos gauge station decreased by an unaccounted for additional 60 $hm^3$ (Table 5.6). This decrease in outflow is not accounted for by a concurrent decrease in water inflows, therefore increasing the likelihood that groundwater pumping affected stream flows in the Upper Rio Grande. Further, there is strong evidence indicating the underlying aquifers are hydrologically connected in this region of the Upper Rio Grande.[12] There is much evidence that groundwater extraction from aquifers hydrologically connected to streams will reduce stream flows.[40] Thus, it can be reasonably concluded that the concurrent increases in groundwater allocations resulted in the reduction of outflow volumes at that time. Recently it was estimated net groundwater extraction to be near 35 $hm^3$, which further increases the likelihood that pumping was the cause for the unaccounted for water diversions.[41] Finally, after the moratoriums went into effect, the unaccounted for diversions of surface waters was reduced by 12 $hm^3$, which indicates the moratoriums effects of groundwater extraction partially reduced the unaccounted for diversions.

It is obvious the additional water extractions were employed in agriculture. Agriculture acreage increased, by about 80,000 ha between 1948 and 1978, with an additional increase of about 40,000 ha after 1978 (Table 5.7 and Figure 5.11). This increase in acreage coincides with increased groundwater extractions which were necessary irrigate the increased acreage. Further, there was an approximate 20,000 ha increase in acreage of alfalfa, the highest water-demanding crop in the SLV, after 1957 (Table 5.7). Center-pivot irrigation systems also began appearing in the region in the early-1960s. Because these irrigation systems do not require surface water sources, wells therefore offered an opportunity to expand acreage, or to reclaim acreage lost to soil salinization in the early-20th Century.[25] Hence, increased groundwater rights also occurred at the same time center pivot began appearing in the SLV.

Conclusion

The arid southwest is vulnerable to periodic droughts. As a result, food and water security are continuing concerns in the region. In the Upper Rio Grande, the developments of water rights, and the resulting number of appropriations and volume of water allocated, follow expected patterns of response to population increase, drought occurrences, policy changes and agricultural expansion. As settlement in the area increased, its surface waters were first appropriated and allocated. New surface water appropriations were largely eliminated within a few decades thereafter, with the agricultural community beginning to exploit groundwater resources. These two elements are negatively correlated. Drought also appears to have influenced the timing of water rights and volumes, with both surface and groundwater appropriations and allocations being higher following drought periods. Crop prices, particularly potatoes, also appear to play a role in new well development. Well development is a capital investment, with farmers tending to re-invest in machinery following high crop prices, examples being pumps, wells and center pivot systems. Because crop prices and drought concurrent in some cases, these factors also likely interacted synergistically. Further, policies, in the form of moratoriums on well development, exhibited a clear delineation in the timeline at the point where further well development ceased.

Surface water allocations increased from 1852 until 1924. The collateral effects of water appropriations and allocations caused a reduction in stream flow volumes by about 400 $hm^3$ annually after 1925. Groundwater extractions appear to have later reduced stream flows by a further 60 $hm^3$ annually, from the mid-1920s to the mid-1960s. Agricultural acreage increased by about 80,000 ha between 1948 and 1978, with an additional increase of 20,000 ha after 1978, thereby increasing the need for water extractions. During the early-1960s to the present time, the introduction of center-pivot irrigation expanded agricultural acreage in the SLV. When all of these factors are considered a nexus of events in the Valley that affected both its water sources and uses, including: (i) increased population; (ii) occurrence of droughts; and (iii) high crop prices, all of which ultimately led to increased surface and ground water demands, with concomitant increased agricultural acreage and decreased stream flows.

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**Tables Figures**

Table 5.1. Change point analysis of the activity of the acquisition of surface water rights for all streams. Allocations are in cubic feet per second.

| Surface | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Appropriations | 1870 | 1870 | 100 | 11.61 | 102.33 |
| | 1876 | 1873-1881 | 98 | 102.33 | 65.73 |
| | 1891 | 1889-1891 | 100 | 65.73 | 18.82 |
| | 1908 | 1905-1910 | 96 | 18.82 | 38.00 |
| | 1912 | 1910-1912 | 100 | 38.00 | 9.47 |
| | 1927 | 1920-1928 | 100 | 9.47 | 2.43 |
| | 1983 | 1981-2001 | 96 | 2.43 | 5.74 |
| Allocation | 1870 | 1867-1880 | 99 | 95.44 | 298.91 |
| | 1881 | 1879-1891 | 99 | 298.91 | 692.09 |
| | 1892 | 1888-1892 | 99 | 692.09 | 172.47 |
| | 1907 | 1907-1911 | 98 | 172.47 | 871.20 |
| | 1912 | 1909-1913 | 97 | 871.20 | 52.12 |

Table 5.2. Change point analysis of the activity of well development in the unconfined aquifer. Allocations are pumping rates of gallons per minute.

| Unconfined aquifer | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Appropriation | 1894 | 1886-1897 | 98 | 2.77 | 1.06 |
| | 1910 | 1910-1934 | 96 | 1.06 | 5.76 |
| | 1935 | 1935-1939 | 100 | 5.76 | 62.87 |
| | 1981 | 1977-1981 | 100 | 62.87 | 1.00 |
| Allocation | 1901 | 1894-1902 | 100 | 3.56 | 0.33 |
| | 1925 | 1925-1933 | 100 | 0.33 | 14.62 |
| | 1934 | 1934-1938 | 100 | 14.62 | 90.93 |
| | 1950 | 1947-1980 | 98 | 90.93 | 160.37 |
| | 1981 | 1976-1984 | 100 | 160.37 | 17.82 |

Table 5.3. Change point analysis of the activity of well development in the confined aquifer. Allocations are pumping rates of gallons per minute.

| Confined aquifer | | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|---|
| Gross | | | | | | |
| | Wells | 1890 | 1889-1899 | 98 | 2.92 | 21.10 |
| | | 1900 | 1899-1967 | 95 | 21.10 | 88.22 |
| | | 1969 | 1955-1969 | 100 | 88.22 | 5.75 |
| | Volume | 1900 | 1900-1934 | 100 | 0.51 | 7.61 |
| | | 1936 | 1935-1936 | 100 | 7.61 | 43.05 |
| | | 1945 | 1945-1950 | 96 | 43.05 | 92.76 |
| | | 1951 | 1951 | 98 | 92.76 | 255.29 |
| | | 1957 | 1957 | 98 | 255.29 | 74.72 |
| | | 1963 | 1963-1967 | 94 | 74.72 | 214.28 |
| | | 1968 | 1964-1968 | 92 | 214.28 | 53.93 |
| | | 1973 | 1969-1973 | 97 | 53.93 | 17.44 |
| | | 1974 | 1974-1975 | 100 | 17.44 | 0.88 |

Table 5.4. Change point analysis of the activity of reservoir construction and volumes of reservoir capacity.

| Reservoirs | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Count | 1879 | 1872-1891 | 100 | 2.17 | 5.36 |
| | 1912 | 1904-1918 | 100 | 5.36 | 1.70 |
| | 1962 | 1959-1976 | 99 | 1.70 | 7.19 |
| | 1978 | 1963-1980 | 95 | 7.19 | 2.17 |
| Volume | 1902 | 1902-1906 | 100 | 556.16 | 38603.00 |
| | 1910 | 1906-1910 | 100 | 38603.00 | 539.97 |

Table 5.5. Correlation analysis of surface to aquifer appropriations. The r-values and significance indicates increases in aquifer appropriations were related to decreases in surface appropriations.

| | r-value | *p*-value | n |
|---|---|---|---|
| Confined aquifer | -0.21 | 0.0149 | 136 |
| Unconfined aquifer | -0.33 | 0.0004 | 114 |
| Combined aquifers | -0.31 | 0.0002 | 136 |

Table 5.6. Annual and growing season water balance of inflows and outflows of the Upper Rio Grande in the San Luis Valley based on change points in streamflow.

| | | Change in outflow | | Change in inflow | Diversions | Percent of inflow diverted during each period | Additional increase or decrease in diversions not explained by changes in inflow |
|---|---|---|---|---|---|---|---|
| Period | Mean outflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | Mean inflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | $Inflow_{pn} - Outflow_{pn}$ | $Cons_{pn} / Inflow_{pn}$ | $Change^{In}_{pn} - Change^{Out}_{pn}$ |
| <u>*Annual changes in flow*</u> | | | | | | | |
| 1912-1924 | 823.34 | N/A | 1,506.55 | | 683.21 | 0.45 | N/A |
| 1925-1957 | 427.56 | -395.78 | 1,170.75 | -335.80 | 743.19 | 0.63 | 59.98 |
| 1958-1964 | 248.63 | -178.93 | 1,005.94 | -164.81 | 757.31 | 0.75 | 14.11 |
| 1965-2007 | 393.15 | 144.52 | 1,137.81 | 131.87 | 744.66 | 0.65 | -12.65 |

Table 5.7. Results of change point analysis for total agricultural acreage and alfalfa acreage.

| Crop | Change point year | Confidence interval | Confidence level | Before | After |
|---|---|---|---|---|---|
| Total acreage | 1948 | 1939-1948 | 94 | 151,170 | 231,340 |
| | 1978 | 1978-2003 | 98 | 231,340 | 266,400 |
| Alfalfa | 1957 | 1957-1965 | 100 | 26,969 | 48,186 |

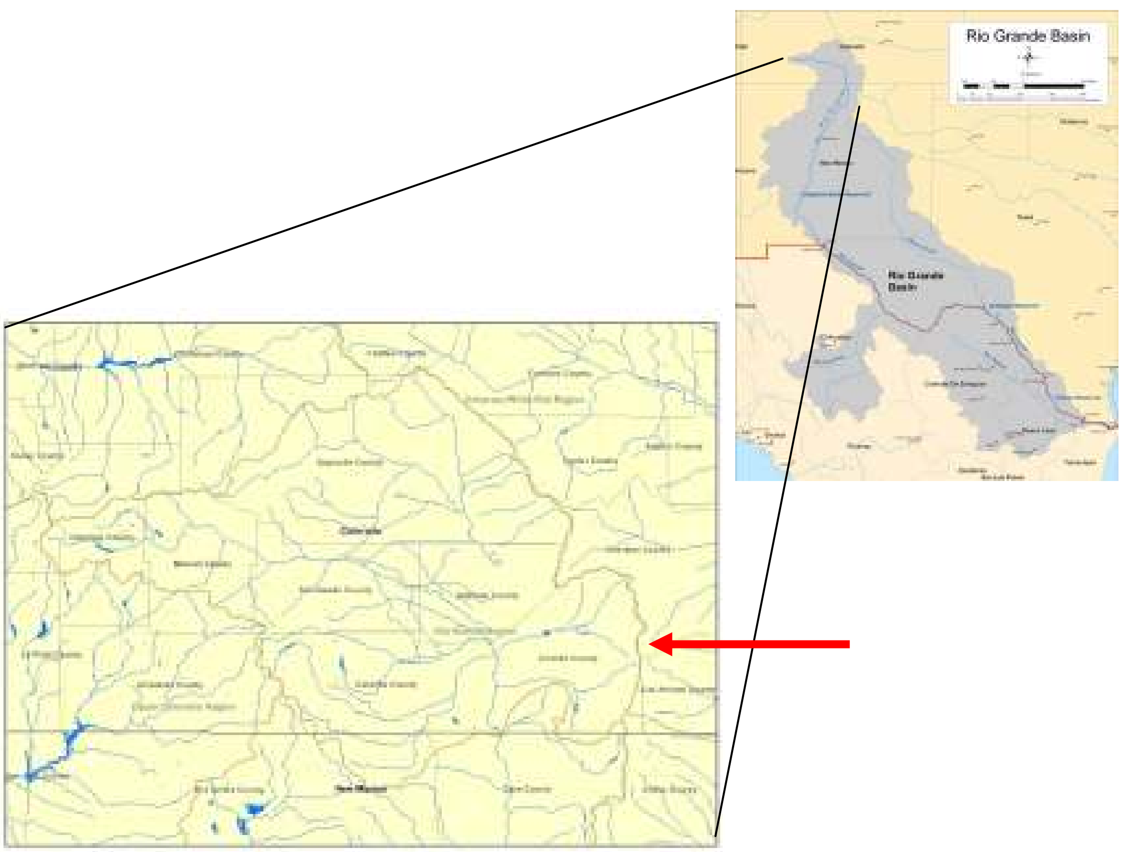


Figure 5.1. The watershed boundary (indicated by red arrow) of the Upper Rio Grande and San Luis Valley.

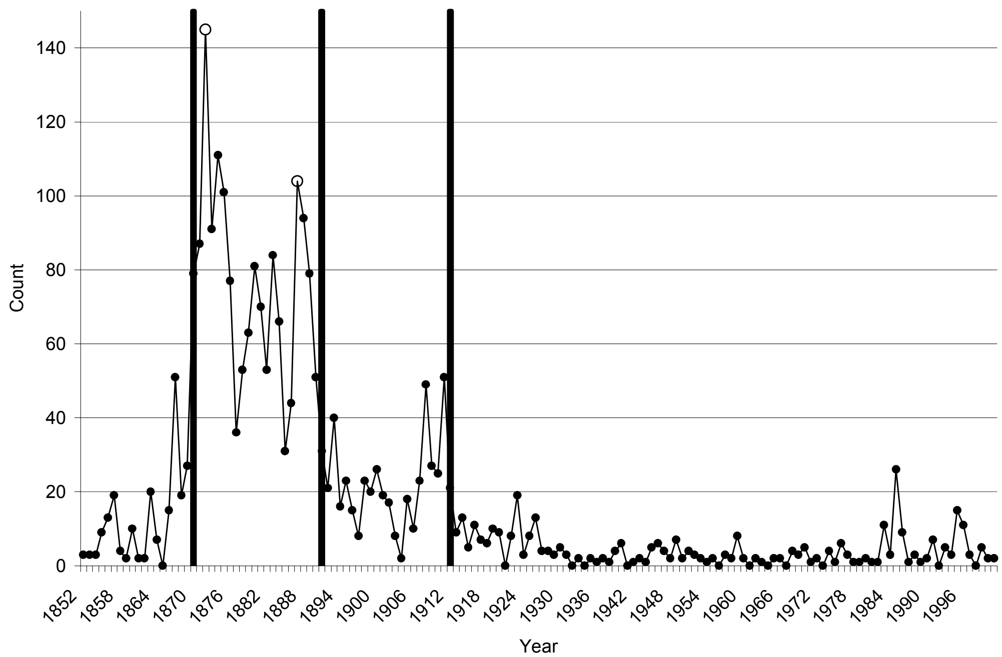


Figure 5.2. Annual surface water appropriations. Vertical bars delineate the combined periods, 1852-1869, 1870-1890, 1891-1911 and 1912-2001 as defined in the change point analysis. Open circles correspond with drought.

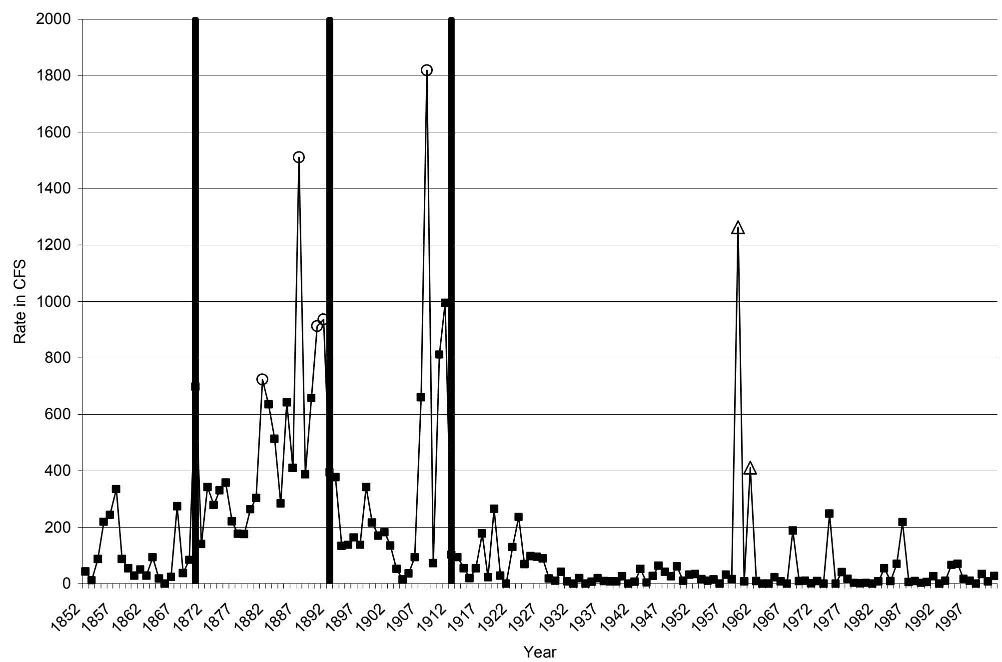


Figure 5.3. Annual surface water allocations. Vertical bars delineate the combined change point periods of 1852-1969, 1870-1891, 1892-1911 and 1912-2001. The open circles correspond with drought. The open triangles correspond with drought and high potato prices.

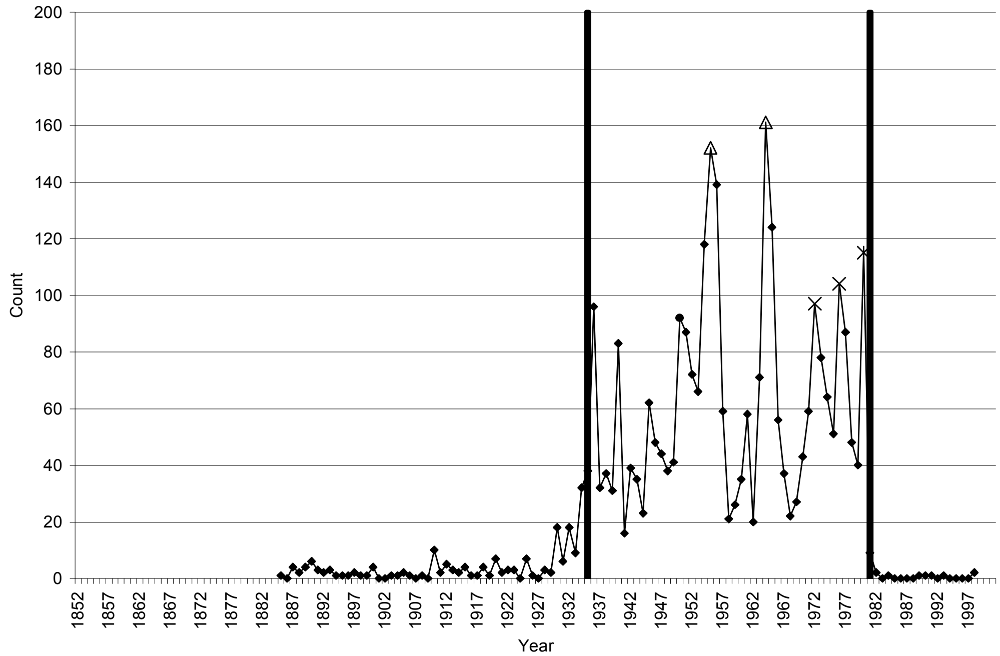


Figure 5.4. Annual appropriations from the unconfined aquifer. Vertical bars delineate the combined change point periods as 1885-1935, 1936-1981 and 1982-2001. The open triangles correspond with drought and high potato prices. The X's correspond with center pivot irrigation.

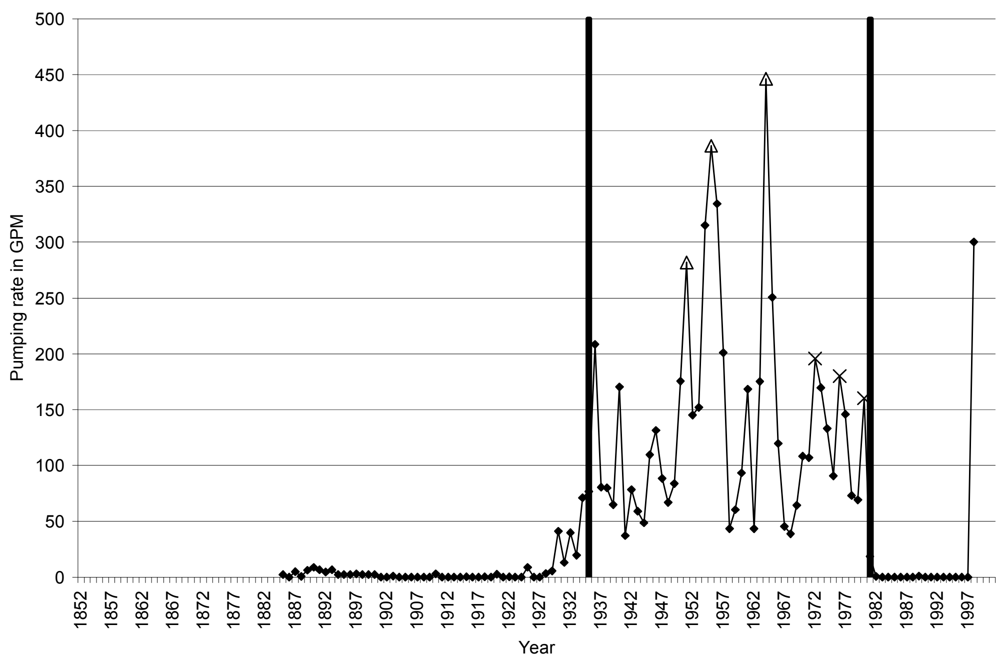


Figure 5.5. Annual allocations from the unconfined aquifer. Vertical bars delineate the combined change point periods as 1885-1935, 1936-1981 and 1982-2001. The open triangles correspond with drought and high potato prices. The X's correspond with center pivot irrigation.

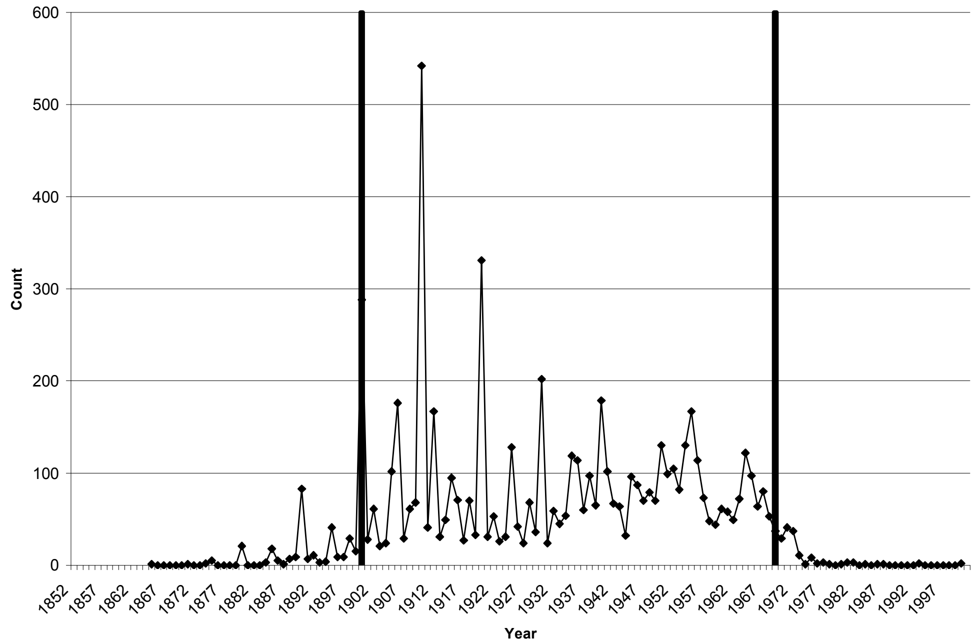


Figure 5.6. Annual appropriations from the confined aquifer. Vertical bars delineate the combined change point periods as 1865-1900, 1901-1969 and 1970-2001.

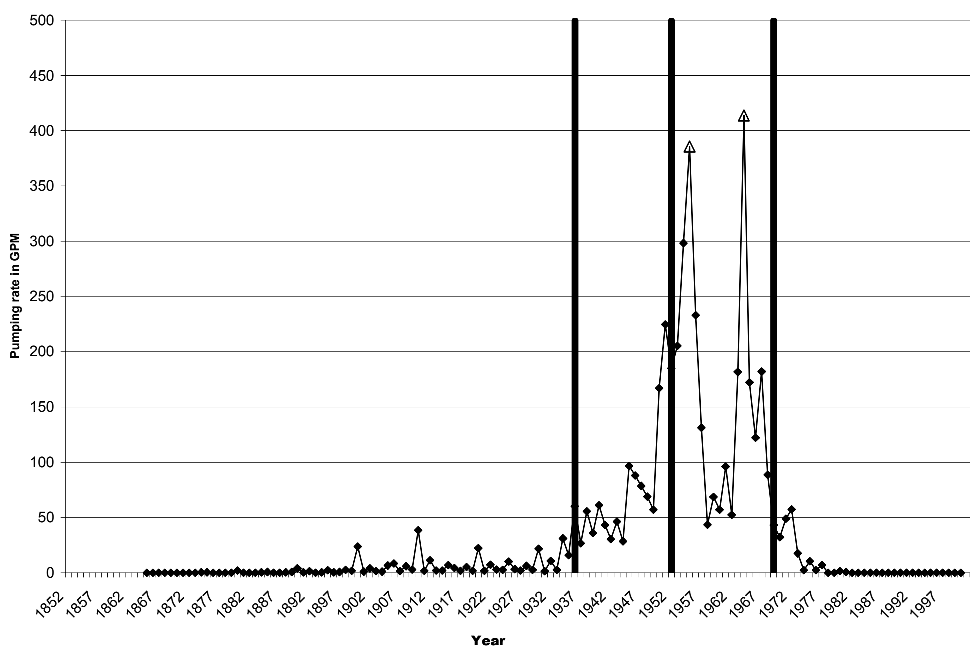


Figure 5.7. Annual allocations from the confined aquifer. Vertical bars delineate the combined change point periods as 1865-1936, 1937-1952, 1953-1969 and 1970-2001. The open triangles correspond with drought and high potato prices.

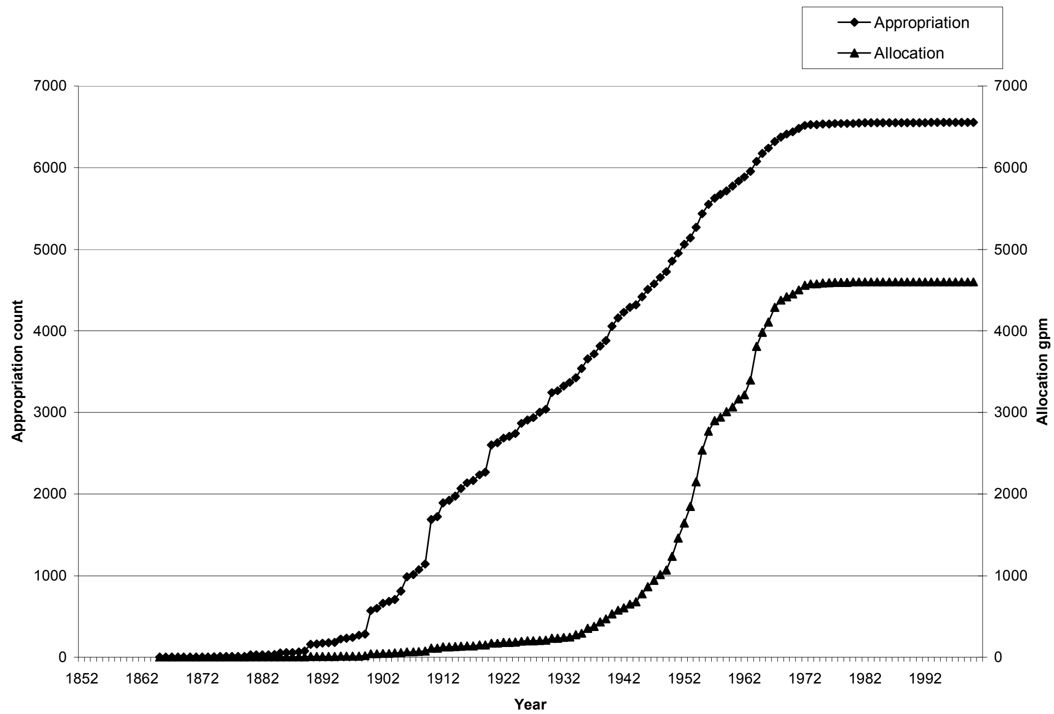


Figure 5.8. Comparison of the cumulative sums of appropriations and allocations in the confined aquifer illustrating how increases in the number of wells are not indicative of an increase in extraction rates.

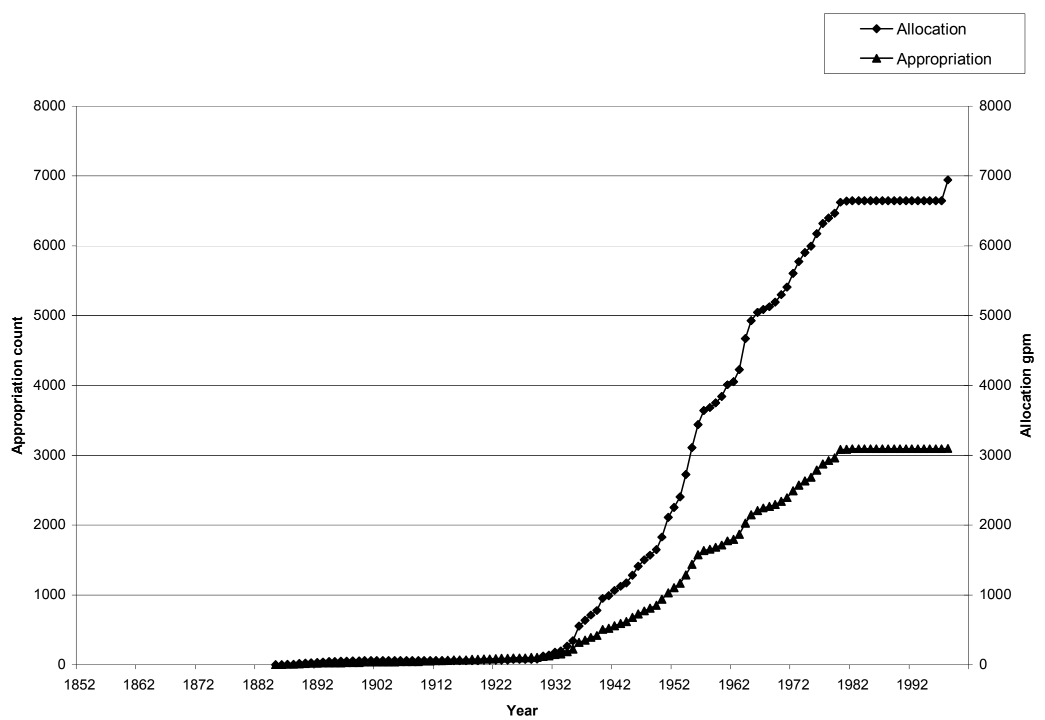


Figure 5.9. Comparison of the cumulative sums of appropriations and allocations in the unconfined aquifer illustrating how increases in the number of wells are not indicative of an increase in extraction rates.

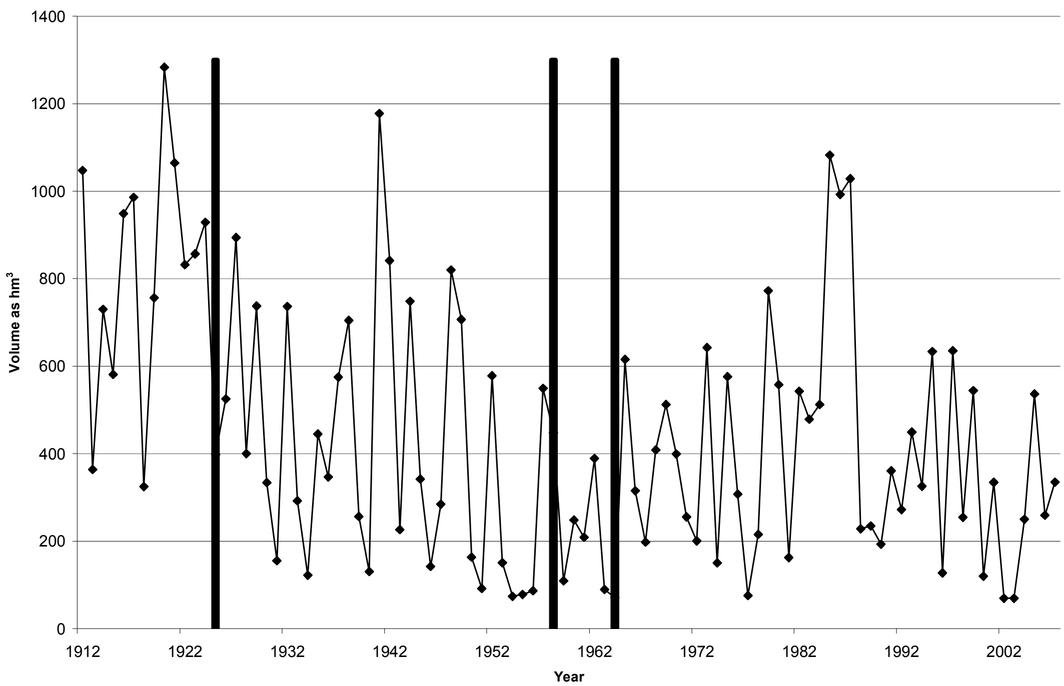


Figure 5.10. Annual Rio Grande streamflow at the Lobatos gauge station. Vertical bars represent change points in flow.

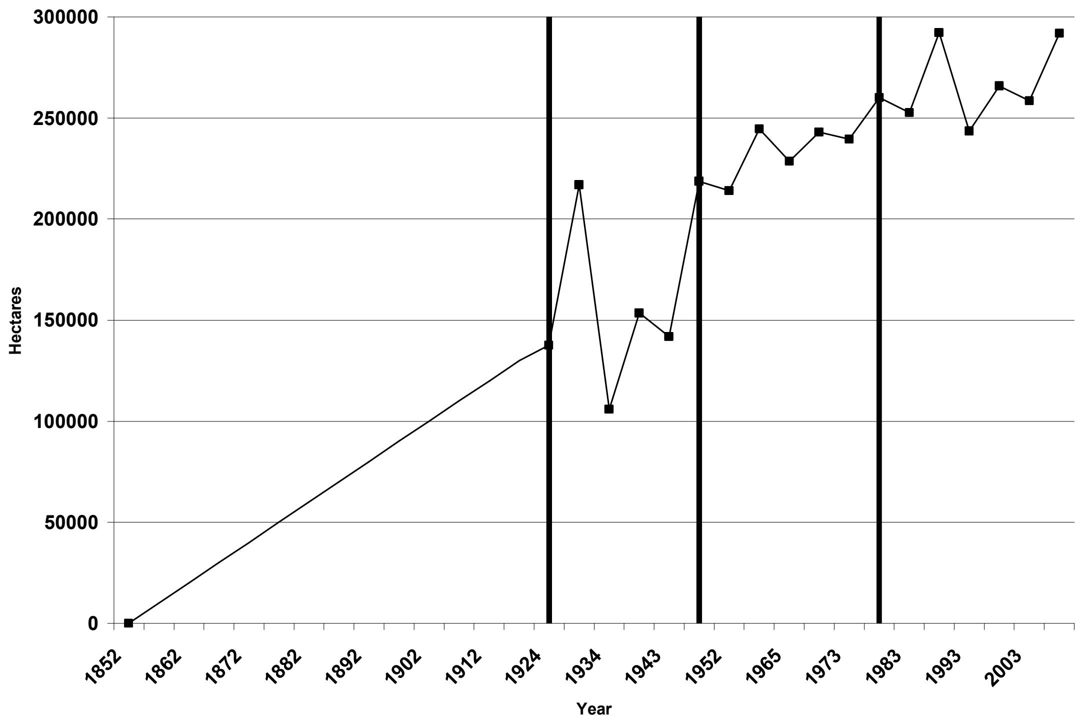


Figure 5.11. Change points in total agricultural acreage. The straight diagonal line from 1852 – 1919 is a result of no available annual data for years prior to 1919. Vertical bars represent change points.


Figure 5.12. Population trend of the San Luis Valley, 1900-1990.

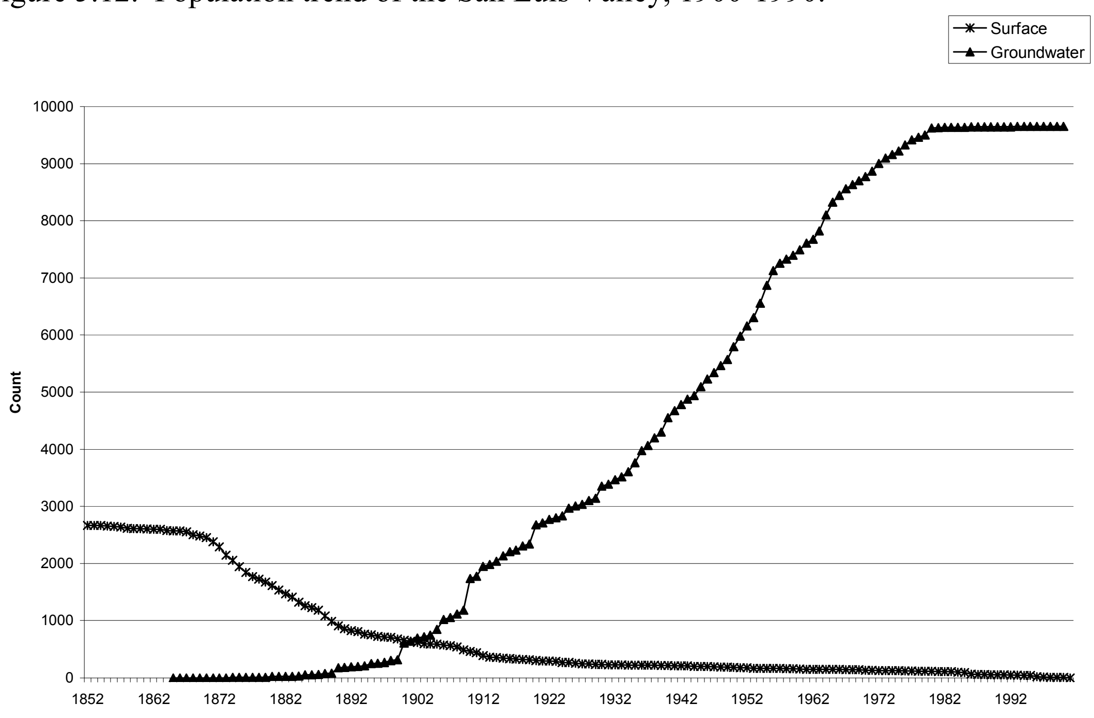


Figure 5.13. A comparison of decreasing cumulative sum of surface water appropriations to increasing cumulative sum of combined aquifer appropriations illustrating the increase in groundwater appropriations as surface water appropriation declined.

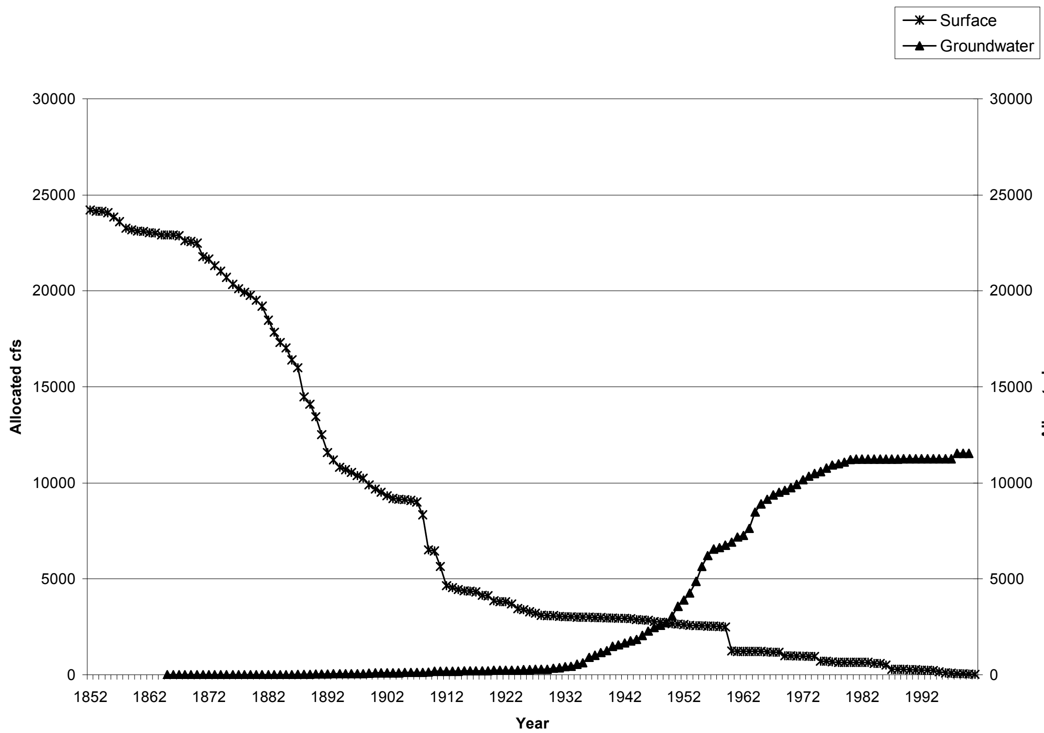


Figure 5.14. A comparison of decreasing cumulative sum of surface water allocations to increasing cumulative sum of combined aquifer allocations illustrating the decline in allocation rates for surface water as groundwater allocations increase.

# CHAPTER 6

ENVIRONMENTAL DRIVERS OF STREAMFLOW CHANGE IN THE UPPER RIO GRANDE

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submitted 5/2010)

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**Abstract:** This study assesses changes in streamflow of the Upper Rio Grande (URG), as it exits the San Luis Valley (SLV) at the Lobatos gauge station, in relation to changes in local environmental drivers. The streamflow record spans 1912-2007. Irrigation-dependent agriculture accounts for more than 85% of surface and ground water withdrawals in the SLV. Four definitive periods of streamflow changes were identified utilizing change point analysis: 1912-1924, 1925-1957, 1958-1964 and 1965-2007. Inflows of the Rio Grande and the Conejos and Los Piños rivers were aggregated into a single inflow into the SLV. Streamflow data were taken from gauges above all major diversions. Results of the analysis indicated annual streamflow at Lobatos declined by 400 $hm^3$ after 1924, coinciding with increases in surface water extractions. Additional reductions of about 50 $hm^3$ in annual streamflow, not accounted for by inflow reductions during the period 1925-1964, coincided with increases in groundwater extractions. In contrast, an increase of 12.5 $hm^3$ in annual streamflow occurred during 1965-2007. The increases coincided with several changes, but were primarily related to extreme peak flow years during the period 1985-1987 and increased water deliveries in compliance with the Rio Grande Compact.

**Keywords:** Upper Rio Grande, climate change, water, streamflow, change point, San Luis Valley, environmental drivers

**Introduction:**

The Upper Rio Grande (URG) – San Luis Valley (SLV) is an active, complex social-ecological system composed of several environmental drivers, including water availability, agriculture, policy and climate, each with diverse characteristics. Due to the interrelated nature of the drivers, changes in a driver can precipitate changes in other drivers.

Agricultural development in the SLV began in the mid 1800s with permanent settlement (Berry and Henderson 2001). All agriculture in the SLV is irrigation dependent and is responsible for 90% to 75% of annual diversions of the combined URG annual flow over the past century (Pat McDerrmott per comm). Surface water was originally the main source of irrigation for the highly developed agricultural system of the SLV; however, groundwater became more important in the second half of the $20^{th}$ Century. Surface and groundwater diversions irrigate more than 240,000 ha, which the SLV community relies upon to provide over 30% of annual revenue to the local economies (SLVDRG 2002).

The URG headwaters are part of a connected surface-groundwater hydrologic system (Emery 1979). The main stem is the Rio Grande with its tributaries the Conejos and Los Piños Rivers. The headwaters of these streams are located in the eastern slopes of the San Juan Mountains inside the boundaries of the SLV in southern Colorado. The primary source of streamflow is melting snowpack in the uppermost elevations of the mountains with some precipitation contributing as rain in the summer months. The streams flow through the San Luis Valley, which contains a vast underlying shallow unconfined aquifer and a deep confined aquifer. Sophocleous et al. (1988) illustrates the effects streamflow from pumping water from a hydrologically connected aquifer. In the SLV both the confined and unconfined aquifers have documented interactions with the streams (Emery et al. 1971) and, until the latter half of the 20th Century, they were largely ignored. Some streamflow originates from groundwater contributions from the confined and unconfined aquifers which underlie the entirety of the valley (Emery 1979). The streams are gaining streams during the winter months since their flow volumes are greater than the contribution of storm runoff. The streamflow at this time primarily originates from groundwater seepage directly into the stream bed or from artesian springs.

Annual evapotranspirative loss from all sources has been estimated to be about 2.98 $km^3$ (Emery 1979). From 1965-1975 groundwater extraction was estimated to be above 1.3 $km^3$ (Emery 1979). Prior to the advent of major increases in groundwater pumping in the SLV, the Conejos River was a gaining stream, but since then it has become a losing stream (Emery 1979). Further, Emery (1979) concludes that groundwater pumping has reduced artesian spring flows by about 27 $hm^3$. Aside from Emery (1979), very little work has been conducted to define the influence of groundwater pumping on streamflow in the URG. Mayo et al. (2007) have redefined the aquifers and recognized their connectivity to the streams. However, there is a lack of data confirming the extent, or lack, of connectivity of the aquifers to the San Juan Mountain streams north of the Rio Grande. Emery (1979) clearly indicated that groundwater interactions with streams occur and increases in groundwater pumping for irrigation have reduced streamflow in the URG. However, the lack of a complete understanding of the hydrologic connectivity to the Rio Grande inhibits accurate evaluation of the effects of groundwater extractions on streamflow.

Agriculture is primarily responsible for all water diversions in the valley since 1852, with minimal municipal and industrial diversions. Thus, increases in water availability not related to precipitation are largely related to diversions. Changes in crop selection and irrigation methods also are potential contributors to changes in water availability. Climate change is also expected to impact water resources, with increased temperatures expected to increase growing degree days and crop water demands, due to increases in crop evapotranspiration (Adams 1989; Schimmelpfennig et al. 1996; Fischer et al. 1996; Ramirez and Finnerty 1996). Herrington (1996) predicts that agricultural crop water demands will increase by about 12% for every 1.1°C increase in temperature.

Changes in streamflow in the URG have also resulted in major political and legal challenges. In the late 1880's surface water diversions for irrigation use in the URG and resultant changes in streamflow of the Middle Rio Grande are cited as the main cause of the cessation of streamflow in the El Paso/Ciudad Juarez reaches of the river (Paddock 2001). Ultimately, downstream water shortages resulted in development of two treaties and one interstate compact governing the use of the waters of the Rio Grande. First, a treaty between the United States and Mexico, committing the United States to deliver 74 $hm^3$ to Ciudad Juarez was signed in 1906. A subsequent Rio Grande Compact was signed in 1938 between Colorado (CO), New Mexico (NM) and Texas (TX), governing water use and limiting the amount of water each state could divert (IBWC). To maintain compliance with the Compact, the US Bureau of Reclamation began groundwater pumping in the closed portion of the SLV basin in 1989, delivering the water to the URG to augment SLV water use (BR). Second, the 1944 Treaty between the United States and Mexico governing the use of the remaining waters of the Rio Grande was signed (IBWC). It is therefore evident the URG waters are of major interest and importance both nationally and internationally. Identifying changes in streamflow and concurrent changes in related drivers of the URG headwaters will allow a better understanding of the complex interrelationships of groundwater allocations, climate change, agriculture and policy, and their impacts on streamflow.

**Objectives**

The treaties and Compact indicate the SLV water use has impacted downstream riparian states; therefore it appears necessary to determine the impact of changes in environmental drivers on streamflow. Several environmentally-related drivers are present in the URG-SLV social-ecological system. Each driver has the potential to affect streamflow and policy; e.g. surface water allocation has influenced policy and streamflow. Surface-groundwater connections in the URG indicate that groundwater extraction has the potential to affect streamflow. Furthermore, groundwater allocations, climate change, agriculture and policy potential can change water demands and uses. Therefore this study was developed to determine the impacts of changes in environmental drivers on streamflow during the growing season (May-September) at the Lobatos gauging station, which defines the exit of the Rio Grande from the SLV.

**Study site:**

Located in south central Colorado, the SLV is roughly bisected by the Rio Grande (Figure 6.1). The river rises in the western San Juan Mountains, which form the western boundary of the SLV, and the eastern boundary is formed by the Sangre de Cristo

Mountains. The drainage area, approximately 20,719 sq km, was created from the Rio Grande Rift, formed as the two mountain ranges began moving apart from each other approximately 300 mya. The elevation of the SLV valley floor is approximately 2200 m, making it one of the highest inhabited and developed deserts in the world, with the surrounding mountain peaks rising to greater than 4200 m.

Much of the moisture in the prevailing westerly winds precipitates out in the San Juan Mountains as orographic events, while the moisture in the easterly winds is precipitated in the Sangre de Cristo Mountains. Thus, each range effectively creates a rainshadow for the valley floor. The Valley receives less than 20 cm of precipitation annually because of the rain shadow effect, while the San Juan Mountains to the west receive 100-200 cm of precipitation annually (Baker 1944; Emery 1979; Mitchell 1993). The area is characterized by periodic droughts, some being intermittently severe and long-lasting (Ryerson et al. 2003). According the National Climate Data Center (NCDC), the region regularly experiences wintertime temperatures of less than -20°C and as low as -40°C. It ranks in the top 20 coldest locations in North America (King 2007). Warm season temperatures can exceed 30°C, but the warm season only lasts 90-110 days. During this time it is not uncommon to have a 20°C diurnal temperature change.

Even though the SLV is cool and arid, it is a major agricultural region for the state of Colorado. Approximately 240,000 hectares are under cultivation in the Valley, and produce the majority of the state's potato crop (14,000-30,000 ha) and a large portion of alfalfa crop (80,000-100,000 ha) (CSUa). All of the Valley agriculture is irrigated by surface or groundwater to compensate for the prevailing aridity (CSUb). There are approximately 10,000 unmetered wells in both the confined and unconfined aquifers, and more than 250 km of surface water irrigation canals.

**Methods**

Daily streamflow data for the three major streams (Rio Grande, Conejos and Los Piños) were obtained from the Colorado Decision Support System (CDSS). Streamflow data for the San Antonio River were not complete and therefore were not used in this study. Further, its mean annual contribution was estimated from the available data to be less than 2% of the Rio Grande streamflow. Gauge station data from the Rio Grande at Del Norte and Conejos and Los Piños rivers represents inflows above influences of major diversions. The Rio Grande streamflow at Lobatos represents stream outflow from the SLV after all water diversions have taken place. The Lobatos station was selected to determine changes in streamflow exiting the SLV, since it is the station utilized for calculating the Colorado contribution to the lower riparian states and Mexico according to Article III of the 1938 Rio Grande Compact. The names and locations of the gauge stations used in this study are shown in Figure 6.2 and Table 6.1.

Daily streamflow data were converted into annual and 5-month (May-Sept) for each gauge station. All streamflow data from gauge stations above water diversions were combined to develop a data set of total inflows. The 5-month data represent the primary months of the growing season (approximately 100 days). A preliminary review of the data, both annual and growing season, indicated that three years (1985, 1986 and 1987) of inflows to the SLV and outflows at Lobatos were extraordinarily high, thereby representing outliers according to the standard: outliers > 1.5 x IQR (interquartile range) plus the mean. Nevertheless, the data were not adjusted to reduce the outlier presence.

In addition, deliveries from the Closed Basin Project, delivered to the Rio Grande since 1989 to improve compliance with the Rio Grande Compact, were removed from outflow totals at Lobatos. The Close Basin Project represents a singular policy response to increase deliveries in accordance with the Rio Grande Compact. Further, it would present a false indication of increased outflows.

Change point analysis (Taylor Enterprises) was conducted on the annual outflow data to identify distinct periods of change for the Lobatos station record. Change point analysis is a widely used technique to determine the location of potential change in a data series. It has been used to determine changes in soil chemistry across boundaries at archaeological sites (Cavanagh et al. 1988), energy flow at hydro-electric plants in Canada (Perreault et al. 2000), streamflow (Zanchettin et al. 2008), phenological changes (Schleip et al. 2008) and climatological data (Mix et al. 2010).

Change point analysis utilizes an iterative cumulative sum (CUSUM) procedure in combination with a bootstrapping method of analysis. The CUSUM chart starts and ends at zero with the maximum distance the CUSUM chart deviates from zero being the measure of change. It then compares the CUSUM chart of the original data with the CUSUM charts of random reordering of the data (bootstraps) to determine if there is a significant difference indicating a change. Because of this bootstrapping approach, the method is distribution free. If a change is detected, the time of the change is estimated and the data split at the change point. The analysis is then repeated on each segment to detect further changes. As a result more than one set of data can be identified as being statistically separate from other sets. Each set or sequence has a statistical distribution more similar to the data within than to data in other sets of the same series. One or more points are estimated that define the moment of change or shift in distribution and a range of points are provided as a likeliest period for change, along with the previous and new mean value.

Unbalanced sets frequently result from change point analysis; therefore a one-tailed General Linear Model (GLM) was performed to determine the level of statistically significant differences in the volumes of streamflow for each period and combination of periods. GLM is a widely used analytic tool for assessing differences between two or more sets of data where the sets are unbalanced. It has been used to determine changes in mean temperature in climate, changes in distribution of biota and streamflow (Jordan et al. 1997; Sexton Guisan et al. 1998; et al. 2003). Further, it allows for contrast tests between all variables in all periods.

Following the GLM analysis, a water balance was conducted on the mean annual inflow and outflow volumes to determine increases or decreases in diversions within the SLV. The URG has been the center of international and interstate disputes based on actual streamflow volumes; therefore this approach provides an accounting measure of actual changes aside from statistical values. Further, the downstream riparian states and Mexico also rely on water deliveries and volumetric changes that were not deemed statistically significant may, in fact, have a practical significance on the downstream users. Thusly, the accounting was conducted first by identifying the difference in mean inflow and outflow volumes between periods. Second, the difference in outflow volume was subtracted from the difference in inflow volume to determine the presence of loss or gain in outflow volume not attributable to change in inflow.

**Results**

*Change point analysis and GLM*

Change point analysis identified 4 distinct periods in annual outflows: 1912-1924, 1925-1958, 1959-1963 and 1964-2007, with mean annual outflow volumes of 806,280,000, 493,570,000, 222,200,000 and 400,640,000 $m^3$, respectively (Table 6.2). Utilizing these periods as outflow change points, a GLM was conducted on the mean annual inflow and outflow volumes with significance set at $p < 0.05$. The GLM indicated the mean annual inflow and outflow volume between adjoining periods was only significantly lower for 1925-1958, compared to 1912-1924 (Table 6.3), with outflows 395 $hm^3$ less and inflows 335 $hm^3$ less than previous values. There were no significant differences in annual mean inflow or outflow between the remaining periods. The GLM analysis of the growing season indicated mean inflows during the period 1912-1924 were significantly higher by 233 $hm^3$ over 1925-1958 and no significant differences occurred between any other adjoining periods (Table 6.4). Analysis of growing season streamflow at Lobatos gauge station indicated mean flows during the period 1912-1924 were significantly higher by 293 $hm^3$ over 1925-1958 and 1925-1958 outflows were significantly higher by 163 $hm^3$ over 1959-1963 outflows (Table 6.4).

*Water balance accounting and percent change in flows*

A water balance analysis was conducted using actual volumes to assess changes in streamflow based on changes in actual inflows and outflows, and changes in the quantity of water diverted between periods. These volume changes, although not statistically significant in some cases, represent real increases or decreases in streamflow, which can potentially impact local and downstream users. Utilizing streamflow change points, notable decreases in streamflow at Lobatos, not accounted for by simultaneous decreases in inflow, include annual and growing season decreases of about 60 $hm^3$ and 70 $hm^3$, respectively, during the 1925-1957 period (Table 6.5 and 6.6). Additionally, during the growing season 1965-2007 period unaccounted for decreases in outflow of 52 $hm^3$ occurred (Table 6.6).

**Discussion**

The environmental drivers in the URG-SLV social-ecological system underwent several changes over the past 95 years. These changes resulted in streamflow increases or decreases of the URG at Lobatos (Figure 6.3); some changes were evident, while others must be separated from influences that mask their impacts. Agriculture has contracted and expanded, the mean annual temperature has risen by about 1°C (Mix et al. 2010), water rights for both surface and groundwater have been exhausted, and some policies have been ignored while others have been adhered to. The influences of these changes on streamflow at the Lobatos gauge station are discussed below in regard to each previously identified change point. With few exceptions, changes in streamflow at Lobatos gauge station were not statistically significant between periods other than the initial period. On the other hand, the water balance accounting revealed important volumetric changes that need to be discussed. Volumetric changes in streamflow can have dramatic impacts on revenue in communities dependent on irrigated agriculture as a primary revenue generator. For instance, 10 $hm^3$ is enough water to irrigate approximately 3300 ha, depending on regional crop water demand. Therefore, an increase or decrease of 10 $hm^3$ can result in an equivalent increase or decrease of about

3300 ha of irrigated acreage or an average change in local revenue of about US $8 million, depending on the crops (CSUa).

*1912-1924*

This period characterizes a mean base condition for annual and growing season streamflow at Lobatos of 823 $hm^3$ and 551 $hm^3$, respectively. During this period, surface water diversions were exhausted (Figure 6.4) and groundwater pumping was still at relatively low levels (Figure 6.5). Crop acreage decreased to about 137,000 ha from a late 1890s peak of about 200,000 ha (Ogburn 1996). Nearly all acreage relied on surface water for flood irrigation. Further, acreage was confined to locations near streams and ditches, with fewer locations in the closed basin portion of the SLV (Figure 6.6). Climate was relatively stable in the SLV during this period as prior to 1994 mean annual temperature hovered around 4.9°C (Mix et al. 2010). Essentially the increase in acreage led to an increase in surface water rights allocations, which resulted in the baseline annual and growing season streamflow volume during this period (Figure 6.7).

*1925-1957*

During this period annual and growing season streamflow at Lobatos declined by 395 $hm^3$ and 293 $hm^3$, respectively. More importantly, a portion of annual and growing season streamflow reductions of 60 $hm^3$ and 69 $hm^3$, respectively, were unaccounted for by changes in inflow. Several factors could be implicated in the reduction of streamflow: climate change, water policy, increases in surface water diversions, reductions in precipitation, increases in population, increases in irrigated acreage, and increases in groundwater pumping. Among these possibilities, climate, policy change, additional surface water diversions and precipitation changes can be ruled out. Climate has been shown to be stable prior to 1994 (Mix et al. 2010), surface water diversions were exhausted by 1924 (Figure 6.4) and, although it is likely precipitation changes did occur, they were adjusted for in the accounting process (Table 6.5 and 6.6). Policy also can be ruled out, since no major policy changes occurred, other than the signing of the 1938 Rio Grande Compact, requiring delivery of water to NM and TX. If this had been a factor, however, an unaccounted for increase in streamflow at Lobatos, rather than a decrease, would have been recorded with increased deliveries per the Rio Grande Compact.

Therefore the increase in water allocations, although in the form of groundwater pumping, was the only major change observed during this period capable of affecting streamflow. Increases in groundwater pumping were caused by increases in irrigated acreage (Figure 6.8); the acreage increases were likely related to concurrent increases in SLV population (Figure 6.9). Starting in 1935 groundwater extraction began to accelerate. In fact, during this period 56% of total groundwater allocated pumping rates were assigned (Figure 6.5). Irrigated acreage during this time both contracted and expanded. The contraction took place after 1929 as the Great Depression began, and in 1934 irrigated acreage dropped to 105,000 ha, its lowest point since 1924. However, by 1957 it had recovered to more than 244,000 ha with a concomitant need for irrigation water. Moreover, alfalfa acreage nearly doubled from 24,000 ha to 45,000 ha and it requires 10% more water than all other crops grown in the SLV (Frank and Carlson 1999). The evidence that groundwater pumping had an effect on streamflow is bolstered by the fact the aquifers underlying the SLV are hydrologically connected to the URG (Emery 1979). Emery (1979) estimated that by 1951 annual upward leakages of groundwater into the URG streams was reduced by 27 $hm^3$. Therefore groundwater pumping is the only likely reason for the unaccounted reductions in streamflow at Lobatos. Further, the increase in groundwater pumping occurred simultaneously with related increases in irrigated acreage.

The 105,000 ha increase in agricultural acreage ultimately caused reductions in streamflow during this period (Figure 6.7). The reductions resulted from increases in groundwater extraction necessitated by the acreage increase. Groundwater was the only option for irrigation waters for new agricultural land as 90% of surface water allocations were granted in the previous period. The resulting reductions in streamflow impacted the lower riparian states and instigated the 1938 Rio Grande Compact (Figure 6.7).

*1958-1964*

This period is characterized by a severe drought (Ryerson 2003) and related increases in groundwater allocations due to reduced surface water availability. Annual and growing season streamflow were reduced by 178 $hm^3$ and 163 $hm^3$, respectively during this period (Figure 6.3). Annually a slight unaccounted for reduction in streamflow occurred of 14 $hm^3$ (Table 6.5). In contrast, during the growing season a 32.5 $hm^3$ unaccounted for increase in streamflow occurred (Table 6.6). Similar to the previous period, there was more than one conspiring factor causing these changes. The drought unquestionably put pressure on farmers to increase groundwater pumping, as can be seen in the additional 23% increase in groundwater allocated pumping rates that occurred in 6 years. No appreciable increases in acreage or population occurred. The unaccounted for increase in streamflow of 32 $hm^3$ during the growing season is most likely a result of irrigation return flows (Figure 6.7). Return flows from groundwater pumping to irrigated acreage can artificially increase streamflow by adding baseflow to the stream. One decade later, Emery (1979) estimated annual groundwater extraction to be 1.2 $km^3$ (94% of total groundwater pumping allocations), of which 60 $hm^3$ became return flow. Therefore, during this period a fraction equaling about 900 $hm^3$, using Emery's figures, is a probable pumping rate, with a similar proportion, 45 $hm^3$ as return flow (Figure 6.11). The probability of this scenario increases in light of the drought condition reducing surface water availability, thus increasing the need for irrigated acreage to become more reliant on groundwater pumping. Further, the percent of new groundwater allocations during this period is nearly half of the previous allocations, but occurred in one fifth of the time. As a result, groundwater pumping is the likeliest cause of the slight reduction in annual streamflow, by reducing aquifer release to the stream, as noted by Emery (1979). Similarly, the slight increase in growing season streamflow can be attributed to groundwater pumping. In this case, however, it is from return flows, which artificially inflate streamflow.

*1965-2007*

During this period annual streamflow at Lobatos exhibited an unaccounted for increase of 12.6 $hm^3$. At the same time, however, the growing season streamflow experienced an unaccounted for decrease of 52 $hm^3$. The period can be characterized by the occurrence of numerous changes in drivers within the URG-SLV social-ecological system. Agricultural acreage increased, and crop and shifts in irrigation technology occurred, water rights policies changed, compliance with the Rio Grande Compact occurred, and annual mean temperature increased by about 1°C (Mix et al. 2010).

From the beginning of this period, agricultural acreage increased by 70,000 ha, to an all time high of 290,000 ha (Figures 6.7 and 6.10). Irrigation practices also changed with the introduction of center pivot irrigation systems in the early 1960s. The expansion of agriculture required an equal additional allocation of water and, with surface water allocations no longer available, groundwater became the only alternative water source. Decreases in the growing season streamflow can be largely attributed to increases in acreage and collateral need for water.

A portion of the increase in acreage can be attributed to increases in alfalfa acreage (Figure 6.11). Alfalfa has a water demand about 10% higher than any other major crop in the SLV. However, center pivot systems were being implemented at the beginning of this period, with the advantage of being 50% more efficient than flood systems (Neibling 2010), the only irrigation system used in prior years. By the end of the period, about 50% of the irrigated agriculture in the SLV was utilizing center pivot systems, thus reducing water demand, although not enough to be a zero net loss because of the increased agriculture acreage.

There were some fundamental shifts in water policy related to groundwater and surface water allocations. Though total allotted groundwater pumping increased from about 81% to 100% during this period (Figure 6.5), no additional wells were developed after 1981 because of the moratoriums placed on well development between 1972 and 1981. Regardless of the moratoriums, Parrish (2005) estimated 800 $hm^3$ is still extracted annually. In 1966, NM and TX jointly sued CO for lack of compliance with mandated water deliveries to downstream states, in accordance with the 1938 Rio Grande Compact (WRRI). The lawsuit was settled in 1985 when the accrued water debt of CO was erased, in accordance with the Rio Grande Compact, when Elephant Butte Reservoir filled beyond capacity and spilled. The compliance has occurred since that time and maintained partly as a result of the Bureau of Reclamation's Closed Basin Project annual streamflow augmentation. Since 1989 the project supplies about 30 $hm^3$ annually from groundwater pumping in the Closed Basin to increase streamflow at Lobatos. By increasing the flow at Lobatos, the augmented streamflow reduces the impact of diversions within the SLV on water availability to downstream users. Further, beginning in the 1980s a surface water rights policy reduced the SLV diversions of surface water from 90% to 75% (Pat McDermott pers. comm.).

Climatological changes also occurred. Three years of high precipitation resulted in the Elephant Butte spills from 1985-87, caused by exceptionally high streamflow, between 600 $hm^3$ and 2.6 $km^3$ above the annual average Lobatos flows (Figure 6.3). These high flows are sufficient themselves to account for the increase of 12 $hm^3$ in annual flow at Lobatos. The annual mean temperature also increased by about 1°C (from 4.9°C - 5.9°C) since 1993. According to Herrington (1996), the increase in annual mean temperature would have increased crop water demand by 10%. Furthermore, the reduction in growing season streamflow can be partly attributed to temperature increase.

The systemic changes that occurred during this time period resulted in a slight increase in annual flows and a large decrease in growing season flows. The reduction in growing season flows clearly reflects the increases in total agricultural acreage, particularly alfalfa acreage, a high water demanding crop. In contrast, the increased water use efficiency of center pivot offset some reductions in streamflow. Moratoriums on well development ended all additional groundwater allocations, although wells previously in place were still extracting. Parrish (2005) and Emery (1979) estimate between 800 $hm^3$ and 1.2 $km^3$ of water are extracted annually, and Emery (1979) estimated 60 $hm^3$ as return flow. This reinforces the concept of artificial inflation of streamflow from groundwater irrigation return flow evident in the slight annual increased streamflow.

High flows during the mid-1980s easily account for the slight increase in the mean annual flow at Lobatos during this period. Further, policy changes in regard to the SLV's compliance with the Rio Grande Compact, by reducing surface diversions to 75% of inflow and groundwater return flow are likely related to increased annual streamflow at Lobatos. At the same time, the use of the Closed Basin Project diversions has allowed growing season diversions to be maintained.

Further increases in agricultural acreage induced increases in groundwater extraction which led to reduced streamflow during the growing season (Figure 6.7). Annually, however, streamflow increased slightly with increased irrigation efficiency from center pivot irrigation systems, compliance with the Rio Grande Compact and most importantly three high flow years (Figure 6.7).

**Conclusion**

Between 1912 and 2007 many changes in environmental drivers occurred within the URG-SLV social-ecological system (Figure 6.7). Surface water allocations were all but exhausted by 1924. Groundwater allocations rapidly increased after 1924 because surface water rights were scarce. Clearly the increased groundwater extractions reduced streamflow at Lobatos by reducing upward leakage of the aquifers. Increases in overall and alfalfa acreage also increased growing season water demands, causing additional reduction in flows. Interestingly, some changes ameliorated the potential groundwater extraction had on reduction in flows. These include return flows from groundwater which artificially inflated streamflow estimates and exceptionally high flows from 1985-1987 which created the appearance of increased annual flows after 1965. The implementation of center pivot irrigation also reduced some diversions by increasing irrigation efficiency, but the efficiency and technology coincided with increases in acreage. Moratoriums on well development halted further groundwater extraction after 1981. Last but not least, a reduction in surface water diversions for compliance with the Rio Grande Compact also reduced the impact of increased groundwater extraction and agriculture acreage on streamflow.

The system is complicated and underwent many changes; some effects were direct, while some effects counteracted others. Primary influences, such as surface water allocations, directly impacted streamflow, while secondary influences, such as the impact of groundwater extraction on streamflow are inferred through known connections. Ultimately, the loss of available surface water rights led to an increase in groundwater extraction, which appears to have been motivated by increases in irrigated acreage (compare Figure 6.6 and 6.10). This caused reductions in streamflow, which in turn led to the 1938 Rio Grande Compact, the law suit against Colorado, the moratorium on well development, and the initiation and completion of the Closed Basin Project.

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**Tables Figures**

Table 6.1. Stations names, locations and elevation.

| Gauge stations | Station name | Station ID | Location | Elevation (m) |
|---|---|---|---|---|
| *Inflow* | | | | |
| Rio Grande | Riodelco | 8220000 | 37°68'N / 106°46'W | 2432.38 |
| Conejos River | Conmogco | 8246500 | 37°05'N / 106°18'W | 2521.82 |
| Los Pinos River | Losortco | 8248000 | 36°98'N / 106°07'W | 2450.59 |
| *Outflow* | | | | |
| Rio Grande | Riolobco | 8251500 | 37°07'N / 105°75'W | 2263.94 |

Table 6.2. Change point analysis of Rio Grande streamflow at Lobatos gauging station.

| *Rio Grande* at *Lobatos* (1900-2007) | Change point year | Confidence interval | Confidence level | Flow Volume | |
|---|---|---|---|---|---|
| | | | | Before | After |
| Annual | 1925 | 1905-1934 | 100 | 806,280,000 | 493,570,000 |
| | 1958 | 1934-1954 | 97 | 493,570,000 | 222,200,000 |
| | 1965 | 1958-2007 | 97 | 222,200,000 | 400,640,000 |

Table 6.3. GLM analyses of streamflow change points in annual outflow and inflow volumes.

| | | | | Level of significant difference between periods | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1925-1957 | | 1958-1963 | | 1964-2007 | |
| Period | Mean flow* | Std Error | Std Dev | F-value | *p*-value | F-value | *p*-value | F-value | *p*-value |
| *Outflow* | | | | | | | | | |
| 1912-1924 | 823.34 | 76.24 | 274.90 | 1.75 | 0.0021 | 19.22 | <0.0001 | 26.32 | <0.0001 |
| 1925-1957 | 427.56 | 50.72 | 291.34 | - | - | 2.30 | 0.0662 | 0.32 | 0.2875 |
| 1958-1964 | 248.63 | 59.31 | 145.27 | - | - | - | - | 1.56 | 0.1072 |
| 1965-2007 | 393.15 | 38.21 | 253.49 | - | - | - | - | - | - |
| *Inflow* | | | | | | | | | |
| 1912-1924 | 1,630.29 | 81.79 | 294.91 | 7.16 | 0.0044 | 7.01 | 0.0046 | 9.29 | 0.0015 |
| 1925-1957 | 1,269.03 | 71.44 | 410.38 | - | - | 0.94 | 0.1675 | 0.14 | 0.3548 |
| 1958-1964 | 1,092.42 | 128.49 | 314.74 | - | - | - | - | 0.63 | 0.2155 |
| 1965-2007 | 1,232.07 | 58.96 | 391.13 | - | - | - | - | - | - |

Table 6.4. GLM analyses of streamflow change points in growing season outflow and inflow volumes.

| | | | | Level of significant difference between periods | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1925-1949 | | 1950-1978 | | 1979-2007 | |
| Period | Mean flow* | Std Error | Std Dev | F-value | *p*-value | F-value | *p*-value | F-value | *p*-value |
| *Outflow* | | | | | | | | | |
| 1912-1924 | 551.48 | 69.49 | 250.53 | 17.72 | <0.0001 | 20.94 | <0.0001 | 23.90 | <0.0001 |
| 1925-1957 | 257.93 | 40.61 | 233.31 | - | - | 3.40 | 0.0343 | 0.53 | 0.2335 |
| 1958-1964 | 94.63 | 40.14 | 106.21 | - | - | - | - | 2.15 | 0.0729 |
| 1965-2007 | 221.94 | 29.86 | 195.78 | - | - | - | - | - | - |
| *Inflow* | | | | | | | | | |
| 1912-1924 | 1,223.97 | 76.92 | 277.32 | 7.09 | 0.0046 | 8.76 | 0.0019 | 8.35 | 0.0024 |
| 1925-1957 | 1,000.15 | 72.26 | 415.09 | - | - | 1.54 | 0.1062 | 0.03 | 0.4266 |
| 1958-1964 | 804.31 | 108.39 | 286.76 | - | - | - | - | 1.35 | 0.1245 |
| 1965-2007 | 983.86 | 58.54 | 383.89 | - | - | - | - | - | - |

Table 6.5. Annual water balance based on streamflow change points.

| | | Change in outflow | | Change in inflow | Diversions | Percent of inflow diverted during each period | Additional increase or decrease in diversions not explained by changes in inflow |
|---|---|---|---|---|---|---|---|
| Period | Mean outflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | Mean inflow volumes* | $Vol_{pn+1} - Vol_{pn}$ | $Inflow_{pn} - Outflow_{pn}$ | $Cons_{pn} / Inflow_{pn}$ | $Change^{In}_{pn} - Change^{Out}_{pn}$ |
| *Annual changes in flow* | | | | | | | |
| 1912-1924 | 823.34 | N/A | 1,506.55 | | 683.21 | 0.45 | N/A |
| 1925-1957 | 427.56 | -395.78 | 1,170.75 | -335.80 | 743.19 | 0.63 | 59.98 |
| 1958-1964 | 248.63 | -178.93 | 1,005.94 | -164.81 | 757.31 | 0.75 | 14.11 |
| 1965-2007 | 393.15 | 144.52 | 1,137.81 | 131.87 | 744.66 | 0.65 | -12.65 |

Table 6.6. Growing season water balance based on streamflow change points.

| Period | Mean outflow volumes* | Change in outflow | Mean inflow volumes* | Change in inflow | Diversions | Percent of inflow diverted during each period | Additional increase or decrease in diversions not explained by changes in inflow |
|---|---|---|---|---|---|---|---|
| | | $Vol_{pn+1}$ - $Vol_{pn}$ | | $Vol_{pn+1}$ - $Vol_{pn}$ | $Inflow_{pn}$ - $Outflow_{pn}$ | $Cons_{pn}$ / $Inflow_{pn}$ | $Change^{In}_{pn}$ - $Change^{Out}_{pn}$ |
| *Growing season changes in flow* | | | | | | | |
| 1912-1924 | 551.48 | | 1,223.97 | | 672.49 | 0.55 | N/A |
| 1925-1957 | 257.93 | -293.56 | 1,000.15 | -223.82 | 742.22 | 0.74 | 69.74 |
| 1958-1964 | 94.63 | -163.30 | 804.31 | -195.84 | 709.68 | 0.88 | -32.55 |
| 1965-2007 | 221.94 | 127.31 | 983.86 | 179.55 | 761.92 | 0.77 | 52.24 |

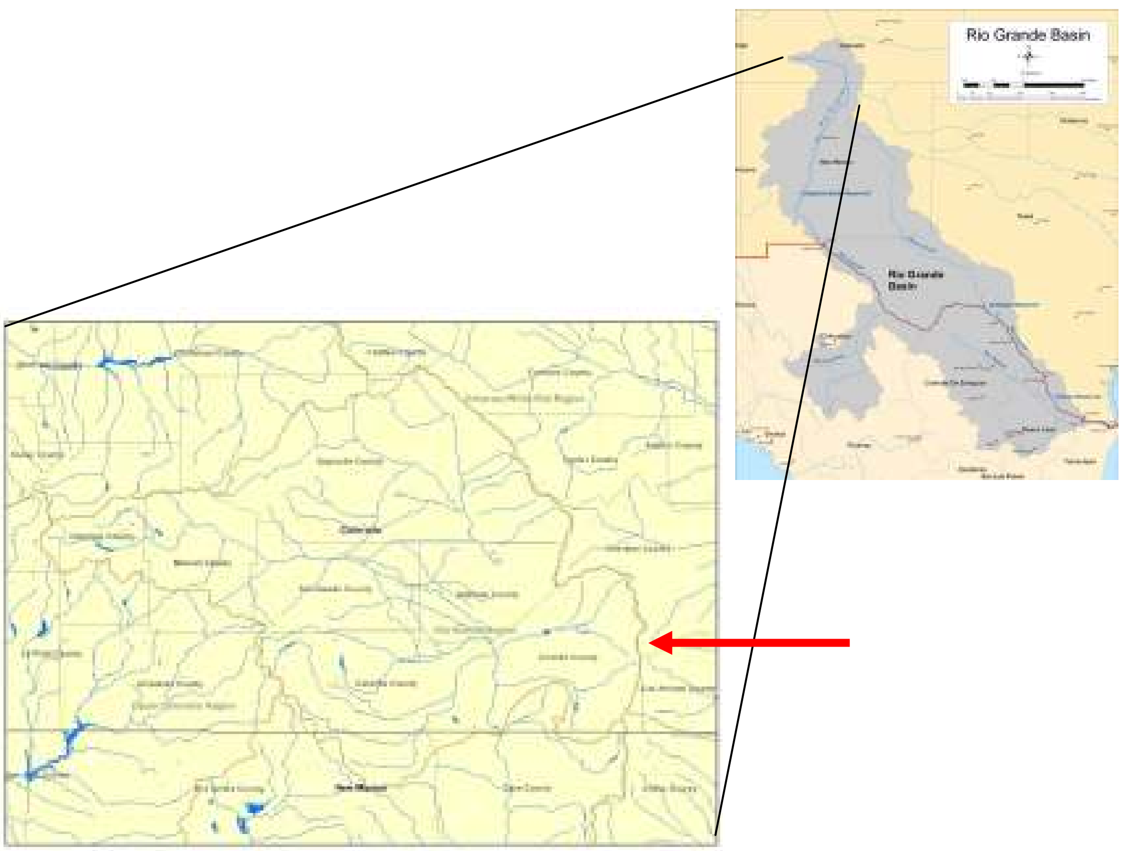


Figure 6.1. The Upper Rio Grande watershed, its tributaries and the San Luis Valley. Red arrow indicates the boundaries of the Upper Rio Grande watershed. Blue lines indicate streams and irrigation channels.


Figure 6.2. Gauge station locations in the Upper Rio Grande watershed.

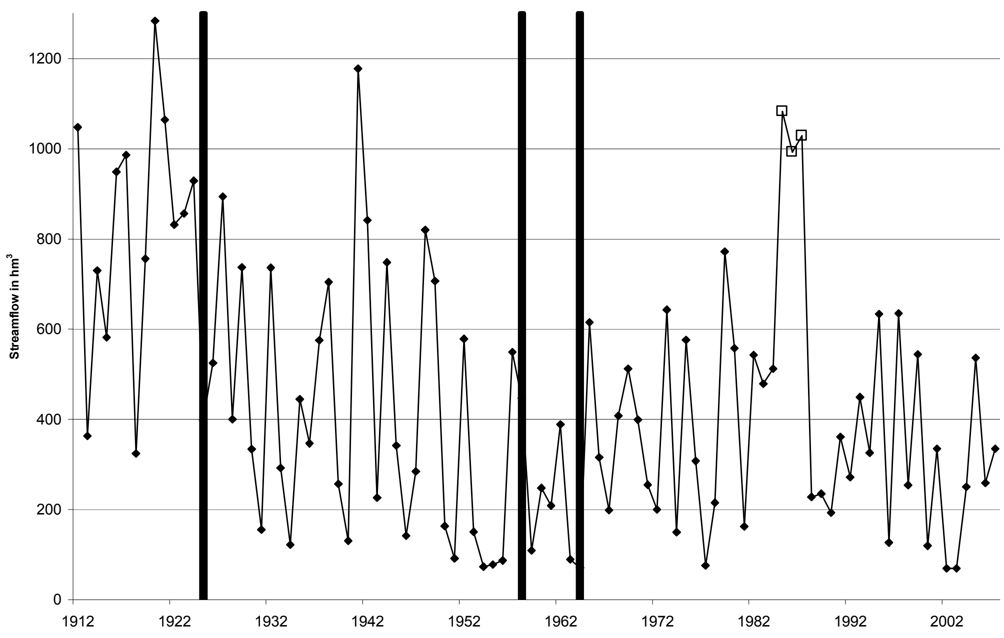


Figure 6.3. Historic annual flow at Lobatos gauge station: 1912-2007. Diamonds represent peak flow years 1985-1987. Vertical bars delineate periods identified in change point analysis. Open square points represent the 1985-1987 high flow years.

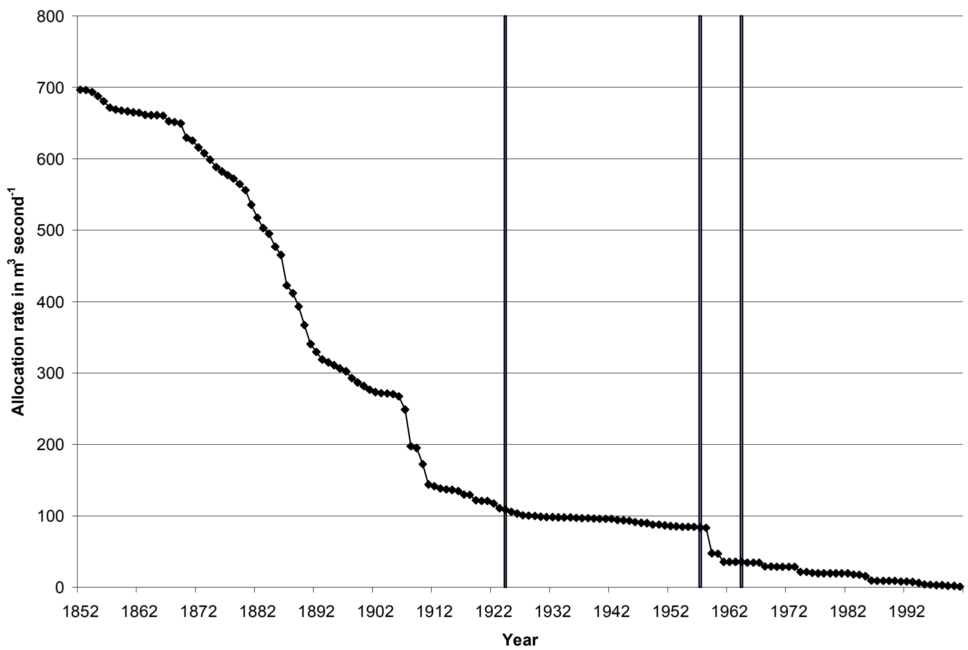


Figure 6.4. Declining cumulative sum of surface water allocations, 1852-2002, indicating the near exhaustion of available surface water allocations prior after 1924. Vertical bars delineate periods identified in streamflow change point analysis: 1924, 1957 and 1964.

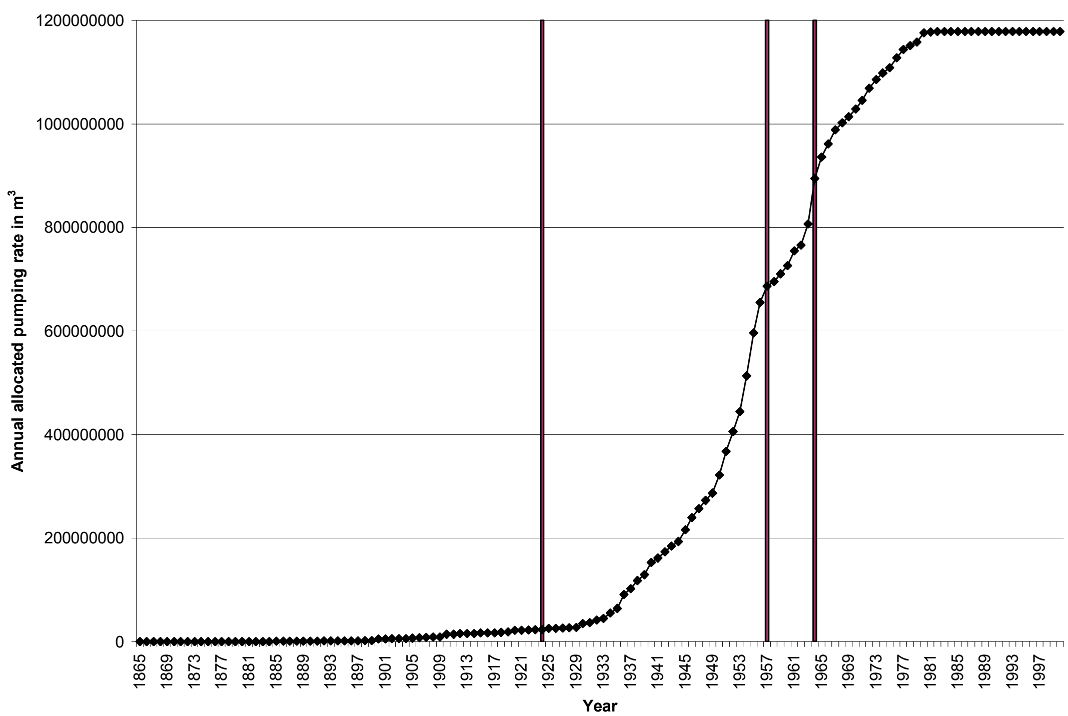


Figure 6.5. Increasing cumulative sum of groundwater allocated pumping rates; 1852-2002 indicating the rapid increase since 1924. Vertical bars delineate periods identified in streamflow change point analysis: 1924, 1957 and 1964.

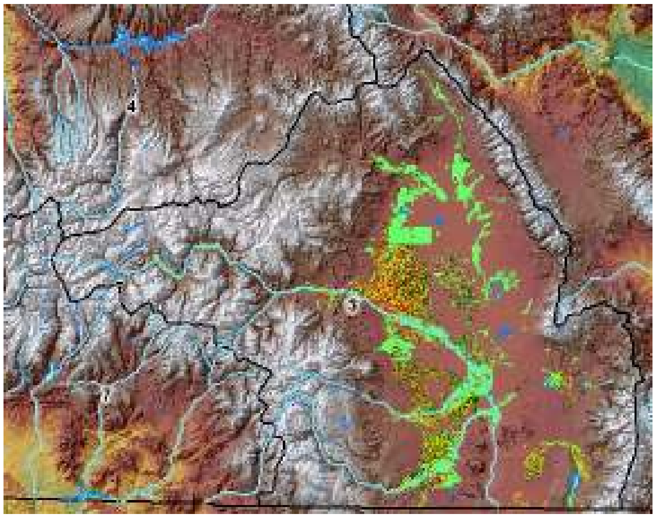

Figure 6.6. Extent of irrigated agriculture in 1936. Image source: Colorado Decision Support System http://cdss.state.co.us/DNN/MapViewer/tabid/62/Default.aspx.

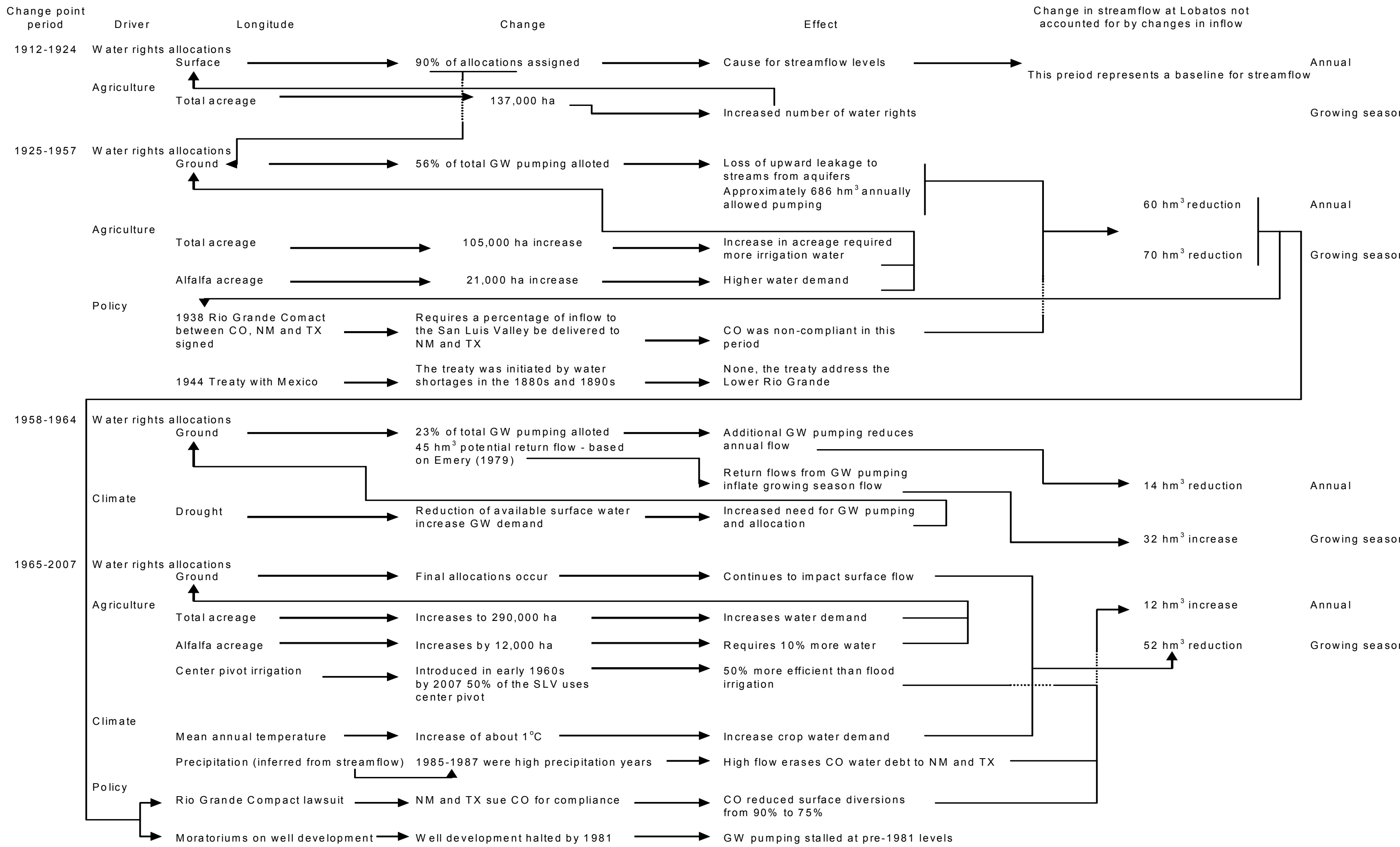


Figure 6.7. Flow chart depicting the changes in drivers and individual longitudes, interactions with each other and effects on streamflow.


Figure 6.8. Total acreage in hectares of all crops in the San Luis Valley: 1919-2007. Vertical bars delineate periods identified in streamflow change point analysis: 1924, 1957 and 1964.

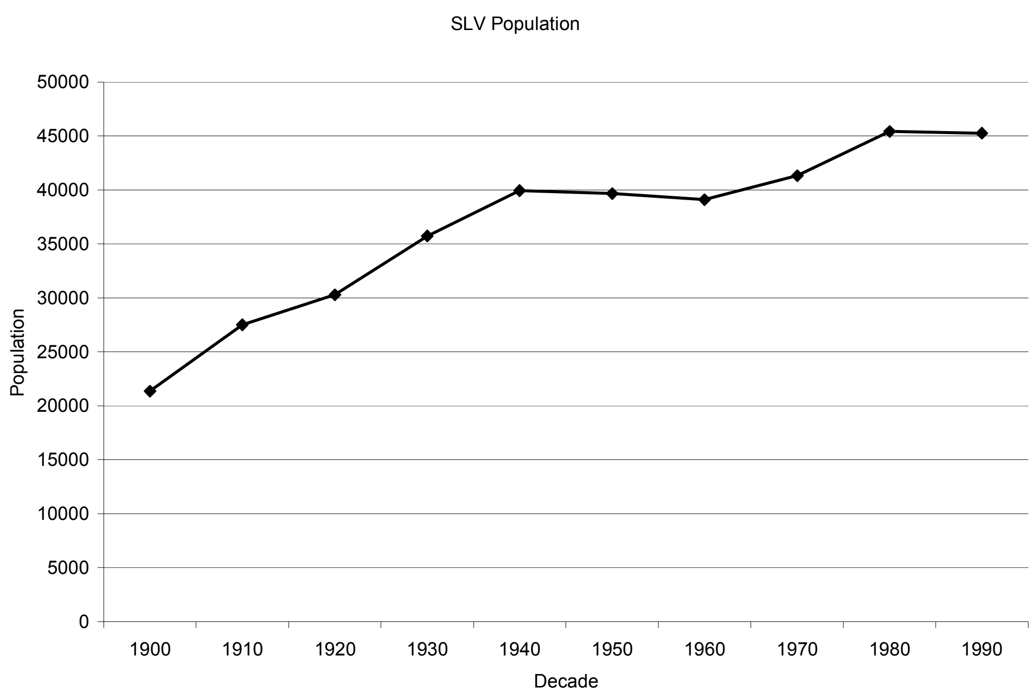


Figure 6.9. Population of the San Luis Valley. Data source: U.S. Census Bureau.

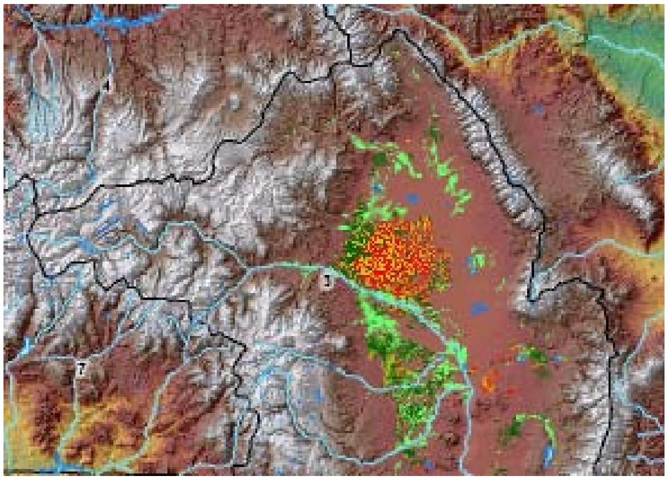

Figure 6.10. Extent of irrigated agriculture in 2003. Image source: Colorado Decision Support System http://cdss.state.co.us/DNN/MapViewer/tabid/62/Default.aspx

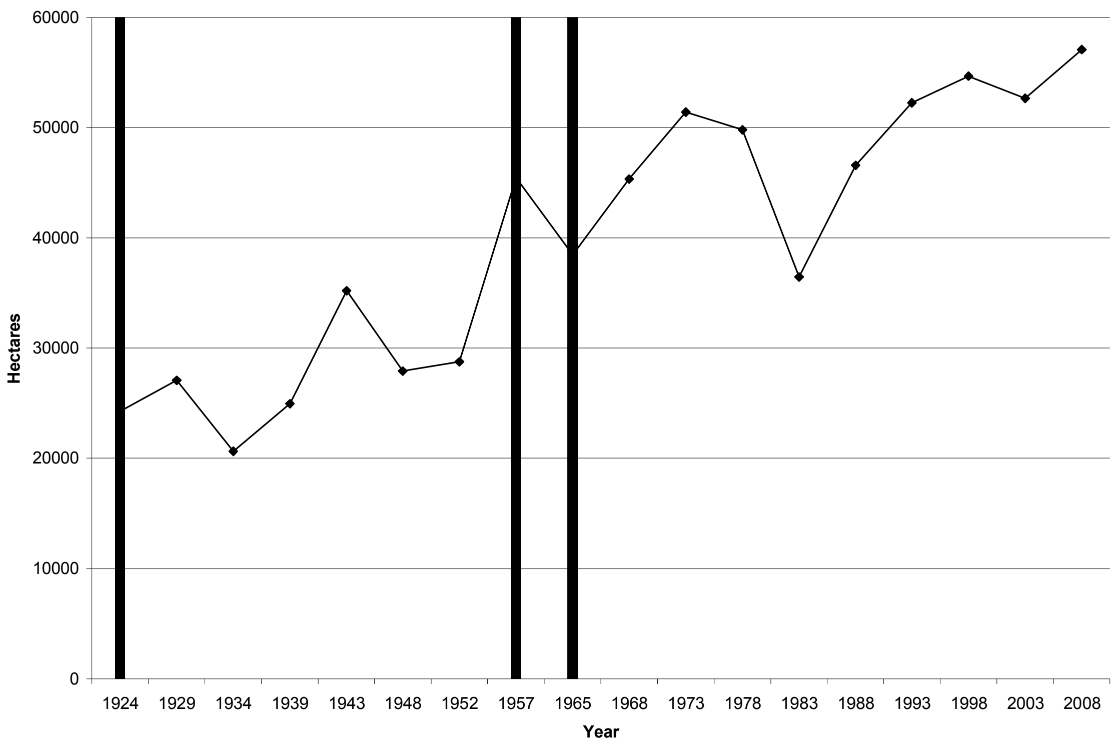


Figure 6.11. Total alfalfa acreage in hectares in the San Luis Valley: 1919-2007. Vertical bars delineate periods identified in streamflow change point analysis: 1924, 1957 and 1964.

## VITA

Prior to beginning his academic pursuits Ken Mix spent 18 years in various careers including art conservator, historic blacksmith and farmer. As a farmer he was a major fresh market vegetable producer in the Indianapolis area; providing several large supermarkets and fine dining establishments with local fresh produce for nearly a decade. It was not until 1996 that he re-entered university combining his experiences from earlier careers and his hobby of birding to obtain a B.S. in Natural Resources and Environmental Management from Ball State University in 1999, with an emphasis in water and soil science. He briefly worked with the environmental consulting firm of Lee and Ryan where he assisted with leaking underground storage tank (LUST) removal and groundwater monitoring. In January 2000, he entered Texas A&M University-Kingsville to begin a master's program in Range and Wildlife Sciences on the fire ecology of breeding birds and invertebrates in mixed-brush grasslands. He completed his M.S. in Range and Wildlife in 2004. He entered the Aquatic Resources Ph.D. program in Biology at Texas State University-San Marcos in 2003 with an interest in improving the understanding of complex systems and water resources.

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