THESIS

WATER CONSERVATION METHODS TO CONSERVE THE HIGH PLAINS AQUIFER AND ARIKAREE RIVER BASIN: A CASE STUDY ON THE ARIKAREE RIVER

Submitted by

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ABSTRACT

WATER CONSERVATION METHODS TO CONSERVE THE HIGH PLAINS AQUIFER AND ARIKAREE RIVER BASIN: A CASE STUDY ON THE ARIKAREE RIVER

Throughout the United States, and especially in Colorado, farmers confront the challenges of meeting water needs for crop production while trying to maintain natural habitats and conserve dwindling water supplies. The challenge of dividing limited resources creates a constant need for evaluation, research, and conservation of our valued water resources. The Arikaree River is a tributary of the Republican River on the Great Plains of Eastern Colorado. The river is groundwater dependent and receives flow from the underlying High Plains aquifer. The river alluvium has mature riparian communities of plains cottonwoods, habitat for threatened fish species such as the *Hybognathus hankinsoni* (Brassy Minnow), and habitat for many terrestrial invertebrates, sustained by water from the High Plains aquifer. In addition to the demands for maintenance of habitats, the surrounding, almost exclusively irrigated agricultural lands need water as well. The irrigation water supply is the groundwater pumped from the High Plains aquifer by high-capacity pumps. In recent years, the river became a series of disconnected pools or has dried up entirely during the late summer. To sustain both a precarious regional agricultural economy and an aquatic/riparian ecosystem, both dependent on groundwater for existence, there must be tradeoffs to preserve this important resource. The results of this research project provided practical guidelines for water conservation and water management practices. This research project identified feasible and realistic conservation measures that water users could voluntarily implement in Yuma County and other river basins around the country.

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CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

The agricultural community and the natural resource community have significant interests in conserving the aquatic biota and the ecosystem. The agricultural community is currently mining the High Plains aquifer (HPA) at an unsustainable rate that could eliminate the opportunity of irrigation farming for future generations. The natural resources communities are observing declines in aquatic habitat and reduced species diversification in many streams in Eastern Colorado due to declining groundwater levels. The results of this research will be useful for implementing water conservation practices and the necessary future planning throughout the region. The agricultural community understands the environmental concerns, especially those related to maintaining suitable stream flows and aquifer water levels. The long-term interest of all parties is proactively reducing water consumption in the agricultural sector, so that water is available for diverse societal needs and future agricultural production. Research results provide practical guidelines for potential water savings and economical water conservation methods with the least impact on the High Plain aquifer and the Arikaree River. Results from this research will allow water users to evaluate how current and future conservation techniques can affect water systems in the region.

The natural resources community and producers in eastern Colorado will benefit from understanding the feasibility of conservation methods identified. The natural resources community will see the benefits to both the ecosystem and the costs to producers to conserve water and maintain the precious agricultural community. The agricultural and natural resource communities will each benefit from a better understanding of conservation options applicable to the High Plains aquifer and habitat in the Arikaree River. The agricultural and natural resource communities will also benefit from a better understanding of the river system, of the surrounding water use, and their interrelationship. The research presented will enable natural resource managers to make decisions regarding best practices for protecting riparian fish species. Most importantly, development of these useful methodologies in other areas throughout the arid west where irrigated agriculture, declining groundwater levels, and critical fish habitat are hydraulically connected and water is a requirement to maintain the robustness of both systems is possible.

1.1.1 Arikaree River

The Arikaree River in Yuma County, Colorado is a tributary of the Republican River. The Arikaree River has headwaters on the plains in eastern Colorado that flow northeast through Kansas before joining the Republican River in the southwest corner of Nebraska. The river is a fluctuating stream (Scheurer et al. 2003b), primarily sustained by inflow from springs or seeps from the High Plains aquifer and by storm events. Based on flow data from the Haigler, Nebraska USGS gauging station, the Arikaree River typically has small flows, averaging 0.50 cubic meters per second (m^3/s) from 1933 to

2007. The Arikaree River has a drainage area of 656 square kilometers (km) with a total stream length of 462 km (U.S. Census Bureau 2006).

1.1.2 High Plains Aquifer

The High Plains aquifer, or the Ogallala Aquifer, is the largest aquifer in the United States underlying 67,182 square km of the High Plains (U.S. Geological Survey 2008). The aquifer is located in South Dakota, Nebraska, Kansas, Oklahoma, Texas, Wyoming, New Mexico, and Colorado (Figure 1.1). The USGS estimated that the High Plains aquifer has 4.0088 trillion m^3 of total usable water (Kromm and White 1992). Colorado only has 4% of the High Plains aquifer available for usable water whereas Nebraska, Kansas, and Texas contain 87% of all water in the High Plains aquifer (Kromm and White 1992).

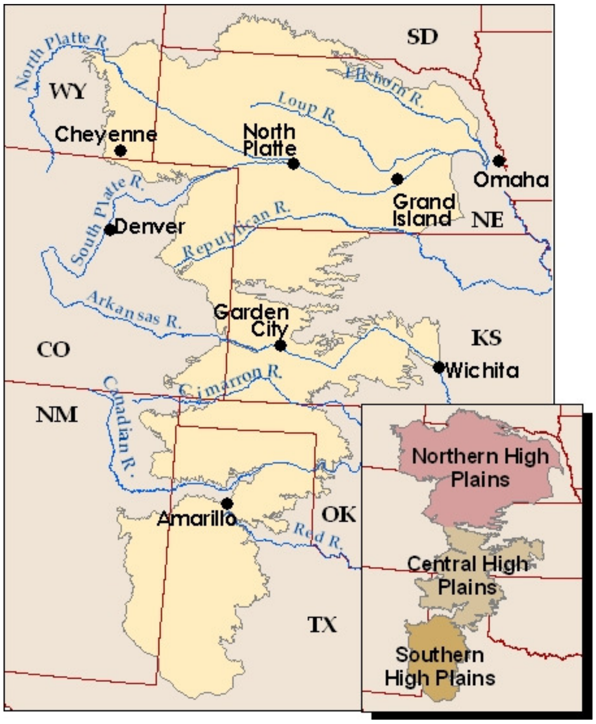


Figure 1.1: Map of the Ogallala Aquifer (U.S. Geological Survey 2007)

Since the High Plains aquifer feeds and connects to the Arikaree River, the aquifer and land geomorphology have a significant effect on flow regimes (Fausch and Bestgen 1997). The aquifer is a water-table aquifer that, for the most part, is composed of Pleistocene alluvium, consisting primarily of poorly sorted gravel, sand, and clay (Topper et al. 2003). The maximum saturated thickness of the High Plains aquifer is about 305 meters, though the average saturated thickness of the aquifer is about 14 m, while the water level varies from 1.5 to 19.5 meters (Topper et al. 2003). In the 1950's, it was believed that the Ogallala was an inexhaustible source of water coming from the distant mountains (Kromm and White 1992). This theory disappeared as high capacity wells for irrigation increased and the water table levels fell (Kromm and White 1992). The decline of the High Plains aquifer can be attributed to groundwater pumping for irrigation, riparian evapotranspiration (ET), and lack of recharge, that have important environmental and economic consequences to agriculture on the Great Plains. The aquifer sustains the agricultural economy and most of the aquatic and riparian ecosystems in the region.

The development of irrigation on the High Plains has transformed the area into one of the principal agricultural regions of the United States. "Irrigated agriculture sustains the High Plains and is central to an integrated agribusiness economy that demands seeds, fertilizers, pesticides, agricultural machinery, and credit….the common thread is water, that, by virtue of irrigated agriculture, nurtures life in a dry region" (Kromm and White 1992). The groundwater irrigation agriculture has brought increased grain production and protection from drought, but has adversely increased the impacted groundwater depletion, decreased stream flow, resulted in loss of vegetative cover, created localized problems with water quality, caused population redistribution, and spurred economic reorganization (Kromm and White 1992).

The State of Colorado passed the Ground Water Management Act to give the Colorado Ground Water Commission (CGWC) authority to establish eight designated basins and thirteen Ground Water Management Districts (GWMDs) within such basins. Figure 1.2 shows these basins and districts. The GWMDs have authorization to adopt additional rules and regulations to help administer groundwater within their district (CGWC 2007).

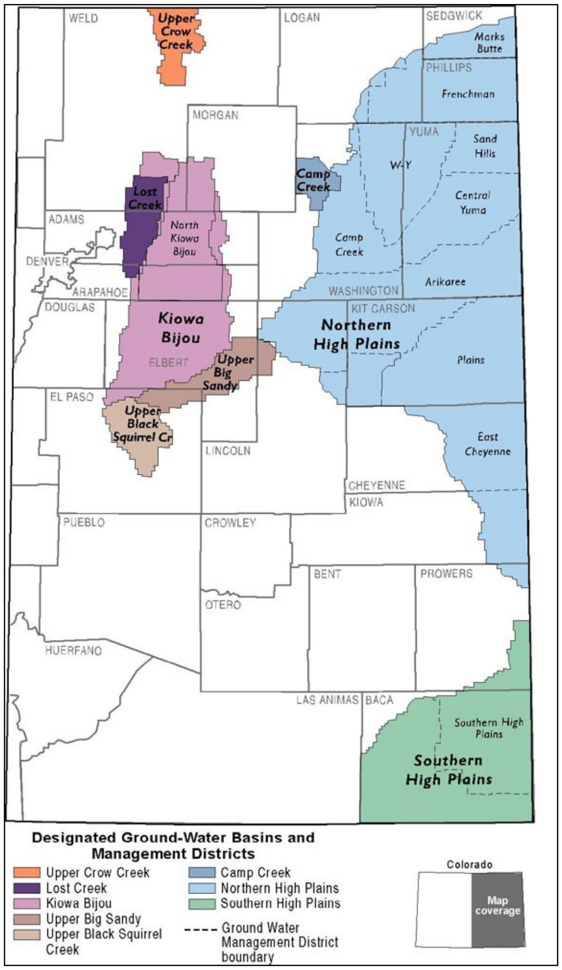


Figure 1.2: High Plains Aquifer in Eastern Colorado (CGWC 2007)

1.2 STUDY SITE LOCATION

The research site is the Arikaree River basin in Yuma County, Colorado as shown in yellow in Figure 1.3. The Arikaree River is a tributary to the Republican River. It is a small, vulnerable river system in Colorado entirely sustained by inflow from the High Plains aquifer. Flows in the Arikaree are typically small, averaging 0.5 cubic meters per second (m^3/s) from 1933 to 2003 (USGS Gauging Station #06821500) (USGS 2010). The yellow section in Figure 1.3 shows the groundwater divide that supplies water to the Arikaree River and the red section identifies the High Plains aquifer.

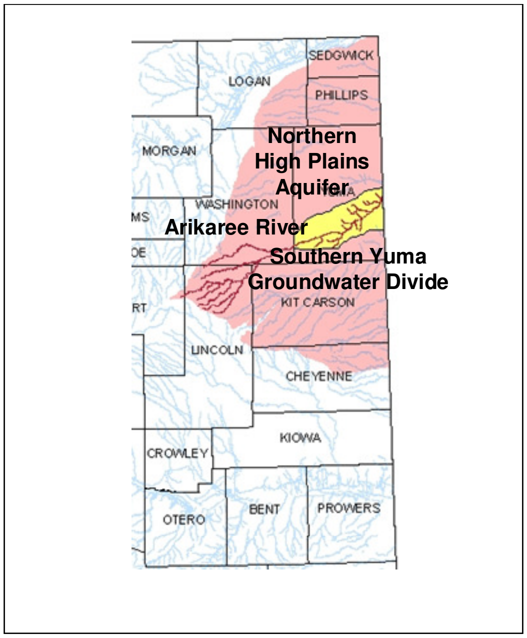


Figure 1.3: Location of the Arikaree River in Yuma County, CO (Squires 2007)

The upstream and middle river segments were the focus of major graduate research shown in Figure 1.4. The downstream segment is typically dry and was not included in the analyses performed. The upstream segment is located on the Nature Conservancy’s Fox Ranch (shown in red on Figure 1.4) where most of the water level wells and the Arikaree River water level research was completed. The thick black line represents the location of the High Plains aquifer's water balance model completed in this research that encompasses the Arikaree River located within Yuma County.

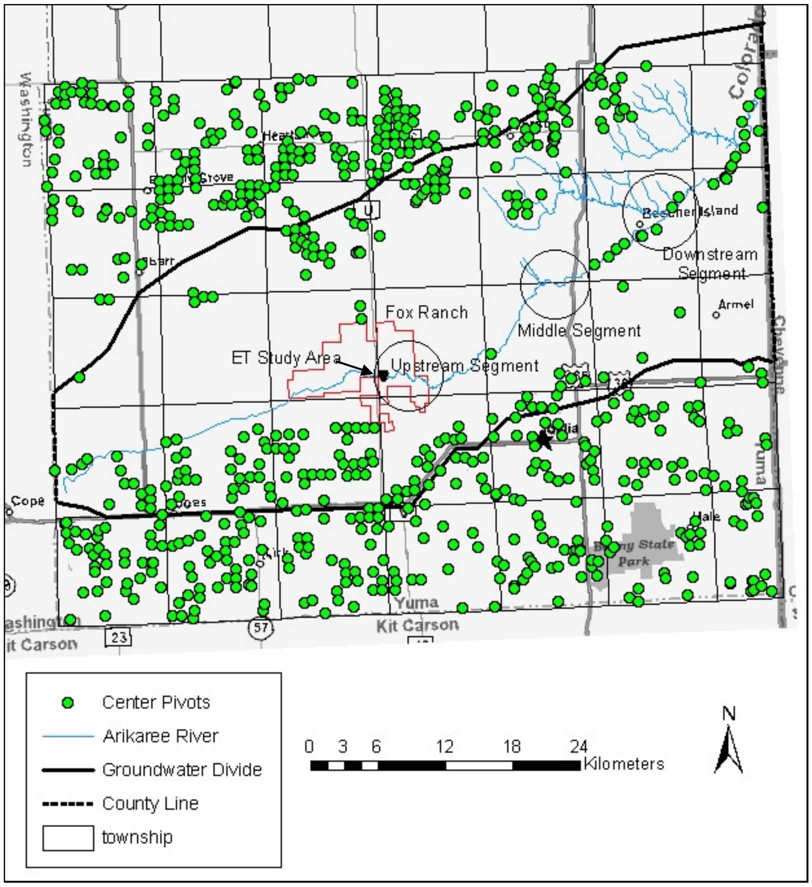


Figure 1.4: The Arikaree River Basin within Southern Yuma County (Wachob 2006)

1.3 PROBLEM STATEMENT

Drought, technological advances in well drilling and pumping equipment and favorable economic factors have led to large-scale irrigation overlying a shallow water table. By 1949, groundwater irrigated about 10 percent of the land that overlies the aquifer in Colorado and New Mexico (Kromm and White 1992). Further advances in drilling and pumping technology, along with the availability of low-cost energy, enabled development of groundwater in areas of greater groundwater depth. The introduction of center-pivot irrigation systems in the 1960's made irrigation of rolling terrain and sandy soils practical. The irrigated acres increased from 1959 to 1978 by approximately 195% in Colorado (Kromm and White 1992). In 1978, the increase in irrigated acreage in the northern part of the High Plains was primarily the result of center-pivot technology. By 1980, the High Plains aquifer in Colorado supplied water to about 311,610 hectares (ha) from approximately 4,000 wells (USGS 2008). Groundwater withdrawal during 1980 was about 1215.0 million cubic meters in Colorado. The 1855.2 million cubic meters of water withdrawn from the High Plains aquifer during 1980 in Colorado and New Mexico greatly exceeded the 241.8 million m^3 per year of natural recharge to the aquifer in these states (USGS 2008). In northeastern Colorado, the High Plains aquifer currently reveals depletion at about 1.5 times the rate of recharge to the aquifer. To balance recharge and discharge, annual pumping needs reduced from 1233.5 to 493.4 million m^3 or approximately 60%. This decline in pumping will adversely affect crop yields and farm income (McGuire et al. 2003). Just as the expansion of irrigation has grown from south to north, the groundwater depletion has followed a similar pattern (Kromm and White 1992).

In the High Plains of eastern Colorado alone, 20.96 billion m^3 of water depleted available supplies from the aquifer during the first 30 years (1960-1990) after introduction of high capacity pumping (USGS 2008). Today, the water table is declining by about 0.25 m/yr near the Arikaree River (Squires 2007) and the average rate of decline of the water table is 0.34 m/yr (Schaubs 2007). This represents removal of approximately 1.25 billion m^3 from the aquifer. A decline of 0.3 meters is equal to depletion of approximately 1110.0 million m^3. Over the years from 2002 to 2007, the basin-wide water level has declined an average of approximately 1.91 m, representing a depletion of approximately 6.95 billon m^3 or more than five percent of the estimated 1965 storage in the aquifer. The depletion for the period from 1997 to 2007 indicates that more than 10.48 billion m^3 have been removed from storage with a decline of 2.88 m (Schaubs 2007). This equates to a rate of depletion of more than one-half percent per year (Schaubs 2007). Assuming that the rate of depletion from 1965 to 2007 is one-half percent per year, approximately twenty-one percent (21%) of the High Plains aquifer has already been depleted up to 2007 (Schaubs 2007). VanSlyke and Joliat (1990) determined the annual water table decline of roughly 0.3 m (one foot) in the Northern High Plains. However, the average rate of depletion is "misleading in that some areas in the basin are experiencing much higher rates of depletion due to a lesser saturated thickness and the fact that 2000 to 2003 were extremely dry years" (Schaubs 2007).

Because water-level declines in the High Plains aquifer have been large, they have substantially decreased the saturated thickness of the aquifer in some areas. The Arikaree Groundwater Management District as a whole is reporting a decline of 1.14 m in saturated thickness from 1997 to 2004 (Davis and Richrath 2005). As the water levels in the High Plains aquifer decline, the cost of pumping water is increasing and the water yield of the aquifer is decreasing (Schaubs 2007). As water levels decline, costs to obtain water increase as the result of the need for deeper wells, larger pumps, and larger energy expenditure to lift the water to the surface. At some point, the irrigation and commercial wells will not produce sufficient volumes of water to continue irrigation and other operations (McGuire et al. 2003). The evidence indicates that unless there is immediate action taken to counteract the decline in the High Plains aquifer, irrigation operations within the High Plains aquifer will eventually terminate (McGuire et al. 2003).

Yuma County, Colorado is entirely located on the High Plains aquifer and the groundwater from the High Plains aquifer is the primary source of irrigation water. The Colorado Department of Agriculture (2007) estimates that total agricultural land (cropland and pasture) is 177,170 ha with 84,500 ha of that acreage being irrigated (47.7%). About 90% of the irrigation systems use center pivots and pump from the High Plains aquifer (Frasier et al. 1999; Colorado Department of Agriculture 2007). Center pivot irrigation systems commonly reported high-capacity wells of 16 to 60 L/s. The high volume pumping for irrigation has caused a disruption of the riparian ecosystem and water levels in the Arikaree River. Reduced stream flow and reduced base flow from water level declines in the adjacent High Plains aquifer causes this disruption. The base flow from the High Plains aquifer supplied the Arikaree River; therefore, experiencing direct impacts to the river system (Labbe and Fausch 2000). Agricultural irrigation use of the High Plains aquifer has contributed to the declines in the regional water table. The declining river flows as well as the declining water table are both apparent in Figure 1.5 that depicts the same river section near the Colorado-Kansas border in 1980, 1996, and 2006 (Kansas Department of Wildlife and Parks 2006). The connections between irrigation pumping and available river water in the Arikaree is apparent in Figure 1.6. Figure 1.6 shows the average annual stream flow from 1932 to 2007 from the gauging station at Haigler, Nebraska (USGS 2007). After the introduction of groundwater pumping in the 1960's, there is a noticeable decline in the average annual flows. An analysis of pre- (1932-1960) and post- (1960-2007) pumping data for average annual flows in the Arikaree River had flows of 0.83 m^3/s and 0.30 m^3/s, respectively. Therefore, aquifer extraction for irrigation affects the aquifer-fed Arikaree River and may be the cause the decline and extinction of native aquatic organisms (Labbe and Fausch 2000).

Figure 1.5: The Arikaree River Photographs Taken in 1980, 1996, and 2006 (left to right) Near the Colorado Kansas Border (Kansas Department of Wildlife and Parks 2006)

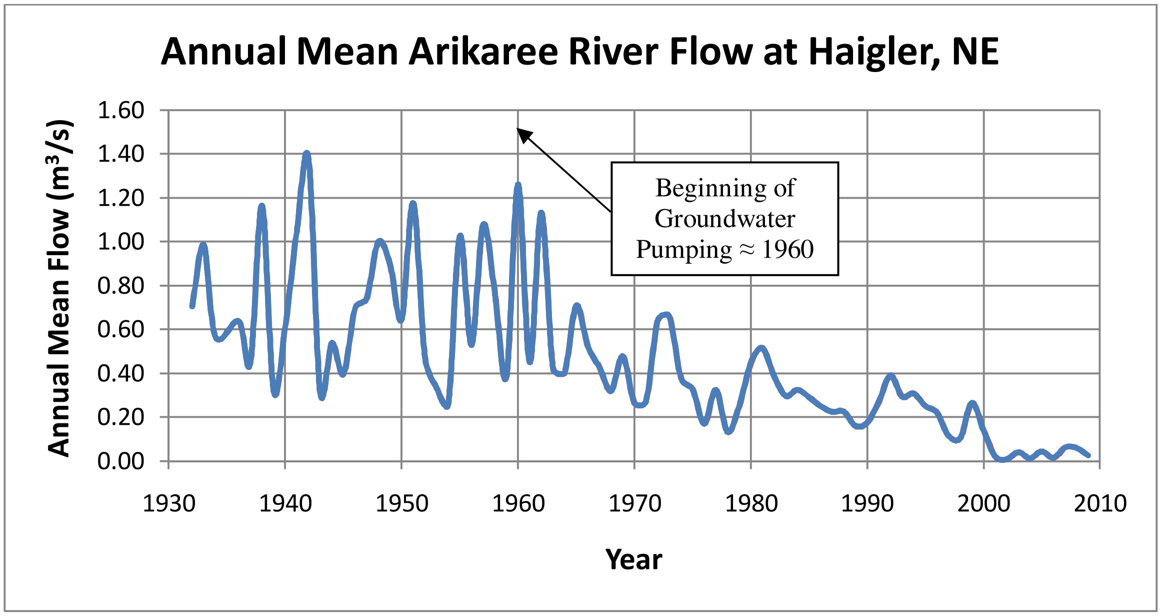


Figure 1.6: Annual Average Stream Flows in the Arikaree River at Haigler, Nebraska from 1932 to 2009 (USGS 2010)

1.4 OBJECTIVES

Extensive research on the alluvium formation of the Arikaree River, agriculture pumping from the alluvium formation of the Arikaree River and High Plains aquifer, and Brassy Minnow habitats located within the Arikaree River provided background information for this research. The extensive research on the Arikaree River demonstrated the need for water conservation. The High Plains aquifer and Arikaree River are water resources critical to the quality of life and economic sustainability of small farming communities. The river also provides unique aquatic and riparian habitat. In recent years, long sections of the river have dried up during the summer and fall months (Scheurer et al. 2003b). There is no doubt that the future of the High Plains aquifer and Arikaree River is uncertain.

The first objective of this research was to examine the water conservation methods possible to implement in Eastern Colorado. The second objective was to determine the water conservation methods feasible to put into operation by producers in Eastern Colorado. The third objective was to quantify the realistic conservation methods and combinations that can prolong the High Plains aquifer water levels and Arikaree River pool habitats for the Brassy Minnow, while simultaneously sustaining agriculture in the region.

CHAPTER 2 LITERATURE REVIEW

Opportunities to address the water needs of irrigators and the stream flow requirements for habitat maintenance are many and diverse. The comprehensive literature review was completed about the conservation methods and practices used throughout the country and in the arid western United States under conditions similar to the High Plains aquifer and Arikaree River alluvium. The literature review identifies practical and effective conservation methods used in other basins that Yuma County could implement. The water conservation alternatives were broken into five different categories that include field conservation practices, irrigation conservation practices, management conservation practices, water conservation programs, and lower consumptive use crop selection. These different water conservation techniques reviewed discover the top three water conservation methods identified by farmers in eastern Colorado practices as possible to implement in eastern Colorado.

2.1 PREVIOUS RESEARCH

Previous studies on the Arikaree River have attempted to quantify the cropping systems and timing, irrigation pumping, riparian water use, and aquifer connection between the High Plains aquifer and the Arikaree River alluvium. Each of these graduate research projects examined specific aspects of the agricultural practices and river habitat to create the foundation for this research project. This research project seeks to combine these aspects of the past projects to offer possible solutions that could prolong the life of the High Plains aquifer and aquatic habitat pools in the Arikaree River.

2.1.1 Arikaree River

The Arikaree River's classification is a gaining river acquiring flows from seeps and springs that originate from the groundwater supply (Griffin 2004). The seeps feed the river largely from beneath the riverbed or laterally from the banks with many of the springs being visible during the winter base flows (Griffin 2004). In general, Griffin (2004) observed that water increased from west to east along the river from seeps and springs along the river. The springs dried throughout May and June of 2003, with many locations along the river having standing water pools that go dry by May (Griffin 2004).

Griffin (2004) estimated the Arikaree River slope of 0.004 to 0.005 m/m along the study reach, based on topographical data with some sections having a lower gradient. The winter flow Manning's n roughness was estimated to be 0.04 and could be higher during the summer growing months due to local grasses and vegetation. In 2003, there was installation of six stage gauges and shallow observation wells in the riverbed within the Fox Ranch boundary (Griffin 2004). Monitoring of the stage gauges and monitoring wells done on a bi-weekly basis of the water levels in the river showed that during the growing season, the water table is lowered beneath the streambed and roughly the same elevation as the water table beneath the riverbank (Griffin 2004). Griffin (2004) found the hydraulic conductivity along the Arikaree River at the Fox Range to have an average of 4.51 m/day from all five sites. The measured hydraulic conductive is quite low and comparable to a tributary or slough channel with large amounts of organic material lining the streambed (Griffin 2004).

Four farmers interviewed through a paper survey to obtain the irrigation practices for approximately 1133 ha. Using a weighted application depth from Griffin (2004) data, Wachob (2006) calculated a total irrigation water use of 52.2 million cubic meters for the whole basin. Griffin (2004) found that while irrigation water use was contributing to the overall decline of the aquifer levels, the riparian water use significantly affected dewatering in the Arikaree. Griffin (2004) used the Blaney-Criddle method to estimate an ET rate for cottonwoods of 126.5 cm/year for the growing season. Wachob (2006) found the riparian ET of 134.9 cm/year using high riparian density wells. The interpolation of his calculations for average value would 87.2 cm/year (Riley 2009). Riley (2009) used the White method and found that the riparian ET along the Arikaree River of 89.2 cm/year.

2.1.2 Hybognathus Hankinsoni (Brassy Minnow)

The Department of Fish and Wildlife Biology at Colorado State University has completed several years of research on the Arikaree River. During the persistent drought of 2000-2001, Scheurer et al. (2003a) found that Brassy Minnow *(Hybognathus hankinsoni*) were nearly extirpated from 3.22 to 6.44 km segments of the Arikaree River that were intermediate and severe in the extent of drying. The Brassy Minnow only persisted in substantial numbers and distribution in the wettest segment that was on the Fox Ranch. The goal of these comprehensive studies was to understand how groundwater influences fish habitat and, in turn, populations of Brassy Minnow, and the other ten native fishes in the Arikaree basin. This research project aimed to understand critical life history stages in order to advise water resource managers on when water is needed, and how much habitat needs to be maintained to allow this fish population to persist in the basin.

The Arikaree Basin in eastern Colorado has a rich agricultural history, but it has been subjected to pressures of reduced flow regimes and habitat depletion associated with the Brassy Minnow *(Hybognathus hankinsoni*) (Scheurer et al. 2003a). Irrigated agriculture in the western United States uses a significant amount of total available water, so it has come under increasing criticism for its contribution to environmental degradation of fish and wildlife habitats (Scheurer et al. 2003a). In 1998, the Colorado threatened species list included the Brassy Minnow (Scheurer et al. 2003a). The basic taxonomic characteristics include average adult body size of 50-70 mm, rounded dorsal, anal, and pectoral fins, the mean number of total radii of 17, and an even eye position (Scheurer et al. 2003a). The historic range of the Brassy Minnow was the Platte, Republican, and Kansas River (Smoky Hill River) basins (Scheurer et al. 2003a). As a native plains fish species, the Brassy Minnow can survive severe physiochemical conditions such as drought, flood, large temperature range (0-40ºC), and low dissolved oxygen content. Documentation has shown that plains fish can endure high temperatures of 36-40ºC for short periods and 30-34ºC for extended periods (Poff et al. 2001; Matthews and Zimmerman 1990). Brassy Minnow spawn in seasonally flooded river areas and backwaters during the spring and hatch in early summer.

Mature Brassy Minnow tend to inhabit pools with complex habitat (e.g. shallow and deep areas, and aquatic vegetation) as adults (Scheurer et al. 2003b). Scheurer (2003b) found that depth of pools and connectivity were the critical factors affecting the persistence of the Brassy Minnow populations. An increased pool depth provides refuge habitat, reduced terrestrial and avian predation, and deep pools are less likely to dry during summer and freeze during winter. The connectivity allows the Brassy Minnow to move between habitats, escape predation, and aids their recolonization in river segments (Scheurer et al. 2003b). The elimination of these critical habitats has the potential to reduce or extirpate Brassy Minnow populations. If the river dries completely, the Brassy Minnow will face eradication from one of its last strongholds in Colorado. In addition to the Brassy Minnow, there are many other threatened aquatic invertebrates and terrestrial wildlife, which depend on the Arikaree River. Despite low flows and ephemeral patterns of the river, seasonal moisture and well-established riparian vegetation in the alluvial valley has created a distinctive oasis for a variety of terrestrial wildlife including whitetail deer, wild turkeys, beaver, and numerous bird species.

2.1.3 Wildlife and Species of Concern

The Arikaree River basin encompasses a wide array of habitat types that support rich and extremely diverse wildlife populations. Grasslands that dominated this region prior to settlement included a mixed mid to tall-grass sand sage community on rolling upland sandy sites (Davis and Richrath 2005). The sites with less relief and heavier soils support the typical short-grass prairie plant species such as buffalo grass and blue gamma (Davis and Richrath 2005). Lowland tall-grass prairie was associated with the streams and rivers throughout much of the region. Trees and other woody vegetation are currently evident throughout many of the stream and river reaches within the area (Davis and Richrath 2005). The rich and diverse wildlife community includes 32 reptiles and amphibians, 33 fish, 45 mammals, and 269 bird species (Davis and Richrath 2005). A partial list of significantly important wildlife species by habitat type that occur in the Republican River Basin that includes the Arikaree River basin are included in Tables 2.1 to 2.4. This list includes species that are federally listed (F), state listed (S), of state concern and/or of significant economic importance to the State of Colorado and the region. Other status indicators in the following tables are unknown (unk.) and stable populations.

Table 2.1: Riparian or Wetland Species (Davis and Richrath 2005)

Common Name	Scientific Name	Taxa	Status
Bald Eagle	Haliaeetus leucocephalus	Bird	F/S
Rio Grand Turkey	Meleagris gallopavo intermedia	Bird	economic
Baltimore Oriole	Icterus galbula	Bird	stable
Song Sparrow	Melospiza melodia	Bird	stable
Marsh Wren	Cistothorus palustris	Bird	stable
Western Yellow-billed Cuckoo	Coccyzus americanus	Bird	F/S
Bell's Vireo	Vireo bellii	Bird	stable
Bobwhite	Colinus virginianus	Bird	declining
Yellowthroat	Geothlypis trichas	Bird	stable
Yellow Warbler	Dendroica petechia	Bird	stable
American Beaver	Castor canadensis	Mammal	stable
Mule Deer	Odecoileus hemionus	Mammal	economic
White-tailed Deer	Odecoileus virginianus	Mammal	economic
Northern Leopard Frog	Rana pipiens	Amphibian	S
Stoneroller	Campostoma anomalum	Fish	S
Suckermouth minnow	Phenacobius mirabilis	Fish	S
Fathead Minnow	Pimephales promelas	Fish	stable
Brassy Minnow	Hybognathus hankinsoni	Fish	S
Plains Minnow	Hybognathus placitus	Fish	S
Stonecat	Noturus flavus	Fish	S
Sand Shiner	Notropis stramineus	Fish	unk.
Red Shiner	Notropis lutrensis	Fish	unk.
River Shiner	Notropis blenniuis	Fish	S
Orangethroat Darter	Etheostoma spectabile	Fish	S

Table 2.2: Shortgrass Species (Davis and Richrath 2005)

Common Name	Scientific Name	Taxa	Status
Long-billed Curlew	Numenius americanus	Bird	S
Western Burrowing Owl	Athene cunicularia hypugaea	Bird	S
Mountain Plover	Charadrius montanus	Bird	F/S
Ferruginous Hawk	Buteo regalis	Bird	S
Prairie Falcon	Falco mexicanus	Bird	unk.
Brewer's Sparrow	Spizella breweri	Bird	declining
Swift Fox	Vulpes velox	Mammal	F/S
Mule Deer	Odecoileus hemionus	Mammal	economic

Table 2.3: Cropland Species (Davis and Richrath 2005)

Common Name	Scientific Name	Taxa	Status
Bobwhite	Colinus virginianus	Bird	declining
Ring-neck Pheasant	Phasianus colchicus	Bird	economic
Mule Deer	Odecoileus hemionus	Mammal	economic
White-tailed Deer	Odecoileus virginianus	Mammal	economic

Table 2.4: Mid-grass/Tall-grass Species (Davis and Richrath 2005)

Common Name	Scientific Name	Taxa	Status
Cassin's Sparrow	Aimophila cassinii	Bird	declining
Lark Sparrow	Chondestes grammacus	Bird	declining
Loggerhead Shrike	Lanius ludovicianus	Bird	declining
Long-eared Owl	Asio otus	Bird	stable
Short-eared Owl	Asio flammeus	Bird	stable
Greater Prairie Chicken	Tympanuchus cupido	Bird	economic
Upland Sandpiper	Bartramia longicauda	Bird	declining
Northern Harrier	Circus cyaneus	Bird	stable
Mule Deer	Odecoileus hemionus	Mammal	economic

2.1.4 Irrigation

In 2002, research was primarily devoted to quantifying the agricultural water use around the Arikaree River (Fardal 2003). The questions asked of six personally interviewed farmers concerned their crop mixes and water use. The collected data came from the six farmers, 31 wells and 2041 ha. When applying a weighted application depth to an irrigated area delineated by Wachob (2006) in 2005, the total irrigation water use in 2002 equaled 65.4 million cubic meters (Wachob 2006). During the driest year on record, 2002, Fardal (2003) found that farmers were deficit irrigating and suffered reduced yields due to the drought. Fardal (2003) also concluded that irrigation water use was the likely cause for reduced flows in the Arikaree River.

In 2005, farmers received the same survey as sent in 2003 that collected data on 14 wells and 900 ha. An average pumping rate was determined from this data and applied to the total irrigated acreage in the basin for a total pumped volume of 75.7 million cubic meters. For the 2005 growing season, Wachob (2006) used data recorded by the Y-W Well Testing Association (YW) who measured discharge rates of irrigation wells for farmers who employ their service. YW uses ultrasonic devices, Collins meters, and power meter coefficients to calculate the pumping rate. These data accounted for 15 wells and 884 ha and resulted in a total pumped volume of 57.6 million cubic meters.

The limited wells and land in a previous research survey could inaccurately represent irrigators in the region. The previous research and State data had little water level table and well data from the Arikaree River alluvium.

The research results show a strong link between groundwater pumping and stream flow declines as shown in Figure 2.1. Fardal (2003) and Griffin (2004) measured the pumping rates from a sample of wells supplying center pivot systems, and found the pumping strongly correlated with declines in stream levels on the Fox Ranch. Stream levels declined soon after pumps were turned on (usually in May), and increased about three weeks after irrigation stopped in September. However, vegetation growth and evapo-transpiration (ET) in the watershed followed the same temporal pattern as irrigation water use, so because of these two situations, effects may be compounded.

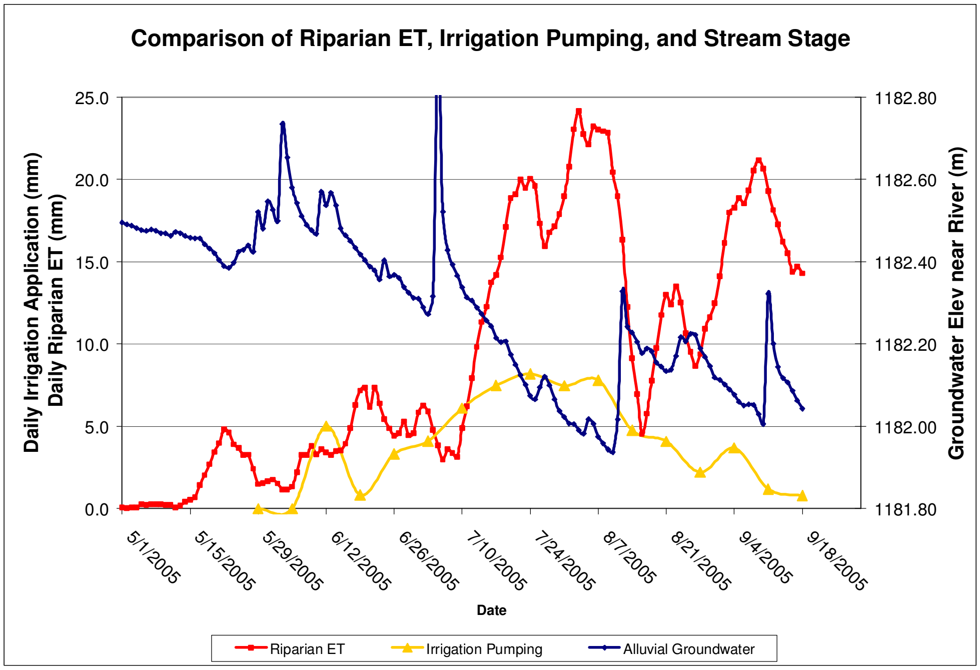


Figure 2.1: Irrigation Pumping and River Stage as a Function of Time (Wachob 2006)

2.1.5 Riparian ET

The research completed by Riley (2009) estimated the riparian ET using the White method, response function, and water balance. Response function calibration using 2006 water table fluctuation data from seven observation wells located within a cottonwood stand resulted in an average seasonal riparian ET value of 86.1 cm/season. The average riparian ET rate resulted in a good estimate of water table fluctuations in the observation wells located in medium density cottonwood areas. However, the average ET rate did not estimate water table fluctuations for observation wells located in either low-density cottonwood areas or high-density cottonwood areas. Observation wells in low-density cottonwood areas were analyzed individually resulting in a low-density ET estimate of 56.1 cm/season as shown in Figure 2.2. Observation wells located in high-density cottonwood areas were also analyzed individually resulting in a high-density ET estimate of 120.1 cm/season. The wells used in the riparian ET analysis were broken into three sections for low density (L), medium density (M), and high density (H) as shown in Figure 2.2.

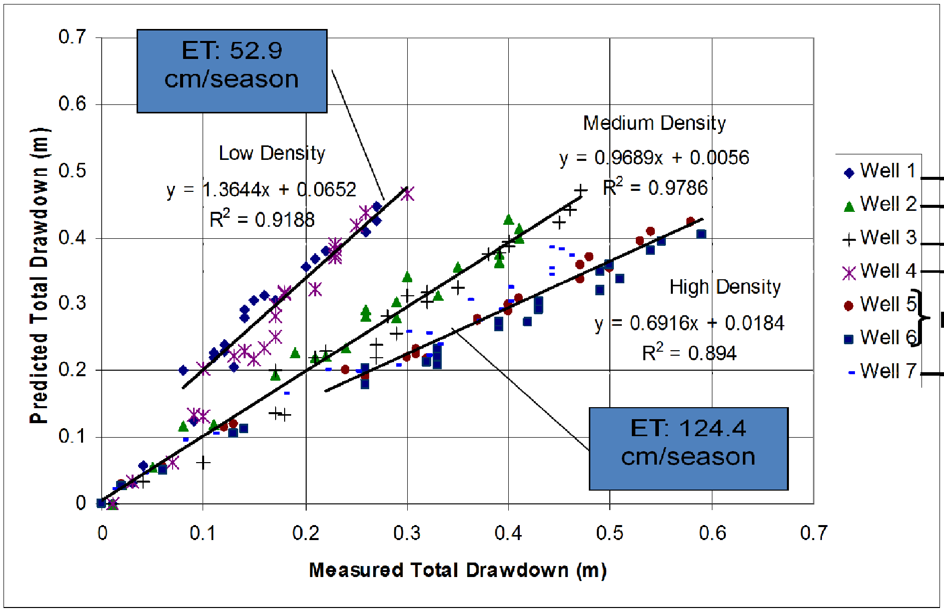


Figure 2.2: Estimate Riparian ET Based on Densities Using the Response Function (Riley 2009)

The groundwater response method for the same seven wells gave an average seasonal riparian ET of 86.1 cm/season (Squires 2007). The White method achieved an average seasonal riparian ET for all the wells of 89.2 cm/season. The White method had many assumptions that can significantly alter the results such as the assumption of a constant or linear recovery rate and that ET was negligible between 12:00 am and 4:00 am. The well data showed a non-linear recovery rate and indicated small amounts of riparian ET throughout the night. These assumptions could change the average seasonal riparian ET from 52.9 cm/season to 102.2 cm/season (Riley 2009). Although the White method had several assumption that could result in varying results, the final ET estimate of 89.2 cm/season was very consistent with the other methods and compares well with other regional seasonal riparian ET estimates. Szilagyi (2005) estimated the riparian ET on the Republican River in Nebraska to be 88.9 cm/season and the Blaney and Criddle method (1949) estimated the riparian ET on the Arkansas River to range from 71.1 to 88.9 cm/season (Riley 2009).

Research continued in 2004 to 2005 and included the installation of 21 observation wells in high and low density areas of cottonwood trees (Wachob 2006). Eight of these wells were equipped with InSitu pressure transducers to monitor the hourly fluctuations of the groundwater table. The White method used to analyze the water table fluctuations, resulted in an ET estimate of 134.9 cm for the growing season for the area of high-density cottonwood trees. The estimated ET for the low-density cottonwood was 69.2 cm for the growing season. The high-density rate applied to the delineated area of cottonwood trees for the entire Arikaree River basin, which resulted in an estimated ET volume of 12.3 million cubic meters for the growing season.

2.1.6 Groundwater

The Arikaree River basin is located on a flat plain with a water table that slopes eastward to northeastward (Weist 1964). The unconfined aquifer feeds the river that is classified as a gaining river (Squires 2007). Shown in Figure 2.3 is the geology of the basin. The oldest formation is the Pierre Shale formation made up of bentonite and limestone. Pierre Shale underlies the basin and is nearly an impervious layer. It outcrops on both sides of the downstream portion of the Arikaree River (Weist 1964). The Ogallala Formation overlies the Pierre Shale and is made of layers of sand, gravel, clay, limestone, and sandstone. The Ogallala Formation has the best water yielding properties of the High Plains aquifer therefore it is loosely referred to as the Ogallala Aquifer (Weist 1964). Peorian Loess is a clay silt layer that overlies the Ogallala Formation. It is not a high-water yielding layer, but it is a good layer for growing crops (Weist 1964). The northern portion of the regional aquifer covered in dune sand that, for the most part, is located above the water table. Due to the hydraulic properties of the sand, it is an important recharge area for the aquifer (Weist 1964).

The alluvium derived from Ogallala Formation and the dune sand deposits result in well-sorted sand and gravel alluvial soils. The alluvium is located in the river flood plain and is typically less than 6.1 m thick (Weist 1964). Hydraulic conductivity in the alluvium is about three times larger than in the Ogallala Formation (Borman et al. 1983). On the eastern project boundary, the estimated hydraulic conductivity was 114.3 m/day and 68.6 m/day on the western project boundary (Weist 1964). Therefore, the groundwater gradient is larger in the alluvium than in the regional High Plains aquifer. Higher recharge in the High Plains aquifer maintains a higher water-table elevation than in the alluvium (Squires 2007).

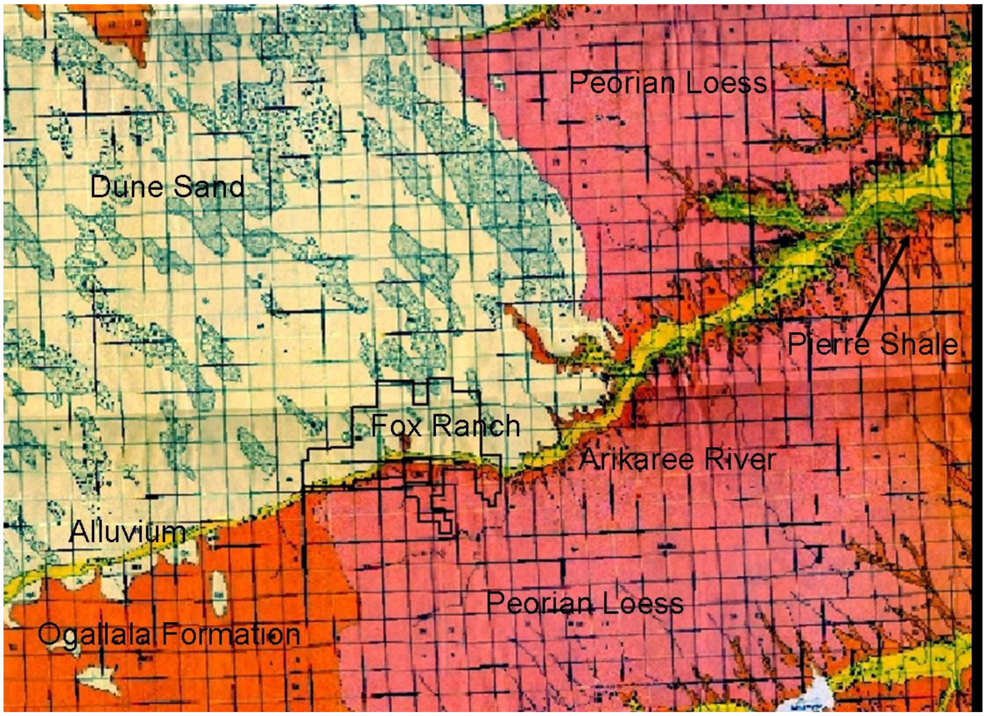


Figure 2.3: Arikaree River Basin Geology (Weist 1964)

In eastern Colorado, the specific yield of the High Plains aquifer averages approximately 0.15 (Weist 1964; Boettcher 1966) and ranges from 0.10 to 0.30 (Gutentag et al. 1984). Precipitation can recharge the High Plains aquifer at a rate of 2.16 cm per year (Boettcher 1966; Opie 2000). The High Plains aquifer transmissibility ranges from 46 to 3725 m^2/day with the alluvium having a transmissibility approximately of 186 m^2/day. The tests indicated that the transmissibility changes when the High Plains aquifer and alluvium are in contact with a value of 1,180 m^2/day (Weist 1964). As shown on the Arikaree River basin geology map, the High Plains aquifer and Arikaree River alluvium form a single unit.

Research conducted by Riley (2009) and Squires (2007) found that the response function calibration using pool depth measurements in the middle segment (influenced by pumping), resulted in an apparent specific yield (Sya) value of 0.12. During two evening storm events, the researcher analyzed the water table fluctuation data to substantiate the Sya of 0.12 found by calibration. Average Sya using this data was determined to be 0.124, which matches the calibration results. The data made use of the response functions to predict pool depths four times throughout the year at twenty refuge pools throughout the 2000 growing season, resulting in modeled pool depths that match measured pool depth.

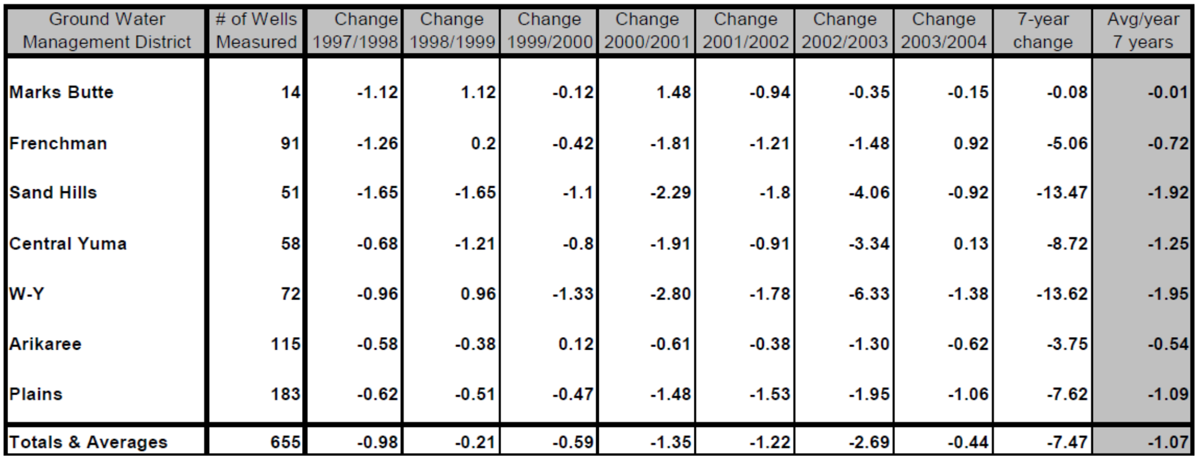
The objective of the Squires (2007) study was to link groundwater dynamics to fish habitat in the Arikaree River. To accomplish this objective, the researcher developed and calibrated a numerical groundwater model, hydrologic response functions, and water balances with the combined model in order to predict river drying. A numerical groundwater model of the alluvial aquifer-stream system developed in order to link groundwater to pool depths in the Arikaree River. Generated from the model were the alluvial response functions, one for each alluvial stress (riparian ET and ten alluvial wells). Utilizing the response functions, the drawdown calculated the past and future at specific pool and monitoring well locations.

The researcher developed the water balances for two conditions: before and after the installation of high-capacity wells in order to determine the relationship between the regional High Plains aquifer and the alluvial aquifer. Squires estimated the interaction between yearly regional water table declines and groundwater flux from the regional aquifer to the alluvium (Squires 2007).

Data collected by Colorado Division of Water Resources (2002) found that the average water table decline of 2.08 m from 1988 to 2002 was is a decline of approximately 0.15 m per year. The wells presented in this report have a water table decline ranging from 0.91 to 4.57 m for the same period of time that shows how groundwater conditions changes laterally in the High Plains aquifer (Griffin 2004). Squires (2007) found that coupling the water balances with Darcy's Law showed that pumping in the regional HPA causes a decline in the water table elevation, linearly approximated at about 0.25 m/yr. The change in groundwater flux from the regional aquifer to the alluvium is non-linear. The calculated changes in water table elevations in the alluvium are also non-linear. The decline starts out small and increases with time because the alluvial aquifer is sensitive to changes in the groundwater flux. When less water feeds the alluvium, there must be more water removed from storage causing the water table elevation to decline (Squires 2007). The analysis by Squires (2007) indicates that the impacts of pumping in the regional High Plains aquifer are likely to be more important on river stage and aquatic habitat over long periods of time rather than intraseasonal fluctuations caused by alluvial stresses. This is because the alluvium is very sensitive to changes in groundwater flux from the regional aquifer. The calculations show that the river is at a critical point for preservation. The river may not have another one hundred or even fifty years in which to take action.

Large capacity wells drilled during the 1950s, ‘60s, and ‘70s almost exclusively for agricultural irrigation have decreased the amount of storage in the Ogallala Aquifer in Colorado. With levels falling on average 0.30 m/year, irrigators have suffered rising pumping costs and diminished well productivity (Davis and Richrath 2005). Table 2.5 shows the High Plains aquifer decline from 1997 to 2004 for the specific groundwater management districts. Well re-drilling activity to deepen wells increased to sustain groundwater production for irrigation, livestock, and domestic users, with re-drilling an average of nearly 30 meters below the previous well level (Davis and Richrath 2005).

Table 2.5: Northern High Plains Aquifer Water Level Changes 1997 to 2004 (Davis and Richrath 2005)



Ground Water Management District	# of Wells Measured	Change 1997/1998	Change 1998/1999	Change 1999/2000	Change 2000/2001	Change 2001/2002	Change 2002/2003	Change 2003/2004	7-year change	Avg/year 7 years
Marks Butte	**14**	**-1.12**	**1.12**	**-0.12**	**1.48**	**-0.94**	**-0.35**	**-0.15**	**-0.08**	**-0.01**
Frenchman	**91**	**-1.26**	**0.2**	**-0.42**	**-1.81**	**-1.21**	**-1.48**	**0.92**	**-5.06**	**-0.72**
Sand Hills	**51**	**-1.65**	**-1.65**	**-1.1**	**-2.29**	**-1.8**	**-4.06**	**-0.92**	**-13.47**	**-1.92**
Central Yuma	**58**	**-0.68**	**-1.21**	**-0.8**	**-1.91**	**-0.91**	**-3.34**	**0.13**	**-8.72**	**-1.25**
W-Y	**72**	**-0.96**	**0.96**	**-1.33**	**-2.80**	**-1.78**	**-6.33**	**-1.38**	**-13.62**	**-1.95**
Arikaree	**115**	**-0.58**	**-0.38**	**0.12**	**-0.61**	**-0.38**	**-1.30**	**-0.62**	**-3.75**	**-0.54**
Plains	**183**	**-0.62**	**-0.51**	**-0.47**	**-1.48**	**-1.53**	**-1.95**	**-1.06**	**-7.62**	**-1.09**
Totals & Averages	**655**	**-0.98**	**-0.21**	**-0.59**	**-1.35**	**-1.22**	**-2.69**	**-0.44**	**-7.47**	**-1.07**

2.1.7 Crop Data

The 2007 Census of Agriculture (2009) showed irrigation used on 62.8% of all the agricultural land in Yuma County. The dominant irrigated crop is corn that makes up 74.3% of all irrigation with forage following with 7.8%. The total crops grown in Yuma County are corn at 54.4%, wheat at 32.4%, and forage crops at 7.3%. Yuma County agricultural economy was 27% of all production and livestock constituted 73% of the Yuma County economy of $711,391,000 (United States Department of Agriculture 2009). Figure 2.4 and Figure 2.5 show the breakdown on irrigated and total crops grown in Yuma County. In the Republican River Basin, irrigated agriculture is 16.6% of the total economic impact and ranching contributing 22.8% to the basin economy (Pritchett and Thorvaldson 2008).

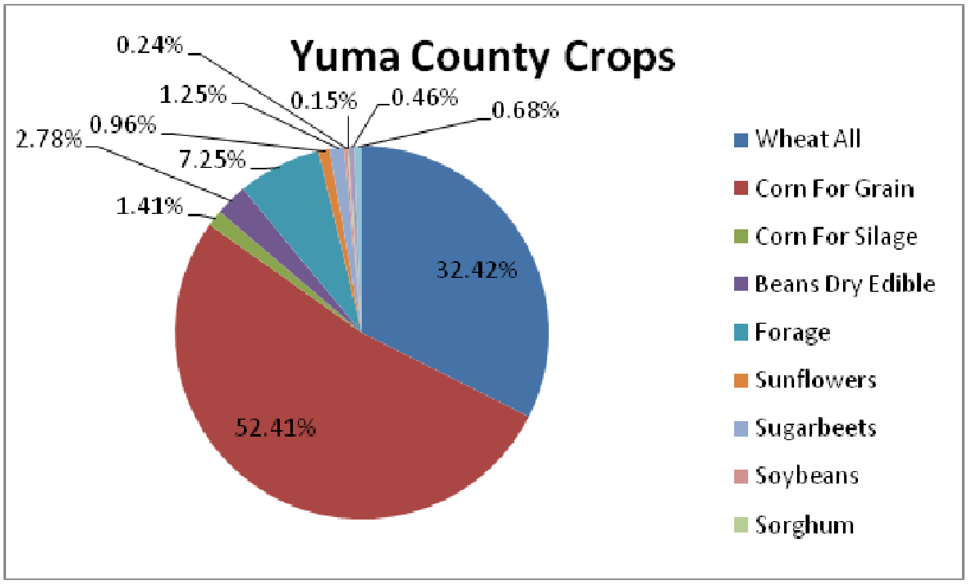


Figure 2.4: Percentage of Crops Grown in Yuma County (2007 Census of Agriculture 2009)

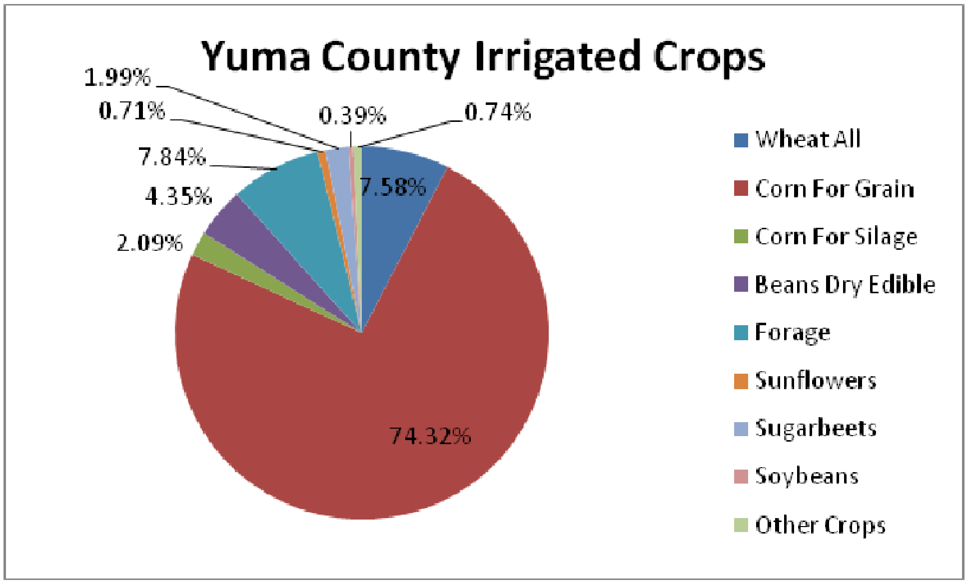


Figure 2.5: Percentage of Irrigated Crops in Yuma County (2007 Census of Agriculture 2009)

2.2 FIELD PRACTICES FOR WATER CONSERVATION

The declining water supplies have forced water users to look at different methods of limiting water usage. Strategies of water conservation in locations where precipitation is less than the crop requirements such as Colorado include land management to increase runoff onto cropped areas and management of crop residue to reduce evaporation. The field practices that meet these objectives in Colorado are no tillage, minimum tillage, strip tillage, mulch tillage, land leveling, management of crop residue, and building of conservation bench terraces. These methods usually increase the amount of water stored in the soil profile by trapping or holding rain where it falls, or where there is some small movement as surface runoff (FAO 1976). Each of the field methods has different merits depending on field types, cropping systems, and the farm operation. This research looked at all options to reduce water usage and allowed local farmers to determine the feasibility of each alternative from the water conservation surveys.

The traditional farming and soil conservation practices have been tested and developed over long periods in order to include all the likely variations of climate. These traditional practices should give good long-term results, bearing in mind that the farmer's interpretation of “good”, based on reliability rather than the maximum yield (FAO 1976). The semi-arid areas are changing rapidly, and the traditional patterns may be no longer relevant. Klocke (2004) found that soil surface evaporation could have a total consumptive use of 30% and demonstrate reduction by half when using crop residue beneath an irrigated crop canopy. Research has shown that 1.27 cm of water is lost from a single tillage event and factors affecting the quantity of water lost depend on depth of tillage, amount of water in the soil at the time of tillage, and weather conditions after tillage (Stone and Schlegel 2006).

2.2.1 No Tillage

About 20% of the corn acres in the United States are currently produced using no-tillage practices. It is apparent from the summary that at least half of the corn-producing regions of the U.S. would see a yield benefit, or at least no reduction, by no-tillage production practices (DeFelice et al. 2008). Global cropland area using no-till has increased from less than 150 million acres in 2000 to over 220 million acres in 2004. From 1994 to 2004, no-tillage adoption ranged from 2.5% to 3.8% for planted cropland in Minnesota (Archer and Reicosky 2009). In the U.S., roughly 41% of all planted cropland farmed used conservation tillage systems in 2004, compared with 26 percent in 1990. Most of that growth came from expanded adoption of no-till, that more than tripled in that time; to the point where it was practiced on 22% of U.S. farmland in 2004 (Huggins and Reganold 2008). This is undoubtedly due to the many benefits that conservation tillage offers to crop producers, including reduced labor requirements, reduced fuel requirements, and conservation of soil and water (Meese 2008).

The no-tillage system does not use tillage to prepare a seedbed; instead, placing the plants in the previous year's residue (Sullivan 2003). The advantages of the no-tillage system include reduced soil erosion, less compaction of field from fewer trips, reduced labor, improved soil quality due to crop residue, increased moisture (Sullivan, 2003), reduced precipitation runoff, and increased infiltration (Nielsen 2005). The negative aspects consist of the need for careful management, expensive machinery, and lower soil temperatures in spring that can cause slower germination or delayed planting, and some reports of increases in insect and rodent damage (Sullivan 2003).

No-till management can save 10.2 to 12.7 cm with the combined growing and non-growing season (Klocke et al. 2008). Klocke based this savings estimate on 36.8 cm the water requirement of full season corn in Garden City, Kansas and center pivot application efficiency of 90%. The field study near Garden City from 2004 to 2006 showed that full irrigation with no-tillage management only required 27.9 to 30.5 cm of irrigation (Klocke et al. 2008). As shown in eastern Colorado from 2000 to 2004, the crop residue can also have a significant effect during the non-growing season (October to April). It was shown that corn residue increases stored soil water by 5.08 cm when compared to conventional stubble mulch (Neilson, 2006) and wheat stubble will increase soil water storage by 5.08 to 6.35 cm when compared to bare soil (Klein, 2008). Also, the discovery that wheat straw and no-till corn stover will save 6.35 to 7.62 cm of water from early June to the end of the growing season (Klocke et al. 2006). Wheat stubble will also increase the precipitation storage efficiency from 15% to 35% when compared to bare soil (Nielsen 2005). In Akron, Colorado, it was determined that no-till with wheat residue accumulated 11.68 cm of recharge over the fall, winter, and spring. The conventionally tilled wheat residue only had 6.35 cm of recharge for a total savings of 5.33 cm during the non-growing season (Nielsen 2005). Klocke et al. (2006) also says the stubble can save 5.08 cm of water in the non-growing season.

DeFelice et al. (2008) did an extensive literature review of published research of 61 corn trials that compared corn yields by tillage system. They found that no-till tended to have greater yields than conventional tillage in the south and west regions. The two tillage systems had similar yields in the central U.S., and no-till typically produced somewhat lower yields than conventional tillage in the northern U.S. and Canada as shown in Table 2.6. No-till had greater corn yields than conventional tillage on moderately to well-drained soils, but slightly lower yields than conventional tillage on poorly drained soils. Corn yields tended to benefit more from no-till in crop rotation as compared to continuous cropping (DeFelice et al. 2008).

Table 2.6: Corn Yield Advantage of No-Till Over Conventional Tillage (DeFelice et al. 2008)

	% Yield Advantage of No-till (Number of comparisons)
All Experiments	-0.5 (104)
Geography	
Southern/Western	12.2 (26)
Transition	-1.8 (16)
Northern	-5.5 (62)
Soil drainage	
Moderate/Well drained soils	2.0 (64)
Poorly drained soils	-4.5 (40)
Crop rotation	
Corn-soybean rotation	1.9 (38)
Continuous soybeans	-1.5 (60)

The data plot in Figure 2.6 used by DeFelice et al. (2008) to identify three areas that appeared to have a different impact of no-tillage compared to conventional tillage on corn yield and these areas were overlaid on the map. These maps show that no-tillage tends to produce greater corn yields than conventional tillage in the southeastern, southern, and western United States (Figure 2.6). The data plot suggests that no-tillage corn performs better in the southern and western United States than in the north. However, this summary indicates that no-tillage is equivalent in performance compared to conventional tillage into the central United States with only the most northerly areas of the Corn Belt showing a negative yield response to no-till. The yield advantage to no-till in the southeastern, southern, and western United States is quite substantial at about 12%.

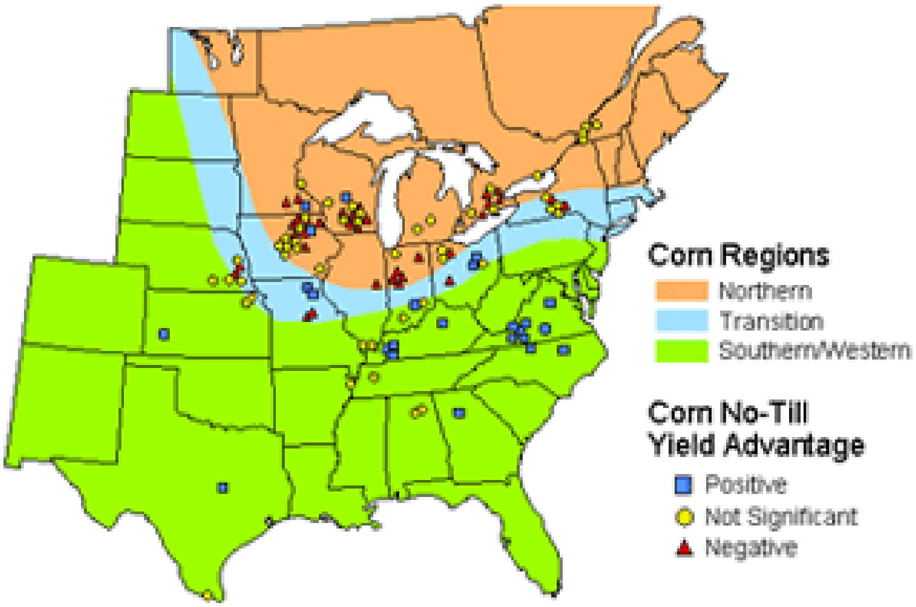


Figure 2.6: Corn Yield Advantage in No-Till vs. Conventional Tillage by Experiment Location and Region (DeFelice et al. 2008)

Norwood and Currie (1996) completed research in Garden City, KS and found that no-tillage increased corn yields by 28% and net return by 69% when compared to conventional tillage. However, the yield disadvantage to no-till in the north-central U.S. and Canada is less at about 6% (DeFelice et al. 2008). Soil drainage also had an effect on corn yield in no-tillage relative to conventional tillage (Table 2.7). As with soybeans, no-tillage had slightly greater corn yields than conventional tillage on moderate- to well-drained soils, but lower corn yields than conventional tillage on poorly drained soils (DeFelice et al. 2008).

Table 2.7: Interactions of Soil Drainage and Crop Rotation by Geography on Corn Yield (DeFelice et al. 2008)

	Southern/ Western	**Transition**	**Northern**
	% Yield Advantage of No-till (No. of comparisons)		
Soil drainage			
Moderate/Well	12.9 (23)	-0.7 (7)	-4.8 (34)
Poor	7.0 (3)	-2.6 (9)	-8.1 (28)
Crop Rotation			
Rotation	13.1 (11)	1.9 (6)	-4.1 (21)
Continuous	12.3 (14)	-4.0 (10)	-6.2 (36)

DeFelice et al. (2008) observed from the literature that no-tillage yields improve after several years of continuous no-tillage. They hypothesized that this was the result of improved soil tilth over time due to increases in organic matter, soil enzyme activity, and microbial biomass, as well as changes in soil porosity and aggregation in no-till plots (DeFelice et al. 2008). There may also be improved drainage in no-till plots over time as old tillage pans and the lack of soil structure eventually correct themselves.

University and private research indicates that there is little effect of tillage on the yield potential of high-performing corn genetic varieties. There may be delayed seedling emergence and development in no-till compared to conventional tillage because spring soil temperatures tend to be lower and soil moisture levels tend to be higher under residue. A delay in seedling emergence often leads to postponement of vegetative growth, silking, and grain dry-down. These delays can result in significant yield loss in the shorter season growing areas and in areas where the relative maturity is long for that region (DeFelice et al. 2008). Soil moisture conservation and retention is a benefit for no-tillage under dry conditions and on moderate- to well-drained soils. However, wet springs and poorly drained soils tend to reduce yields in no-tillage compared to conventional tillage (DeFelice et al. 2008). The conventional tillage decreased soil porosity by 33 to 45% after two years when converting from no-tillage (Peterson 2006).

No-till may not be well suited for some poorly drained soils though no-till has many advantages over more intensive tillage methods. No-till minimizes fuel and labor costs, while maximizing soil and moisture conservation. Some possible reasons for the lack of adoption of strip and no tillage practices are the increased difficulty of handling higher levels of residue (Lamm et al. 2008). Table 2.8 summarizes the advantages and disadvantages of several tillage systems (Meese 2008).

Table 2.8: Tillage System Comparison (Meese 2008)

Tillage System	Field Operations	Advantages	Disadvantages
Moldboard Plow	Plow Disk or field cultivate (1 or 2 trips) Plant Cultivate	Suited to most soils and mgt. Suited to poorly drained soils Fine seedbed	Soil erosion Moisture loss Fuel cost Labor cost
Chisel Plow	Chisel plow Disk or field cultivate (1 or 2 trips) Plant Cultivate	Less erosion than clean till Suited to poorly drained soils	Soil erosion Moisture loss Fuel Cost Labor cost
Disk	Primary Disk Disk or field cultivate (1 or 2 trips) Plant Cultivate	Less erosion than clean till Suited to medium textured, well-drained soils	Soil erosion Moisture loss Fuel Cost Labor cost Soil compaction
No-Till	Spray Plant Spray as necessary	Maximum erosion control Maximum moisture conservation Minimum fuel and labor costs	Not well suited to poorly-drained soils Dependence on herbicides

2.2.2 Minimum Tillage

Field practices, sometimes called conservation tillage, refer to a number of strategies and techniques for establishing crops in previous crop residues left on the soil surface. Conservation tillage can include reduced tillage, minimum tillage, no-till, direct drill, mulch tillage, stubble-mulch farming, strip tillage, and plough-plant (Mannering and Fenster 1983). Typically, dry land farming used conservation tillage to utilization of seasonal precipitation and storage of water during the non-growing season (Barta et al. 2004). These practices are also becoming more common for irrigated agricultural in order to conserve water (Barta et al. 2004). The compressive literature review determined that minimum tillage and no-tillage field practices are very similar practices. In this research, the no-tillage and minimum tillage field practices use that same calculation values.

Conservation tillage, referred to as reduced tillage or minimum tillage, defined as leaving at least 30% residue cover on the soil surface prior to planting (Barta et al. 2004). The minimum tillage principles are equally effective in any conditions to maximize cover by returning crop residues and not inverting the top soil. Conservation tillage also has the advantage of reducing the need for terraces or other permanent structures. However, the disadvantages that hinder the application of conservation tillage in semi-arid conditions include, crop residues that may be of value as feed for livestock and planting through surface mulches that requires specialized equipment. Conservation tillage can improve yield, reliability, and decrease the inputs of labor or fertilizer that lead to improved land practices.

2.2.3 Strip Tillage

Strip tillage is the creation of ridges by cultivation during planting. Originally developed in the Southeastern United States, strip tillage manages soil compaction in the Coastal Plains soils by combining deep tillage with crop residue cover (Archer and

Reicosky 2009). Often strip tillage is proposed and used in cooler and wetter locations to increase the early-season soil temperatures and increase corn yields (Archer and Reicosky 2009). After pushing the residue out of the way and slicing off the surface of the ridge, place the seed on the top of the ridge (Sullivan 2003). Strip tillage usually reduces the use of herbicides since it relies on cultivation to control weeds and reform the ridges (Sullivan 2003). Lamm et al. (2008) says that strip tillage could be a good compromise between conventional tillage and no-tillage systems because it has the benefits of water conservation and soil quality management. Strip tillage also has the added advantage of managing increased crop residue and increased soil temperature similar to conventional tillage. Strip tillage still reduced soil evaporation and aerated soils for optimum root growth and function (Lamm et al. 2008). Strip tillage is best suited for poorly drained soils (Barta et al. 2004). The advantages of strip tillage include: reduced wind and water erosion, water savings, lower fuel costs, minimization of soil compaction, maintains or improved yields (Barta et al. 2004), deeper root development, increased water infiltration, increased root mass (Tichota 2006), and improved soil structure with natural bio-organisms (Peterson 2006). Peterson and Tichota (2006) found that strip tillage corn root depth was 172.7 cm and only 142.2 cm for conventional tillage at 105 days after emergence. Conversely, the disadvantages of strip tillage are its poor match for some crop rotations and the requirement of equal wheel spacing for all equipment (Barta et al. 2004).

Research by the Kansas State University Northwest Research Extension Center found that strip tillage and no tillage increased corn yields when compared to conventional tillage. Strip tillage had an increased corn yield of 8.1% or 1132 kg/ha and no-tillage increased yields by 6.4% or 880 kg/ha (Lamm et al. 2008) (The results reported by Lamm et al. (2008) were reported in bu/acre that were converted to kg/ha assuming a bushel weights 25.4 kg of corn). Strip tillage tended to have the highest grain yields of all tillage systems (no-tillage, strip tillage, and conventional till). The strip tillage had the most impact when using lower irrigation capacities in four years of study (Lamm et al. 2008). This research also found that conventional tillage used less water 1.27 cm than the strip tillage and no-tillage systems. The additional water use of strip tillage and no-tillage systems attributed to higher grain yields of approximately 1006 kg/ha.

2.2.4 Other Field Practices

- Mulch tillage consists of leaving crop residues on the field for the following non-growing season and the growing season of the next crop. Mulch tillage of wheat stubble under a corn crop canopy reduced evaporation to 0.076 cm per day from bare soil evaporation of 0.18 cm per day (Todd et al. 1991). Klocke (2008) found that corn stover and wheat straw mulch tillage reduces evaporation to 0.076 and 0.10 cm per day respectively, from 0.15 cm per day for bare soil.
- Land leveling improves the distribution uniformity of irrigation water and used typically with flood irrigation practices.
- Managing crop residue catches moisture, reduces evaporation, and helps with weed control (Colorado Agriculture Water Alliance 2008)
- Building conservation bench terraces can eliminate irrigation runoff, soil erosion, and help to reduce large contours.

2.3 IRRIGATION SYSTEM WATER CONSERVATION

Irrigated agriculture uses approximately 80% of the available water supplies in the Western United States (Oad et al. 2009; Oad and Kinzli 2006; Oad and Kullman 2006; Barta et al. 2004). Throughout the last decade, the pressure for irrigated agriculture around the world to increase water use efficiency has become substantial (Gensler et al. 2009). These demands to increase water use efficiency have developed from increases in population and interstate compact requirements, as well as the water needs for aquatic ecosystems and endangered species. In order to improve water use efficiencies in the Arikaree, a study conducted to examine improvements to the irrigation system that could concurrently reduce overall water demand, while still providing farmers with sufficient water to meet crop water requirements. The Arikaree irrigation system relies heavily on pumping for irrigation and the study examined several aspects of possible improvements to the irrigation system. Several options for improvements to irrigation water use exist and include developing multi-functional irrigation systems, upgrading sprinkler systems, retrofitting pumps, replacing deteriorated underground pipelines, switching to drip irrigation, and utilizing remote and automated controls to schedule irrigation.

2.3.1 Multi-Functional Irrigation Systems

Multi-functional systems such as sprinklers, surface drip and subsurface drip system, allow farmers to practice precision irrigation and simultaneously apply herbicides, pesticides, and fertilizer along with irrigation water. Having modernized pressurized irrigation systems provides water users with the flexibility to vary frequency, rate, and duration of water delivery (Garcia-Vila et al. 2008). Multi-functional irrigation systems allow for water management that maximizes sustainable yield and profitability, while minimizing water use due to improved application efficiencies through precision irrigation. Precision irrigation can save between 15% and 50% of water used in conventional irrigation and on average saves from 8 to 20% depending on previous irrigation management strategies (Sadler et al. 2005). It is possible to use all sprinkler, surface drip, and subsurface drip as multi-functional systems for applying chemicals and fertilizers during precise irrigation events.

2.3.2 Retrofit Well with Smaller or More Efficient Pump

Retrofitting or replacing pumps with units that are more efficient potentially reduces water use and energy consumption simultaneously. Rising energy costs have increased operating expenses for pumps to the point where irrigated farming might be unprofitable. Irrigation pumping is responsible for 23% of the total on-farm energy use (Gilley et al. 1983). In Nebraska, 40% of all energy consumed for agricultural production is for irrigation pumping and in Texas irrigation pumping is 65% of total energy (Gilley et al. 1983). Field tests in Colorado and Wyoming have shown that wire to water efficiencies for electrically driven pumps average less than 50% (Barta et al. 2004). Many pumps are inefficient because the impellers are out of adjustment, damaged, or lack the required maintenance. This result in higher energy requirement and delivery of a flow rate that is below the design capacity of the irrigation system that then leads to decreased efficiency. Irrigation systems operated within the design guidelines maximize application efficiency. Retrofitting aging pumps has the potential to save water and it will reduce operating expenses for farmers.

The pump is the main source of pressure for center pivot systems. If the pump operates inefficiently or functions incorrectly, the pump will not create uniform irrigation pressure. Non-uniform pressure can either cause some sections of the field to be under or over watered. Reduced pump efficiency can result from impellers being out of alignment, pump bowls being designed for a higher pumping rate, damaged impellers, differences in operating conditions, or failure to perform required maintenance (Chavez et al. 2010). The improper impeller adjustment can reduce pumping rates and efficiency when the energy used, recirculating water around the impellors instead of pumping it into the irrigation system (Chavez et al. 2010). When the design of the pump bowls demand a higher pumping rate than a well can supply, the results are poor pumping plant efficiency. These poorly designed bowls can develop from declining water levels that force the pump to operate at lower flow rates and at a higher lift than intended. In addition, poor pump performance results from damaged impellers from cavitations, sand pumping, and improper impeller adjustment. A final efficiency problem develops from the failure to perform maintenance resulting in pressure variance in the irrigation system (Chavez et al. 2010). End guns on center pivots can also create uniformity problems and typically have application efficiency of 60% to 75% that can be 5% to 10% lower than typical center pivots (Dukes 2010). By lowering pressure requirements as much as a 20% to 40%, energy savings can be achieved (Gilley et al. 1983). Field-testing in Colorado, Wyoming, Nebraska, Texas, and Louisiana shows the electrically driver pumps average efficiencies are 45 to 55 percent with realistic achievable efficiencies of 72 to 77 percent (Chavez et al. 2010).

2.3.3 Low Pressure Sprinkler Packages (MESA, LPIC, LESA, LEPA)

Center pivot sprinkler irrigation systems are the most common form of irrigation used in the High Plains of Colorado (Barta et al. 2004). Although sprinklers are most common, there is still some surface irrigation used. Changing from surface irrigation application to sprinkler irrigation is one of the most common conversions used to save water (Yonts 2002). Sprinkler systems always utilize water more efficiently than surface irrigation methods (Bresler 1981). Replacing flood and furrow irrigation with efficient sprinkler systems can reduce water use by 25% (White et al. 2006). Nogues and Herrero (2003) found that upgrading the Flumen Irrigation District in Spain from flood to sprinkler irrigation would save 7% of the water supply. In California, the switch from furrow to sprinkler irrigation resulted in an overall water savings of 27% (Wichelns and Cone 1992) with an increase in application efficiency from 0.69 to 0.84 (Wichelns et al. 1997). Other studies have shown that sprinkler irrigation can achieve application efficiencies between 54 and 80% (Chimonides 1995)

Center pivot sprinkler irrigation systems provide the advantages of greater water use efficiency, minimized labor, and overall irrigation cost reductions. Sprinkler systems also provide flexibility when used as multi-functional systems to apply both water and agricultural chemicals and fertilizers. The development of multi-functional systems such as low energy precision application (LEPA) allow farmers to apply water and also practice precision application of herbicides and pesticides and allow for fertigation (New et al. 1990). New et al. (1990) found that LEPA systems were effective at controlling corn borers and spider mites while simultaneously applying irrigation water. LEPA systems are highly efficient and can achieve application efficiencies in the 95% to 98%

range (Schneider 2000; Hill et al. 1990) while other research suggests efficiency ranges from 80% to 95% depending on management (Barta et al. 2004).

The benefit of LEPA systems is that they can be used to practice prescription irrigation. Prescription irrigation applies only the necessary water to a field based upon soil types, and the requirements of soil-plant-water continuum for optimal yield (Hoffman and Martin 1993). An additional benefit of LEPA is that the water application method minimizes evaporation and drift loss if applying water below the crop canopy, optimally 20 to 40 cm above the ground (Fipps and New 1990). LEPA systems also utilize spray heads operating in three modes, bubbler, spray, and chemigation/fertigation mode. The LEPA system can achieve application efficiency, in bubbler mode, of 95% to 98% (Lyle and Bordovsky 1983) with overall water saving of 20% to 30% compared to conventional center pivots (Hoffman and Martin 1993). Control techniques used together with LEPA systems result in realistically achievable application efficiencies between 80% and 90% (Schultz and De Wrachien 2002).

A common water saving upgrade to center pivots is to reduce operating pressure and apply water within or below the crop canopy. Upgrading sprinkler systems to low pressure heads with drop tubes reduces evaporation from the plant surface, especially for corn (Lamm and Manges 2000). Water can be applied as mid-elevation spray application (MESA: 1.5-2.4 m above ground), low pressure in canopy (LPIC: 0.3-1.8 m above ground) application, or low elevation spray application (LESA: 0.3-0.6 m above ground) (Barta et al. 2004). Although lowering nozzles reduces wind drift and evaporation, there is a significant potential for increased runoff and it decreases application uniformity (Howell 2003; Lamm 2000; Yonts et al. 2000; Yonts 2000; Yonts et al. 1999; Lamm

1998). It is important to choose the appropriate techniques to minimize runoff. If properly utilized, MESA, LPIC, or LESA can result in water savings of 10% to 15% compared to traditional center pivot applications (Barta et al. 2004).

The use of low to medium pressure sprinkler packages to upgrade irrigation systems provides several economic and water related benefits. Traditional gun sprinklers require high operating pressures, that distribute large water drops that results in high runoff and sediment yield (DeBoer 1992). Low and medium pressure systems deliver smaller drops and provide for a uniform spray, especially under windy conditions. The use of low to medium pressure sprinkler heads can improve irrigation uniformity, decrease runoff, increase yield, and improve the overall water use efficiency of the sprinkler irrigation system (Silva et al. 2007; Schneider and Howell 1995; Deboer 1992). The overall benefit of low-pressure sprinkler packages is that they can reduce total water use by 30% (Perry et al. 2009) as compared to standard irrigation methods. Using low-pressure sprinkler packages results in high uniformity coefficients achieved even in windy areas (Dechmi et al. 2003). Operating at low pressures also reduces pumping costs (Barta et al. 2004; Hoffman and Martin 1993; Cahoon et al. 1992). Another upgrade to sprinkler systems involves retrofitting systems to minimize wind losses. Zapata et al. (2009) presented sprinkler system design and management policies if utilized, would minimize spray losses while improving the coefficient of uniformity in windy regions.

Modernized sprinkler irrigation systems also account for variability in soil type, infiltration rates, and water holding capacity across a field. The Clemson variable-rate lateral irrigation (VRLI) system allows site-specific application of water to match field variability (Han et al. 2009). In such a system, assigning nozzles into specific groups across a field allows for variable-rate application through the nozzles by utilizing pulse technology and has the potential to improve water and energy use efficiency (Han et al. 2009).

2.3.4 Use Drip Irrigation

Converting current irrigation systems to surface drip (SD) irrigation can reduce overall water usage without yield reductions. During a drought period, hand moved sprinkler systems upgraded to SD systems in Spain resulted in decreased overall water use (Garcia-Vila et al. 2008). In the Middle Rio Grande Basin, the SD irrigation resulted in less water applied to crops, while the total water related to economic benefits increased (Brinegar and Ward 2009). Researchers found SD drip irrigation to achieve high application efficiencies between 80% and 91% (Chimonides 1995; Battikhi and Abu-Hammad 1994).

Sharma et al. (2009) found that shifting from furrow irrigation to SD irrigation reduced water inputs and improved nitrogen use efficiency. Drip systems generally use half as much water as furrow irrigation (Perry et al. 2009). Sammis (1980) and Bogle et al. (1989) found that transitioning furrow systems to SD increased irrigation water use efficiencies (IWUE) by a factor of 2.5. In the Murray Darling Basin of Australia, White et al. (2006) found that trickle and micro drip systems could achieve water savings of 25%. In a far-reaching effort to improve water use efficiency, the Spanish government has sponsored a modernization program incorporating SD systems (Rodriguez-Diaz et al. 2008). Rodriguez-Diaz et al. (2008) also found that irrigation districts with the lowest water use efficiencies were operating older gravity irrigation systems. Khan et al. (2008)

found that drip irrigation showed a water savings potential of 7% for corn, 15% for soybeans, 17% for wheat, 17% for sunflower and 35% for barley.

Drip irrigation can also be adapted to center pivot irrigation systems using precision mobile drip irrigation (PMDI) (Olson and Rogers 2008). With the PMDI system, first, the drip hoses attach to a center pivot; then they lay out over the ground surface. The water use efficiencies with PMDI are similar to LEPA irrigation because water is delivered directly to the ground surface so air evaporation, canopy interception, canopy evaporation, and the area of the wet soil surface are minimized (Olson and Rogers 2008; Howell 2006). The irrigation application efficiencies for PMDI approach 95% (Olson and Rogers 2008). In a comparison of PMDI to conventional center pivot nozzles, Helweg (1989) found that the use of PMDI reduced overall water application by 40% with no yield differential between the two methods.

The water pillow (WP) is a new irrigation method that combines drip irrigation and mulch. It offers significant water savings especially for row crops such as soybeans and corn (Gerçek 2006). WP irrigation uses elastic polyethylene pipes that are perforated and have a diameter that covers the row spacing between crops. The water fills the large elastic pipe and gradually the water trickles out of small holes (1mm diameter) at the bottom of the pipe due to the action of gravity (Gerçek et al. 2009). The efficiencies of WP irrigation are similar to surface drip irrigation with the added benefit that WP irrigation does not need an external water source once the pipe is filled (Gerçek et al. 2009).

Subsurface drip irrigation (SSD) can result in even more water savings. SSD systems can deliver water and chemicals to the root zone of plants more efficiently than most irrigation systems (Thorburn et al. 2002) and the efficiencies achieved are outstanding (Barth 1999). Application efficiencies using SSD can exceed 90% (Burt 1995; Sourell 1985). Water consumption in SSD systems is 50% less than sprinkler irrigation and up to 30% less than surface drip systems (Barth 1999). A study conducted by the USDA spanning 15 years, showed that SSD irrigation increased yield and water use efficiency for all crops studied (Ayars et al. 1999). In Iran, water savings of 15% were realized when switching from furrow to SSD irrigation for corn (Hassanli et al. 2009). Hanson et al. (1997) found that implementing SSD required 43% to 74% less water than furrow irrigation. IWUE using SSD can increase between 3.3 and 4 times when compared to furrow irrigation (Sammis 1980; Bogle et al. 1989). In Virginia, irrigated corn required 30% less water using SSD, while maintaining yield (Camp 1998).

Air injection into SSD irrigation systems offers another method to improve system efficiency. Air injection into the soil provides for aeration that support root respiration and increases earthworm and microbial activity. Air injection does not necessarily result in the use of less irrigation water, but it does allow for more crop per drop because yields are increased. In a study in California, yields increased by 15% while water deliveries remained steady (Goorahoo et al. 2007). Bhattarai et al. (2005) found that yields of vegetables increased by 25% with the same water supply. This technology offers much promise; however, further research needs to develop protocols and implementation strategies.

2.3.5 Other Irrigation Systems Components for Water Conservation

Other irrigation conservation methods developed to reduce agricultural water usage identified in the project were:

- Install low pressure heads on drop tubes
- Replace old or leaking underground pipes
- Air injection in drip system
- Remove end guns
- Remote and automated controls

2.4 MANAGEMENT PRACTICES FOR WATER CONSERVATION

In eastern Colorado, the climate is semi-arid and needs some level of irrigation during drought years to maximize crop yields. Although irrigation may be required at some level, crops may not require full irrigation. Full irrigation is meeting the crops' total water requirements for maximum crop yields (Barta et al. 2004). Full irrigation will usually maintain the full capacity of the soil and minimizes available water storage for rainfall (Barta et al. 2004). In eastern Colorado, the High Plains aquifer that is a part of the larger Ogallala aquifer primarily provides irrigation water. The Colorado Department of Agriculture (2007) estimates that total agricultural land in Yuma County (cropland and pasture) is 177,243 ha with 84,537 of that land being irrigated agriculture (47.7%). About 90% of the irrigation systems use center pivots and pump from the High Plains aquifer (Frasier et al. 1999; Colorado Department of Agriculture 2007).

2.4.1 Plant Crops That Use Less Water or Drought Tolerant Crops

Drought stress is responsible for more lost bushels of corn yield than any other cause, costing farmers in the US more than three billion dollars annually (Butzen and Schussler 2006) and one-third of U.S. corn acres will probably experience yield-reducing drought stress (Pioneer Hi-Bred International Inc 2006). From 1984 to 1992, 67% of major crop losses were due to drought and 85% of corn grown in the U.S. suffers from varying degrees of drought during each growing season (Monsanto Company 2009). Among the corn-growing states of the Midwest, severe drought conditions are most common in the Great Plains states from Texas to North Dakota, but all states have some drought-stressed areas nearly every year (Butzen and Schussler 2006). Because of the impact of drought on corn yields, developing hybrids with drought tolerance and lower water requirements has been a primary goal of corn breeders for decades.

Drought conditions develop in the non-irrigated Midwest usually during August grain fill. A deficiency of water resulting from inadequate water sources can cause a loss of grain yields during all growth stages. The yield reduction depends on the growth stage of the crop at the time of the stress, the severity and duration of water shortage, and the susceptibility of the hybrid to stress (Lorens et al. 1987b). Water stress occurs as available soil moisture progressively depletes from the root zone due to high summer temperatures and insufficient rainfall. In the semi-arid Great Plains, moisture limitations are also most common during grain fill, but diminished by irrigation where available. For dry land corn in this region, however, drought conditions can also occur at other growth stages like pollination and sometimes even vegetative growth (Butzen and Schussler 2006).

Water demands by the plant are high during pollination, especially for silk elongation, pollen germination, and pollen tube growth. Under drought conditions, delayed silk emergence will not coincide with the pollen-shed timing. If this delay is several days, pollen may be limited when the silks emerge; therefore, causing incomplete pollination and reduced kernel number. Drought and high temperatures can also lead to desiccation of silks, causing poor pollen germination, pollen tube growth, and reduced kernel number. Drought during the early reproductive period can also result in kernel abortion (Claassen and Shaw 1970; Tollenaar and Daynard 1978). Kernels are most susceptible during the first two weeks following pollination. Because of the critical relationship between available moisture and successful pollination and early kernel development, yield losses may be as high as 377 kg/ha (six bushels per acre) per day when severe drought occurs during this period (Butzen and Schussler 2006).

Drought stress during the dough and dent stages of grain fill decreases grain yield primarily due to decreased kernel size rather than decreased kernel number. Drought reduces the rate of photosynthesis in the plant, resulting in less assimilate production (Butzen and Schussler 2006). In response to inadequate water, corn plants typically begin to shut down their metabolism, slowing photosynthesis and growth-rate metabolism. Seed manufacturers must engineer corn to maintain photosynthesis and metabolism for a longer period during drought stress (Monsanto Company 2009). Lorens et al. (1987a) demonstrated that corn with deeper root profiles could help the plant withstand drought conditions. Drought may also cause premature black layer formation in the kernels, terminating starch deposition. Researchers estimate that drought stress during the grain fill stages of development can cause yield losses of up to 188 kg/ha (three bushels per acre) per day (Butzen and Schussler 2006).

Butzen and Schussler (2006) and Pioneer Hi-Bred International, Inc (PHBI) wanted to achieve the objective of developing hybrids with superior performance under both drought and well-watered conditions. To gauge their improving hybrids for drought tolerance, Butzen and Schussler (2006) conducted studies comparing historical and modern hybrids for performance under drought conditions. In this study, top hybrids from each decade over the last 80 years were grown in a managed stress environment in that they received only 30.5 cm of irrigation during the growing season (full irrigation would be about 63.5 to 76.2 cm (Butzen and Schussler 2006). As Figure 2.7 indicates, the yield production has improved dramatically over the years, especially in the 1980s and 1990s. This figure shows how seed developers such as PHBI have advanced corn tolerance to drought (Butzen and Schussler 2006).

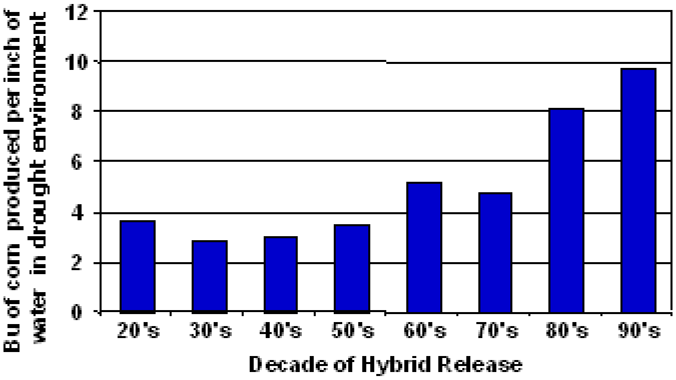


Figure 2.7: Hybrids from Eight Decades (1920s to 1990s) Grown Under Drought Demonstrate Significant Improvement for Drought Tolerance, Especially in the Last 25 Years (Butzen and Schussler 2006)

The levels of drought tolerance achieved in today's best hybrids are significantly higher than the hybrids of just 20 years ago. Many corn growers and researchers have estimated that if today's hybrids had been grown during the drought of 1988, corn yields could have been double what they were that season (Butzen 2007). Butzen based this estimate on hybrid performance measures under drought stress such as the 2005 drought in central and northern Illinois. Although 2005 drought stress levels in that area were similar to those of 1988, yields of over 6,289 kg/ha were common in 2005 (Butzen 2007). Continued improvements in hybrid drought tolerance in the next 20 years may result in even more impressive gains. Corn plants will never be able to tolerate very arid conditions and produce grain, but the ability to withstand significant periods of moisture stress needs improvement. Today's best drought-tolerant hybrids, developed through conventional breeding, often yield within 75% to 80% of their average low-stress yields under drought stress. Monsanto Company (2009) found that during field trials in the Western Great Plains, drought-tolerant corn showed a six to ten percent yield increase. Other research comparing hybrid yields for the last three decades showed that genetic improvements have increased yields 2.6% per year (Tollenaar 1989) due to hybrid water stress tolerance (Tollenarr and Wu 1999). The increasing yields are also demonstrated by the average corn yield in 1970 that was 4,528kg/ha and 9,685 kg/ha in 2008 (increase of 135 kg/ha (Monsanto Company 2009). O'Neill et al. (2004) found that newer corn hybrids that stressed at 50% of crop required ET produced 27% higher yields, but under adequate water, both hybrids produced similar yields. Corn breeders have found a new germplasm that can reduce water usage by 10% (Ledbetter 2008). Xu and Lascano (2007) found new corn hybrids that produce the same silage yield under 75% crop water requirement (CWR) as the 100% CWR (Ledbetter 2008).

PHBI compares performance of new hybrids tested in managed stress environment (MSE) locations to determine hybrids that produced good yields during water stress and full irrigation. Figure 2.8 shows how PHBI evaluates seed hybrids with each point representing a corn hybrid. The points with green circles in the upper right-hand quadrant are exciting new hybrids now moving through PHBI's advancement process (Butzen and Schussler 2006).

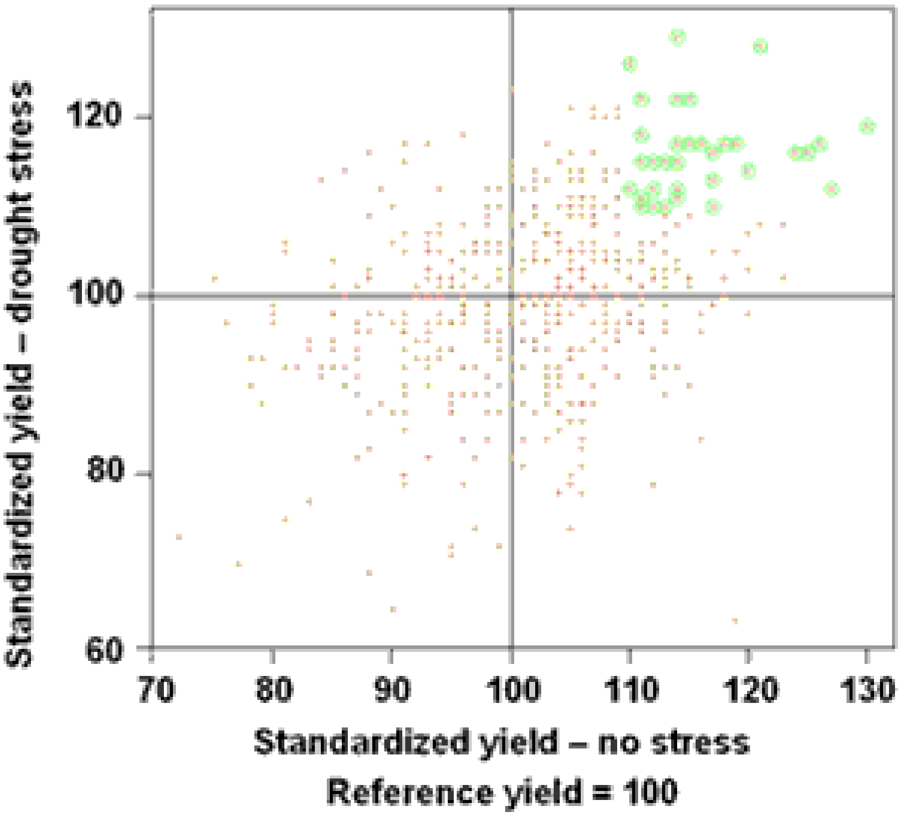


Figure 2.8: Hybrid Yields Under Drought and Non-Stress (Well-Watered) Conditions, The Upper Right Hand Quadrant Represents Hybrids that do Well in Both Environments (Butzen and Schussler 2006)

Seed developers use many different methods to improve corn seed tolerance to drought, including conventional breeding, molecular breeding, map-based cloning, and the use of novel genes from other species (transgenes) (Pioneer Hi-Bred International Inc 2006; Butzen and Schussler 2006). Using molecular breeding to identify corn genes associated with superior drought tolerance and moving those genes into new germplasm improves drought tolerance of all new hybrids. Map-based cloning is another genetic tool used in developing more drought-tolerant hybrids. This technique helps breeders optimize the use of natural variation for drought tolerance. The goal of map-based cloning is to identify the specific gene segments responsible for the phenotype (appearance, performance) of a hybrid. Using molecular breeding technology, PHBI scientists can move the gene into elite lines by traditional plant breeding or clone the gene that is responsible for the desired phenotype and introduce it into hybrids through genetic engineering. A third approach to improving drought tolerance is the use of novel genes from other species (transgenes). Like other familiar transgenes drought genes are inserted into corn germplasm in the laboratory and the plants are subsequently tested in the field (Butzen and Schussler 2006). PHBI has developed new drought tolerant corn seeds that are supposed to be available commercially in 2010 and 2012. The drought I initiative combines native drought genes with needed traits in the most elite adapted hybrids for drought-prone areas. Drought I hybrids will be marketed in dry land and limited-irrigation growing environments of the western Corn Belt where yield expectations typically are lower than 9433 kg/ha (<150 bu/acre) due to lack of adequate rainfall and available water. Yield improvement targets for Drought I corn hybrids are 5 to 10 percent above hybrids currently available in these limited-water environments (Butzen and Schussler 2009). The Drought II initiative focused on transgenic gene evaluation and integration into the most elite and adapted germplasm. Averaged across all hybrids and all yield environments, the transgenic Drought II hybrids expressed an 8% yield increase in three years of trials and the 2008 research results demonstrated a 16% advantage when compared to their conventional hybrids in drought-stress environments (Pioneer Hi-Bred International 2009). The goal is to have Drought II corn hybrid on the market between 2014 and 2016 (Pioneer Hi-Bred International 2009).

First, researchers conduct tests in managed stress environments during the proof-of-concept stage. If the gene proves efficacious, testing then continues more broadly in environments throughout the Midwest. The level of drought tolerance exhibited must be significant and consistent enough to satisfy customers and justify the high cost of regulatory approval. Hybrids with drought tolerance traits must not only perform well under drought, but also under well-watered conditions. It is no surprise that only a handful of genes out of hundreds tested meet these demanding criteria and advance toward commercialization each year (Butzen and Schussler 2006). Protecting plants against insect damage also improves a plant's water utilization, while herbicide-resistance technology allows growers to have better weed control, channeling more water to plants (Pioneer Hi-Bred International Inc 2006).

Hybrid traits that contribute to drought tolerance include a well-structured root system, insect and disease resistance, strong silking characteristics, and yield stability across environments, including those with moisture stress (Butzen 2007). The root system must efficiently access all available moisture in the soil. A broad and shallow root structure may not provide adequate drought protection to the plant even though it may support the plant against lodging. A root system that penetrates deeply into the soil is preferred for reaching soil moisture as drought develops. Root systems must also be healthy to impart drought tolerance. If the root systems demonstrate impairment due to insects, diseases, or physical conditions such as compaction or cultivator pruning, the plant will be more vulnerable to drought (Butzen 2007). Insects such as white grubs, wireworms, grape colaspis larvae and corn nematodes can attack the corn plant from germination through grain development (Butzen 2007). A fast-growing plant and root system is the best genetic defense against these early feeders. Seedling diseases can limit root systems and drought tolerance of hybrids (Butzen 2007). Drought stress in June and July often delays corn reproductive development that can delay silk emergence much more than pollen shed. When the silk emergence has been delayed several days, pollen shed may be mostly complete before silks finally emerge. This can result in poor pollination and dramatically reduced yield. Hybrids with strong silking characteristics under drought, exhibit less yield loss by maintaining synchronization of pollen shed and silking during this critical period (Butzen 2007). Corn hybrids with proven yield stability across environments usually tolerate a variety of stresses, including drought (Butzen 2007).

2.4.2 Plant Crops with Shorter Growing Season

Short season corn hybrids have the ability to both reduce water requirement and allow an earlier harvest. Howell et al. (1998) conducted research in Bushland, TX for two different corn hybrids developed by PHBI to compare the evapotranspiration of the short season (98 day) and full season (115 day) corn hybrids. The short season corn hybrid reaches physiological maturity 12 days earlier than the full season and harvested 11 days sooner. Research discovered that the short season hybrid only used 90% to 95% of the ET usage of the full season corn. The full season corn used 841 mm while the short season corn only used 741 mm, but both hybrids had approximately the same peak daily water requirement (Howell et al. 1998). Although the short season corn did reduce the total water usage, there was also a reduced yield with the shorter season. Howell et al. (1998) concluded that the short season hybrid, allowing for earlier harvest, could facilitate a double cropping of winter wheat and may afford opportunities to market the crop at higher grain prices. Howell estimated that the potential irrigation savings is six to eight times less than the sacrificed crop production from using the short season corn (Howell et al. 1998). Producers also have the possibility of using a longer season corn that could achieve higher yields and still allow the planting of winter wheat. The balancing these two objectives could yield better economic returns and achieve water savings.

Predominately, growers do not plant dry land corn due to the lack of drought tolerance corn in the central Great Plains, including northwestern Kansas, southwestern Nebraska, and northeast Colorado (Norwood 2001). Before 1990, growers believed that corn lacked the drought tolerance to grow in these semi-arid areas. However, new hybrids have more dry matter accumulation (Tollenaar 1989), improved radiation use efficiency (Tollenaar and Aguilera, 1992; Sinclair et al. 1990), and improved nutrient and water use efficiency (Castleberry et al. 1984). Corn needs managed in order to tolerate the semi-arid regions with lower precipitation and higher temperatures that can limit crop yields. The management farming practices for eastern Colorado includes selecting hybrids, planting dates, and planting populations (Norwood 2001). Norwood (2001) conducted research from 1996 to 1999 evaluating five different Pioneer Brand hybrids with full maturity days of 75 days (H1), 92 days (H2), 98 days (H3), 106 days (H4), and 110 days (H5). He also evaluated planting dates of mid April (D1) and early May (D2) and plant populations of 30,000 plants per ha (P1), 45,000 plants per ha (P2), and 60,000 plants per ha (P3). This research concluded hybrids planted in early May (D2) yielded 97% and 85% higher water use efficiency than corn planted in mid April (D1). The first planting date produced lower yields since soil temperatures are typically lower that can reduce root and shoot weights (Kasper et al. 1987), requires more days for the growing point to reach the soil surface (Swan et al. 1987). Staggenborg et al. (1999) found that full season hybrids generally produced more yield than short season hybrids when planted early. However, short season hybrids can produce as much or more than a full season hybrid when planted at later planting dates. The average yields form D2 were 42, 28, 26, and 32% higher than planting date D1 for hybrids H2 through H5, respectively (Norwood 2001). The general trend was that later maturing hybrids used more water, yielded more, and had higher water use efficiency. Although in 1997, the 92-day hybrid yielded as much as later maturing hybrids, researchers concluded that there might be no advantage to later maturing hybrids in dry years (Norwood 2001). Based on this research, producers in eastern Colorado must manage their farms to optimize the corn production based on available soil water profile, choosing early May planting date for higher yields, and corn hybrid maturity days to optimize yield and save water. Each producer's choices will be different based on farm characteristics, field conditions, and water available for crops. A TAES hybrid C3A654 x B110 was 5-days earlier than the widely grown DKC66-80, but produced the same grain yield and higher silage yield with better quality. This shows that short season hybrids and stress-tolerant hybrids are feasible to reduce irrigation without yield penalty. Use of short-season and high yielding hybrids may save one late season irrigation or reduce 10% of total irrigation water (Xu and Lascano 2007).

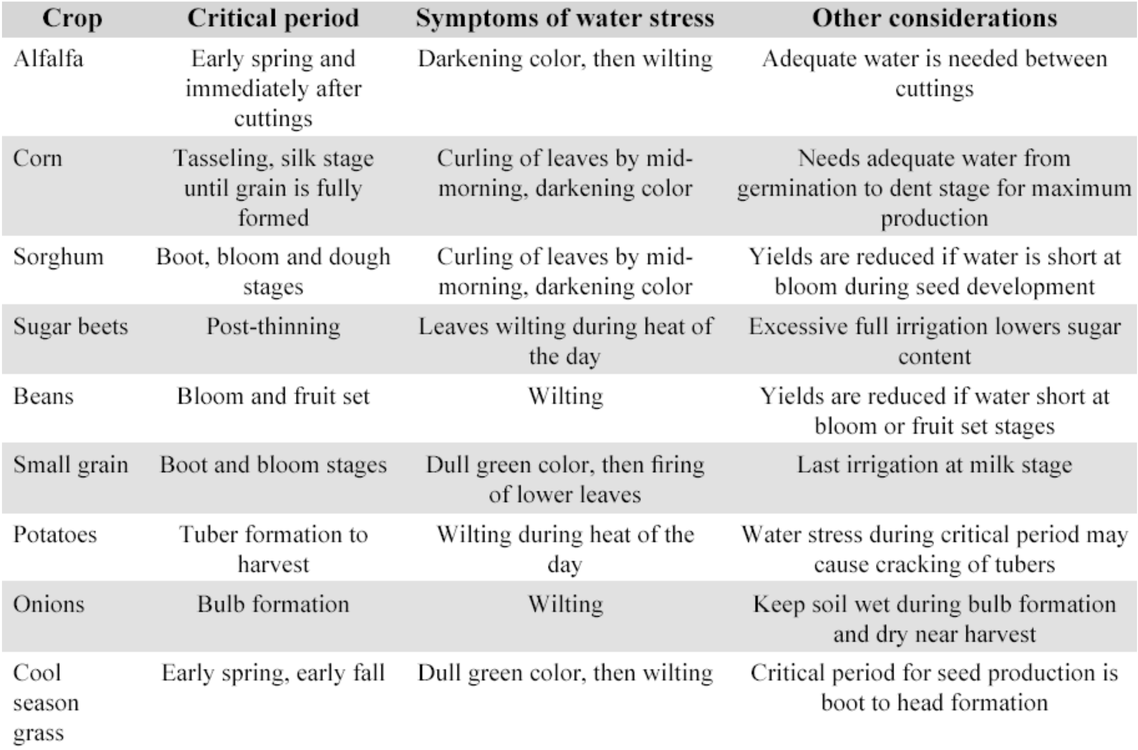
2.4.3 Reduced Irrigation Early in the Season, But Irrigated Fully Later in the Season

One of the methods to reduce water usage is implementing deficit irrigation practices that will help during drought conditions, inadequate water supplies, and mandated water allocations (Schneekloth et al. 2004). Reducing irrigation early in the season, but fully irrigating later in the season is a form of deficit irrigation. Deficit irrigation means full evapotranspiration demands are not met due to restricted water supplies in some way or controlled plant water stress (Barta et al. 2004). Deficit irrigation will stress the crop, but the goal of deficit irrigation is to manage cultivation practices and irrigation timing to limit water stress and limit negative impact of crops (Hergert et al. 2008). Deficit irrigation is also referred to as regulated deficit irrigation, pre-planned deficit evapotranspiration and limited irrigation (English et al. 1990).

To accomplish deficit irrigation, the grower exposes crops to a certain level of stress over the entire growing season and/or certain growth periods to limit yield reduction (Kirda 2002). Farmers must know the level of water stress allowable without considerable reduction in crop yields since the objective of deficit irrigation is to increase the water use efficiency of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for that water would normally be insufficient under traditional irrigation practices (Kirda 2002). The saved water can reduce total water usage in groundwater or surface water sources.

Many of the commonly grown crops in eastern Colorado are potential deficit irrigation crops, but it all depends on when crops are most sensitive to water deficits. Selection of appropriate crops per region is an essential requirement for this type of deficit irrigation systems (Stone and Schlegel 2006). Barta et al. (2004) presents the potential dry land and deficit irrigation crops possibly grown in eastern Colorado as shown in Table 2.9. These crops have the possibility of achieving optimum crop yields under deficit irrigation practices by allowing a certain level of yield loss from a given crop with higher returns gained from the diversion of water for irrigation of other crops. Deficit irrigation, where properly practiced, may increase crop quality. For example, the protein content and baking quality of wheat, the length and strength of cotton fibers, and the sucrose concentration of sugar beet and grape all increase under deficit irrigation (Kirda 2002). Klocke et al. (2008) found that dry land corn extracted water from as much as 2.13 m in the soil profile, whereas fully irrigated corn only utilized the top 0.91 m of soil profile. Farre and Faci (2008) found that corn under mild irrigation deficit extracted more water than plants under severe deficit irrigation and concluded that less stressed plants developed deeper and more dense rooting systems.

Table 2.9: Summary of Potential Crops for Deficit or Dryland Agricultural Practices in Northeast Colorado (Barta et al. 2004)

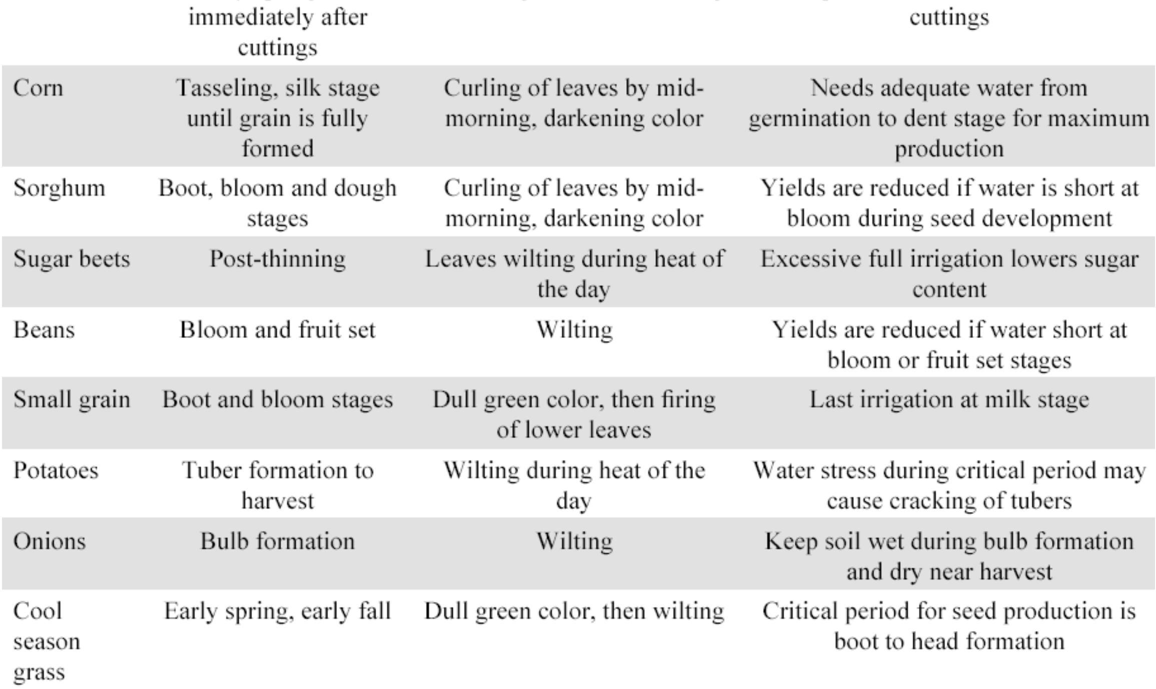


Crop	Critical period	Symptoms of water stress	Other considerations
Alfalfa	Early spring and immediately after cuttings	Darkening color, then wilting	Adequate water is needed between cuttings
Corn	Tasseling, silk stage until grain is fully formed	Curling of leaves by mid-morning, darkening color	Needs adequate water from germination to dent stage for maximum production
Sorghum	Boot, bloom and dough stages	Curling of leaves by mid-morning, darkening color	Yields are reduced if water is short at bloom during seed development
Sugar beets	Post-thinning	Leaves wilting during heat of the day	Excessive full irrigation lowers sugar content
Beans	Bloom and fruit set	Wilting	Yields are reduced if water short at bloom or fruit set stages
Small grain	Boot and bloom stages	Dull green color, then firing of lower leaves	Last irrigation at milk stage
Potatoes	Tuber formation to harvest	Wilting during heat of the day	Water stress during critical period may cause cracking of tubers
Onions	Bulb formation	Wilting	Keep soil wet during bulb formation and dry near harvest
Cool season grass	Early spring, early fall	Dull green color, then wilting	Critical period for seed production is boot to head formation

Before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, both during defined growth stages and throughout the whole season (Kirda and Kanber 1999). Sometimes the uniformly applied deficits do not produce the maximum yield or value for a given crop. To maximize crop yields and crop value, the ideal deficit or stress level must vary with stages of growth (Trout 2007). The crop response to applied irrigation depends on the rainfall amount, soil water storage and soil type, timing of irrigation, evaporative demand, irrigation method and efficiency, and crop selection (Trout 2007). Crops or crop varieties that are most suitable for deficit irrigation are those with a short growing season and are tolerant of drought (Stewart and Musick 1982). Yield sensitivity to a water deficit has a varying impact based on the growing periods and types of crop. The crop yield to ET relationship is a linear relationship in which the more sensitive crops have a steep linear slope (Barta et al.

2004). For example, corn has high sensitivity and yield impact from the removal of a 2.54 cm of ET water not applied during flowering (Schneekloth et al. 2004; Farre and Faci 2008). Farre and Faci (2008) found that full irrigation during the flowering produced higher grain yields than corn subject to deficit irrigation during the flowering stage. The recognized growing periods for water deficit are seed formation, vegetative, grain formation and ripening (Stone and Schlegel 2006). Doorenbos and Kassam (1979) said that in general, grain crops are more sensitive to deficit irrigation during flowering and early seed formation and that rain or irrigation during these sensitive periods will provide more yield increase per unit of water. This could imply that ideal times for deficit irrigation would be during vegetative and ripening periods for grain crops (Stone and Schlegel 2006).

Table 2.10: Common Crop Growth Stages to Select the Correct Times for Deficit Irrigation (Barta et al. 2004)



Crop	Critical period	Symptoms of water stress	Other considerations
Alfalfa	Early spring and immediately after cuttings	Darkening color, then wilting	Adequate water is needed between cuttings
Corn	Tasseling, silk stage until grain is fully formed	Curling of leaves by mid-morning, darkening color	Needs adequate water from germination to dent stage for maximum production
Sorghum	Boot, bloom and dough stages	Curling of leaves by mid-morning, darkening color	Yields are reduced if water is short at bloom during seed development
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Cool season grass	Early spring, early fall	Dull green color, then wilting	Critical period for seed production is boot to head formation

Lytle et al. (2008) found that deficit irrigation was feasible for corn, sunflowers, and soybeans crops. This research showed reduction of 15% of the corn yields for a saving of 17.78 cm when compared to full irrigation (Lytle et al. 2008). Soybeans showed a slight increase in yield and a saving of 3.56 cm when compared to full irrigation. Sunflowers yields for deficit irrigation showed a reduction of 25% with a saving of 10.16 cm relative to a fully irrigated crop (Lytle et al. 2008). Nielsen et al. (2002) found that a water reduction of 15.24 cm during the vegetative development and have no yield reductions in Akron, Colorado. They, also, interpolated that corn yield increases 654 kg/ha for every 2.54 cm of water used after 22.86 cm of water is applied during the growing season (Nielsen et al. 2002).

The proper application of deficit irrigation practices can generate significant savings in irrigation water allocation. The crops that are ideally suited for drier environments and deficit irrigation are crops that have lower water stress sensitivity (Stone and Schlegel 2006). Kirda (2002) showed that cotton, corn, wheat, sunflower, sugar beet and potato are well suited to deficit irrigation practices, with reduced evapotranspiration imposed throughout the growing season. For example, deficit irrigation imposed during flowering and boll formation stages in cotton, during vegetative growth of soybean, flowering and grain filling stages of wheat, vegetative and yielding stages of sunflower and sugar beet will provide acceptable and feasible irrigation options for minimal yield reductions with limited supplies of irrigation water. This list may also include common bean, groundnut, soybean and sugar cane where reduced evapotranspiration is limited at certain growth stages (Kirda 2002).

Hergert et al. (2008) research in North Platte, Nebraska by the Natural Resource District combined the no-tillage (discussed further in Section 2.2) and timing limited irrigation to evaluate the impact of yield and income. He found that only applying limited irrigation of 15.24 cm per crop would have limited impact on crops yields. This research showed that winter wheat yields are 99% of full irrigation, corn yields were 86% and soybean were 88% of fully irrigated yields. Yonts found that late season water stress reduced yields by 7% and that delaying the first irrigation by only one week will reduce dry beans yields by 5% (Yonts, et al. 2003). These deficit irrigation yields also benefited from an average of 43 cm of rainfall per year in this region. These results show that less water (25% to 50% reduction) can decrease income, but proper management can minimize income reduction to only 10% to 20% (Hergert et al. 2008).

2.4.4 Other Management Practices

- Reduce irrigation (deficit irrigate) throughout the season
- End the irrigation season earlier than usual

- Schedule irrigation based on crop requirements (monitor soil moisture, rainfall, ET, crop consultant
- System performance (well water meter, routinely check pumping efficiency
- Incorporate a fallow period into the crop rotation
- Grow a dry land crop as part of a crop rotation that includes irrigated crops
- Fallow a portion of a formerly irrigated field and fully irrigate the remainder
- Convert to a non-irrigated crop or pasture
- Switch to cool season crops
- Splitting pivots between crops that use irrigation at different times

2.5 PROGRAMS FOR WATER CONSERVATION

Water conservation programs can be broken into four methods, which include reliance on agricultural advisors, leverage incentives, performance standards, and mandatory actions. Agricultural advisors try to motivate irrigators to reduce water use in order to lower energy cost and groundwater depletions (Sawyer 1984). Leverage incentives encourage water conservation without enactment of mandatory regulation. Performance standards set specific performance requirements for withdrawal and consumption reduction without selecting the techniques needed to achieve the goals. Mandatory water conservation actions are the most direct strategies and can be inflexible and intrusive into private and local affairs. The overlying questions for any water conservation program should be how to put it into practice and how the actual conservation benefits compare with potential cost in a given management setting.

A wide range of programs to conserve water through state and national agencies exist in Colorado, Yuma County, and the Arikaree River. One of the leading organizations working to conserve the Arikaree River is The Nature Conservancy (TNC). TNC’s mission is to “preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive”

(The Nature Conservancy 2008). TNC and other state agencies manage programs like the Conservation Reserve Program (CRP), that compensates farmers for planting permanent covers of grass and trees to prevent erosion, improve water quality, and provide food and habitat for wildlife (The Nature Conservancy 2008). Recent litigation concerning the Republican River in eastern Colorado has resulted in a program to retire certain irrigation wells with state funded programs run by the Republican River Water Conservation District (RRWCD). The Conservation Reserve Enhancement Program (CREP) and the Environment Quality Incentives Program (EQIP) provide monetary incentives for voluntarily retiring wells (Republican River Water Conservancy District 2006). While well retirement may be appropriate for some farmers, many farmers wish to continue production of crops. Because of the limited conservation choices, there is great need for researching other conservation measures and possible options to farmers in Yuma County. These conservation measures could include more efficient irrigation applications, rotational fallowing of fields, and use of low water requirement crops. These conservation measures could reduce the water usage and potentially decrease the declining groundwater and water levels in the Arikaree River. The United States Department of Agriculture (USDA) has adopted water conservation measures in the Pacific Northwest that have resulted in water savings irrigation conservation of 73.7 cm per irrigated acre from 1987 to 2000 (Wilkins-Wells et al. 2002). These savings are approximately 6.5 cm of water per year from irrigation conservation programs and a 37% reduction in the volume of water applied (Wilkins-Wells et al. 2002). The lowest water savings from irrigation programs was 20.3 cm or 1.6 cm/year in the Plains region (Wilkins-Wells et al. 2002). The Western states had a total water reduction of 33.0 cm or

2.5 cm per year from irrigation conservation programs, which was a 25% reduction in usage (Wilkins-Wells et al. 2002).

D.J. Case & Associates (2006) conducted a survey about awareness of playas, wildlife, and information about conservation both currently used and possible practices for the future. The survey conducted in Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas with 429 respondents. The survey respondents said that 28% of landowners were "highly willing" to implement certain conservation practices if given incentives and 46% were "moderately willing". The 2007 Census of Agriculture (2009) said that 432 farms out of 970 total farms in Yuma County participated in agricultural conservation programs. The 2002 census found that 241 out of 864 farms participated in agricultural conservation programs. The farm participation in conservation programs increased from 27.89% in 2002 to 44.54% in 2007 (2007 Census of Agriculture 2009). If this trend of increasing participation by Yuma County farmers continues, the participation could be 61.18% in the 2012 census. These participation percentages from the Census of Agriculture in Yuma County also correlate with the D.J. Case & Associates survey results presented previously.

2.5.1 Rotational Fallow Incentive

Fallowing is a traditional agricultural practice to restore productivity, primarily through accumulating water and/or nutrients. The soil is tilled for at least one growing season to destroy weeds, to encourage moisture storage, and to promote decomposition of plant residue. The rotational fallow concept is chosen to conserve water. This concept is relatively new in Colorado and little published information is available. Several rotational fallow concepts have been proposed for rural to urban water transfers instead of the traditional “buy and dry” method of municipalities acquiring water rights from agricultural uses.

One rotational fallow program instituted by the Lower Arkansas Valley Water Conservancy District or Lower Ark Consortium that allows irrigators to maintain ownership of water rights with water made available to municipalities and other non-agricultural users through leases (HDR 2008). The lease-fallow programs are popular among farmers in the South Platte basin with a 63% participation rate if adequately compensated (Woodka 2008). Most farmers say the compensation range of $679 to $1,420 per ha per year is acceptable compensation for fallowing (Woodka 2008). The farmers in the Lower Ark would create the Super Ditch Company to allow irrigators to control the leasing of water created from a rotational fallow program with the participating ditch companies and irrigators (HDR 2008). HDR estimated that 65% of the Lower Ark would participate and the fallowing rate would be a 1-in-4 year rotation (HDR 2008). The Lower Ark Consortium has also created the first leasing agreement with Pikes Peak Regional Water Authority to lease 2.46 x 10^6 m^3 of water for $500 per share from the Super Ditch Company (Vickers 2009).

Another rotation fallow program developed between the Palo Verde Irrigation District and the Metropolitan Water District of Southern California comprised of the Palo Verde Valley farmers agreeing to supply 3.64 x 10^6 m^3 to 145.6 m^3 each year with a fallow area of 7% to 28% (MWDSC 2007). The participating farmers would receive a one-time payment of $7,830 per ha for participating and $1,487 per ha per year for fallowed land maintenance payments (MWDSC 2007). This program piloted from 1992 to 1994 with 22% of the valley participating, which saved 229.4 m^3 of water during the test period (MWDSC 2007). MWDSC suggested that the participating land be taken out of production and rotated once every five years.

Another concept developed by the Northern Colorado Water Conservancy District (NCWCD) (2010) to meet future urban water demands in Northern Colorado involved removing irrigated parcels from production on a periodic basis, once every three or four years and transferring the water to an economically higher valued use such as municipal use (HDR 2008). HDR concluded that by rotating the impact of fallow land that farms would be less impacted and lease revenue would generate much needed financial infusions into the local agricultural economy (HDR 2008). The NCWCD concept has the potential to save 31.2 million cubic meters m per year from the rotational fallow program (HDR 2008).

2.5.2 Water Use Limits Over Certain Period Incentive

States, groundwater districts, and municipalities have experimented with and tried to implement water use limits. These forms of limits can have a significant effect on reducing water usage, but also have negative impacts on local economies if not done effectively. Water limits of 36.83 cm are currently required in the Pumpkin Creek Watershed in the Nebraska Panhandle (Hergert et al. 2008; Adelman 2003). Hergert et al. (2008) conducted research over a 10-year period showing that applying 15.24 cm per crop using limited irrigation can achieve winter wheat yields at 99%, corn yields at 86%, and soybean at 88% of the full irrigation yields. The research concluded that less water means less income. With proper management of 25-50% water application reductions, the income reduces only 10-20% (Hergert et al. 2008). Another successful water use limits project done by the Nebraska Upper Republican Natural Resources District

(URNRD) allows 1842 mm of water per certified hectare in any five-year period (Adelman 2003). The water use limits have required farmers to be more resourceful and creative in managing water allocations. Reduction of water use is accomplished by increasing irrigation efficiency in crop rotations, developing irrigation technologies, favorable growing season precipitation, tracking daily crop ET to schedule irrigation, delaying irrigation application to critical reproduction phases, drying up portions of formerly irrigated land, alternating dry land and irrigated crops, and plant less water demanding crops such as wheat and sorghum (Adelman 2003). Research from 1986 to 1999 showed that, if required, farmers could survive with less water since they were only using 80% of the allocated water for the five-year period. The Yuma Conservation District has the Republican River Basin Pathways Project that is helping producers move to lower water use crops and learn how to grow traditional crops on less water (Yuma Conservation District 2007). The Yuma Conservation Districts anticipates reduced future water allocations that could require only 38.1 to 45.7 cm of water annually for irrigation (Yuma Conservation District 2007). The Pathways Project has analyzed pilot farms where producers had three crop circles, raised 2722 kg wheat, 5080 kg corn, and 32,656 kg beets on less than 76.2 cm of total irrigation (Yuma Conservation District 2009). Receiving payments, the Texas irrigators suspend groundwater pumping in dry years for the sake of maintaining flows in nearby streams and to relocated aquifer resources (Keplinger et al. 1998).

2.5.3 Incentive for Conversion to Less Water Intensive Crops

Approximately one-third of Colorado's irrigated acres have already converted to more efficient sprinkler or drip systems. In particular, irrigators that rely on deep or nonrenewable groundwater already have significant incentive for water conservation (Colorado Agriculture Water Alliance 2008). Since many irrigators are already using water resources wisely, the next water conservation step may be reducing the crop consumptive use. Growers reduce crop consumptive use by decreasing irrigated acreage, changing from a summer crop to a cool season crop, changing crops to one with a shorter growing season, and choosing lower water use crops (Colorado Agriculture Water Alliance 2008). Implementing water conservation measures such as crop selection can results in increased equipment, labor, and management costs that are associated with a learning curve. The cost of changing to lower income crops must be borne either by the irrigator or by those who benefit from the conserved water (Colorado Agriculture Water Alliance 2008). It may require financial incentives to mitigate the increased risk and loss of productive capacity that occurs under reduced water supplies. For on-farm implementation of conservation measures, incentives need to be considered and evaluated in the context of compacts and basin wide hydrology. To create incentives for implementing water conservation measures, the cost of water conservation measures should be borne by the beneficiaries of the conserved water. The agricultural user is unlikely and/or unable to bear the costs if the benefits only accrue as improved stream flow, water quality, or as improving the basin as a whole (Colorado Agriculture Water Alliance 2008).

In addition to financial and marketing risks, many different factors dictate crop selection. These factors include:

a) labor constraints,
b) lack of capital or credit,

c) lack of information on market demand, agricultural techniques and agrochemicals, or inadequate farming skills,

d) land tenure uncertainty hindering investments and adoption of perennial crops,

e) soil, drainage, or climatic constraints,

f) high marketing costs due to poor transportation means and infrastructure,

g) unreliability of irrigation supply, and

h) farmer strategies (Molle and Berkoff 2007).

Governments often seek to promote agricultural diversification that may save water but the primary objective is generally to promote agricultural growth and raise farm incomes. Some equate the two, arguing that, if raising the price of water to its opportunity cost (ideally), low-value crops are less attractive and farmers shift to higher value crops (Rosegrant et al. 1995; Bazza and Ahmad 2002). In principle, of course, it is true that water-intensive crops become increasingly less profitable relative to less water intensive crops if water charges are increased. However, in practice, water costs usually comprise only a small part of farm costs, and very high increases in water costs and farmer income reduction are necessary to make these less water-intensive crops more attractive (Molle and Berkoff 2007).

2.5.4 Other Possible Programs

- Permanent voluntary retirement of irrigation well
- Temporary well retirement program (varied period of 3, 5, 10, and 15 years)
- Federal land retirement program (e.g. CRP, CREP, GSWC, WRP, GRP)
- Voluntary conservation incentives to implement conservation practices (e.g. EQIP and CSP)
- Financial incentives for conservation irrigation equipment upgrades
- Tax or payment incentive for ceasing to irrigate less productive land and convert to dry land farming or environmental easements

2.6 CROP SELECTION FOR WATER CONSERVATION

One method of reducing water usage is changing to crops with lower consumptive use. Low consumptive use crops can be cool season crops that are subject to lower atmospheric demand that directly relates to lower ET rates. Switching to crops with shorter growing seasons will reduce crop water and irrigation demands in order to conserve water. This research has identified lower use crops as any crop that has a lower consumptive use than corn, because corn, is the dominant crop in eastern Colorado. Table 2.11 shows the seasonal consumptive use of typical crops, planting and harvesting dates, and total growth times in Holyoke, Colorado.

Table 2.11: Growing Season and Consumptive Use for Various Crops, Holyoke, Colorado (Colorado Agriculture Water Alliance 2008)

	Growing Season (Holyoke, CO)		**Seasonal Consumptive Use**
Crop	**Average Dates**	**Days**	**cm/Season**
Alfalfa	3/20-10/10	204	89.4
Sugar beets	4/25-10/10	168	75.9
Corn Grain	5/5-10/5	153	64.5
Soybeans	5/25-10/5	133	41.7
Spring Grains	4/1-7/25	115	38.6
Dry Beans	6/1-9/5	96	18.7

2.6.1 Corn (Maize)

Corn (*maize*) grown for grain and silage, is one of the most important cereals both for human and animal consumption. In 2007, Colorado planted 427,062 ha of corn that produced 3.5 million metric tons (2007 Census of Agriculture 2009). The crop is grown in climates ranging from temperate to tropic during the period when mean daily temperatures are above 15°C and frost-free. Successful corn production is dependent on the right choice of varieties so that the length of growing period of the crop matches the length of the growing season and the purpose for that the crop is to be grown. Typical growing times for early grain varieties take 80 to 110 days and medium varieties 110 to 140 days to mature as shown in Figure 2.9. For germination, the lowest mean daily temperature is about 10°C, with 18 to 20°C being optimum. Corn is very sensitive to frost, particularly in the seedling stage but it tolerates hot and dry atmospheric conditions so long as sufficient water is available to the plant and temperatures are below 45°C. The plant does well on most soils but less so on dense clay and extremely sandy soils. The preferable soils should be well aerated and well drained, as the crop is susceptible to water logging. Water logging during flowering can reduce grain yields by 50 percent or more (FAO 2002). For maximum production, a medium maturity grain crop requires between 500 and 800 mm of water depending on climate (FAO 2002).

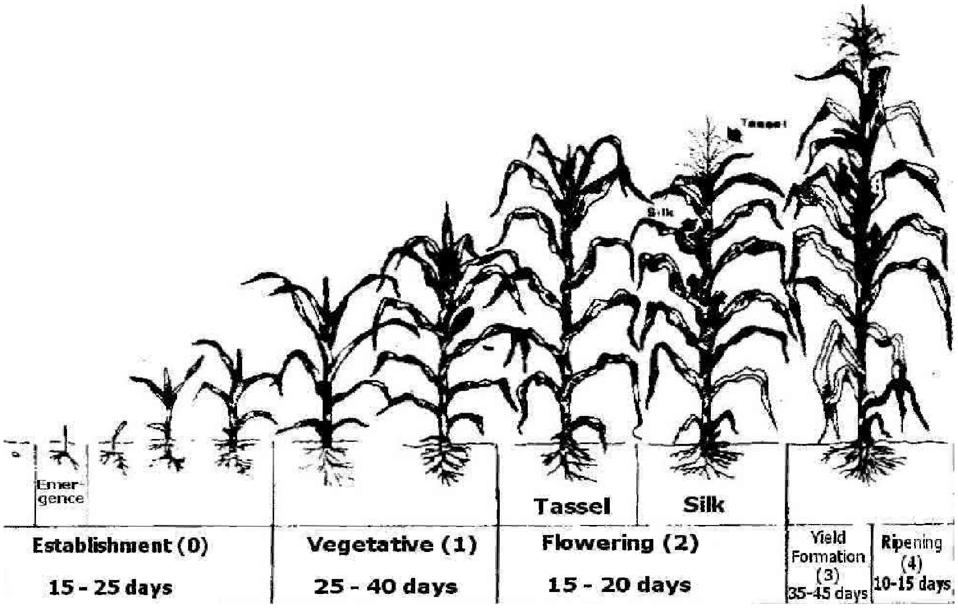


Figure 2.9: Corn Development Stages and Time Periods (FAO 2002)

Corn appears relatively tolerant to water deficits during the vegetative and ripening periods. The greatest decrease in grain yields is the cause of water deficits during the flowering period including tasselling, silking, and pollination, due mainly to a reduction in grain number per cob. Water deficit during the ripening period has little effect on grain yield (FAO 2002). If not managed correctly, the effect of deficit irrigation on corn can have considerable grain yield impacts. Water deficit can enhance rapid and deep root growth at greater depletion of water during early growth periods. In fact, corn can withstand depletion of 80 percent or more water during the ripening period. Although in deep soils the roots may reach a depth of 2 m**,** the highly branched system is located in the upper 0.8 to 1 m and about 80 percent of the soil water uptake occurs from this depth (FAO 2002).

2.6.2 Bean, Dry

Dry beans *(Phaseolus vulgaris)* grow as a vegetable crop for fresh pods or as a pulse crop for dry seed. Colorado production of dry beans is about 35.6 million kg from about 18,878 ha (2007 Census of Agriculture 2009). The common bean grows well in areas with medium rainfall, but the crop is not suited to the humid, wet tropics. Excessive rain and hot weather cause flower and pod drop as well as an increase in the incidence of diseases. The optimum mean daily temperatures range between 15 and 20°C. Typical growth periods are 90 to 120 days for dry beans, depending on the bean variety. Table 2.12 and Figure 2.10 show the bean development stages. The bean is sensitive to soil-borne diseases and grows most effectively in a rotation; wheat, sorghum, onion and potato are common rotation crops (FAO 2002).

Water requirements for maximum production of a 90 to 120 day crop vary between 300 and 500 mm, depending on climate. Water supply needed for maximum yield for both fresh and dry produce is similar during much of the growing period, but varies during the ripening period. For dry beans, discontinuing the water supply about 20 to 25 days before crop harvest still yields maximum harvest. By careful timing, the provision of the water supply in order to induce a slight water deficit to the crop during the ripening period maximizes yields. Soil water depletion to about 50 percent of the total available water may hasten the onset of maturity (FAO 2002).

However, a severe water deficit during the vegetative period generally retards plant development and causes non-uniform growth. During flowering and the yield formation, frequent irrigation results in the highest response to production, although excess water increases the incidence of diseases, particularly root rot. When water supply is limited, some water savings could be achieved during the vegetative period and during the ripening period without greatly affecting yield, provided water deficits are moderate (FAO 2002).

Table 2.12: Bean Development Stages and Time Periods (FAO 2002)

		Green Bean	**Dry Bean**
0	Establishment	10-15 days	10-15 days
1	Vegetative (up to first flower)	20-25	20-25
2	Flowering (including pod setting)	15-25	15-25
3	Yield formation (pod development and bean filling)	15-20	25-30
4	Ripening	0-5	20-25
		60-90	90-120 days

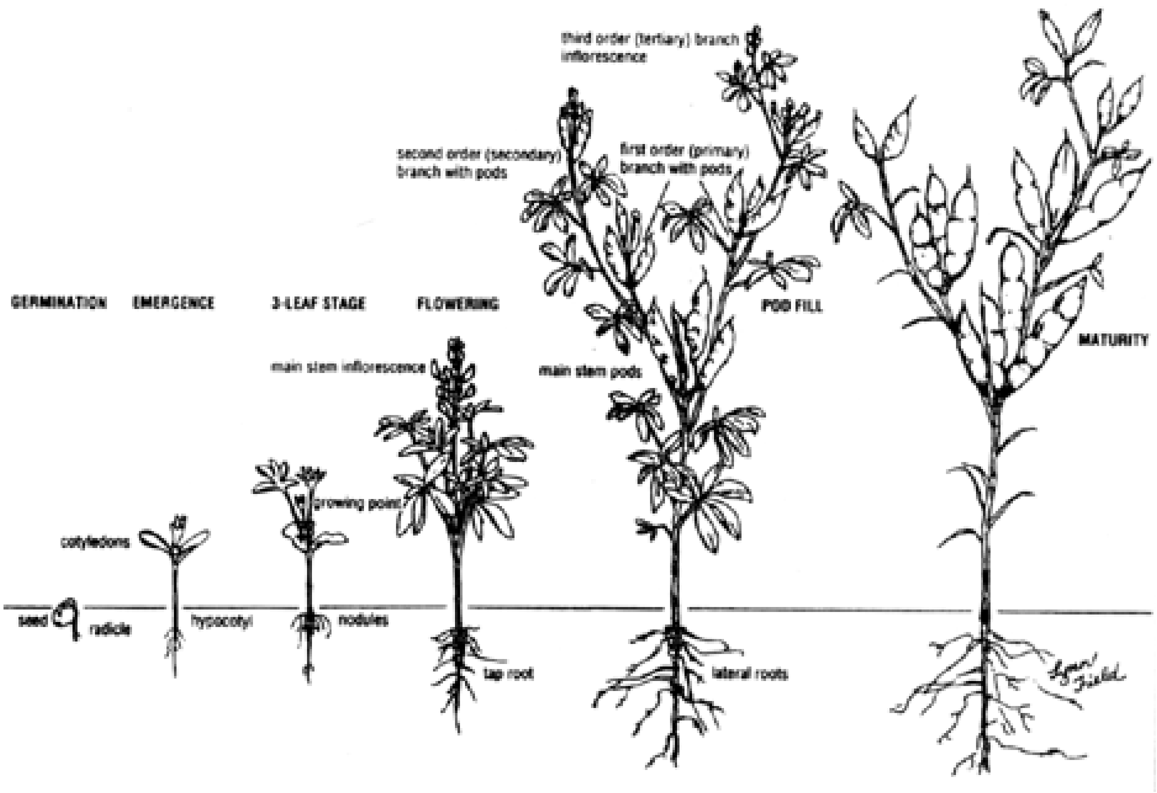


Figure 2.10: Bean Development Stages (Putnam 1993)

2.6.3 Soybeans

Soybean (*Glycine max*), produced for oil and protein, is one of the most important crop worldwide. Colorado production is about 4,562 metric tons of beans over 1,190 ha. The crop mainly grows under rain fed conditions with supplemental irrigation used increasingly. Soybean is relatively resistant to temperatures extremes but growth rates decrease above 35°C and below 18°C. The length of the average total growing period is 100 to 130 days (FAO 2002). Figure 2.11 shows the growth development stages of soybean. Soybean is an effective rotation crop in combination with cotton, corn, leguminous and sorghum. The crop grows on a wide range of soils with the exception of prohibitively sandy soils. Water requirements for maximum production vary between

450 and 700 mm per season depending on the climate and the length of growing period (FAO 2002).

Water deficiency or excess water during the vegetative period will stunt or prohibit growth. Growth periods most sensitive to water deficits are the flowering and yield formation periods, particularly the latter part of the flowering period and early part of the yield formation (pod development) period when water deficits may cause heavy flower and pod dropping. The drought resistance of the crop during flowering and early yield formation (pod development) is the result of the flowering period extending over one month. Small water deficits during a part of this month long period compensate by better retention of later-formed flowers and pods setting. Water savings should be minimal during the late flowering period and early yield formation period (pod development). However, the crop water demands during the establishment period and early yield formation are a necessity (FAO 2002).

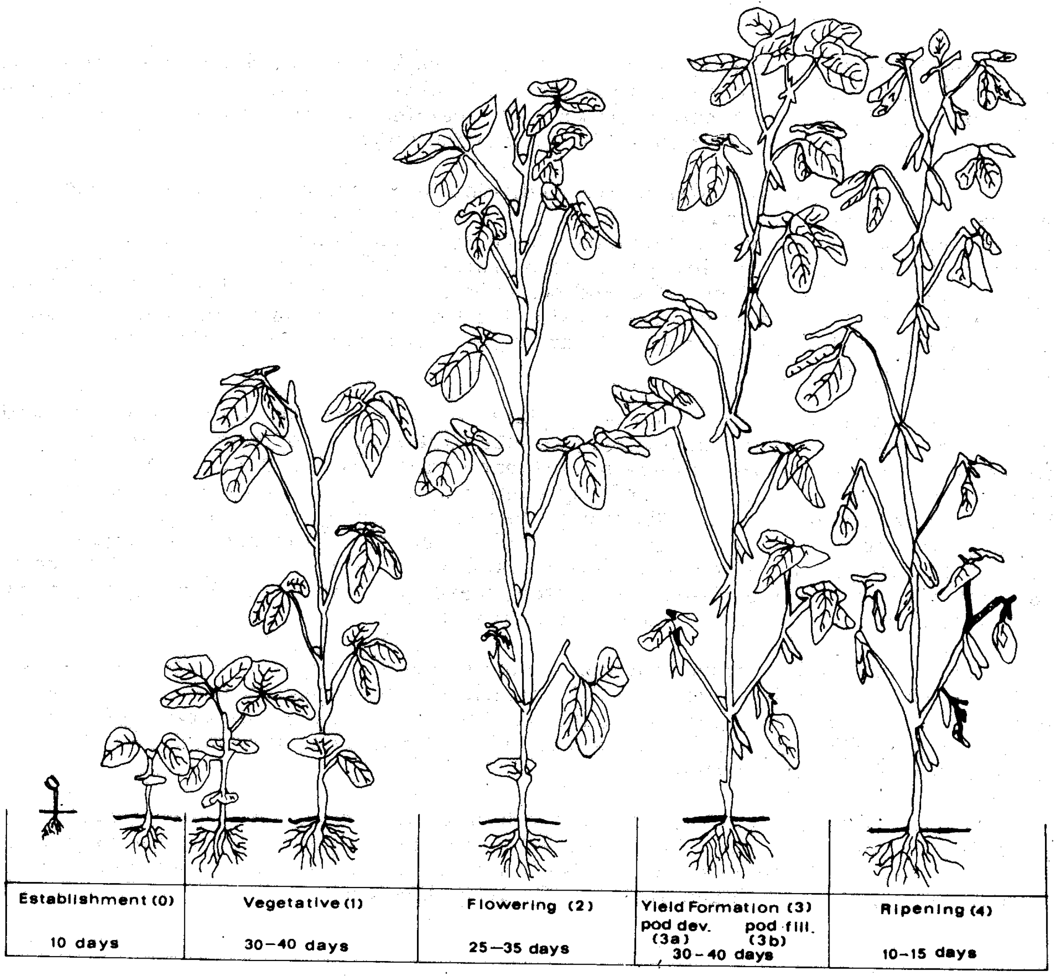


Figure 2.11: Soybeans Development Stages and Time Periods (FAO 2002)

2.6.4 Winter Wheat

The domestication of wheat (*Triticum aestivum* and *T. turgidum*) advanced in the Middle East. Colorado production is about 2.43 million metric tons from 2.37 million ha (FAO 2002). Commonly grown as a rain fed crop in the temperate climates, wheat has a total growing period for spring wheat ranging from 100 to 130 days, with winter wheat needing about 180 to 250 days to mature. Figure 2.12 shows the growth development stages of both types of wheat. Grouping varieties as either winter or spring types is in accordance to the particular chilling requirements, winter hardiness, and day length sensitivity (FAO 2002). Winter wheat requires a cold period or chilling during early growth for normal heading under long days. Winter wheat in its early stages of development exhibits a strong resistance to freezing, down to - 20°C. The resistance is during the active growth period in spring and during head development and flowering periods. Wheat grows on a wide range of soils but medium textures are preferred. Avoid growing wheat in peaty soils containing high sodium, magnesium or iron (FAO 2002).

Wheat often grows in rotation with legumes, sunflower and corn. For high yields, water requirements are 450 to 650 mm depending on climate and length of growing period. The water deficit sensitivity is somewhat higher in spring than in winter wheat, and this difference is the result of "conditioning" of winter wheat that enables it to adjust growth better in relation to a water deficit (FAO 2002). When an adequate amount of stored soil water is available, significant water deficits may occur only in the yield formation period. Slight water deficits in the vegetative period may have little effect on wheat development or may even hasten maturation. The flowering period is most sensitive to water deficit and will experience yield reductions. Pollen formation and fertilization seriously affect wheat under heavy water stress and during the time of head development and flowering, water shortage will reduce the number of heads per plant, head length, and number of grains per head. At the time of flowering, water reductions can cause a decline of root growth and possible even termination (FAO 2002).

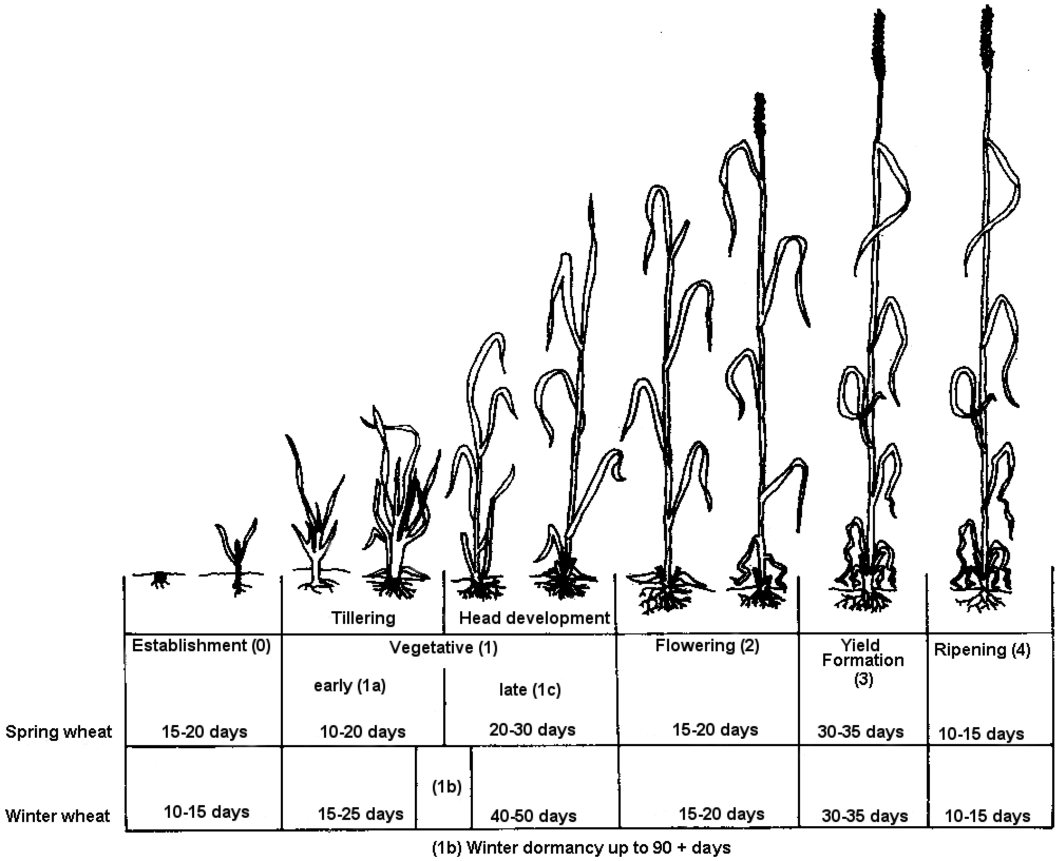


Figure 2.12: Wheat Development Stages and Time Periods (FAO 2002)

2.6.5 Other Low Water Use Crops

- Barley/Oats
- Hay Millet
- Proso Millet
- Sorghum, grain
- Sudan for Hay
- Sunflowers
- Wheat/Barley, spring
- Perennial forage crops

2.7 ECONOMIC IMPACTS OF WATER CONSERVATION

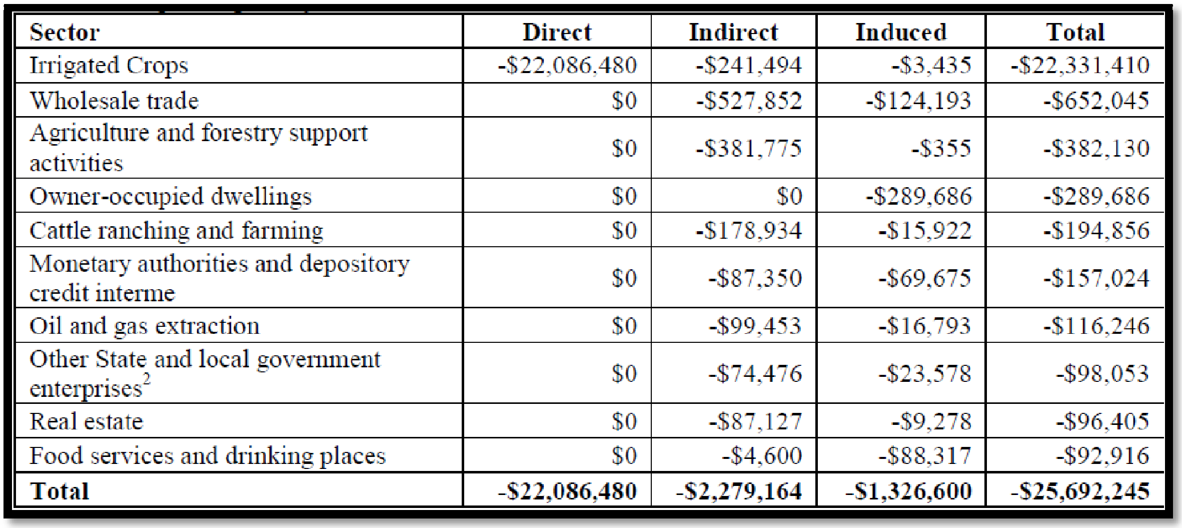
The agricultural community and municipal cities are currently mining the High Plains aquifer at an unsustainable rate that is causing water scarcities throughout Colorado. The population in Colorado projected to grow 65% by the year 2030 will increase the demand for water, also. The increase in population causes a projected increase in the water demand by 53% in the South Platte and Republican River basins (Thorvaldson and Pritchett 2006). The increased water demand, declining water levels in the High Plains aquifer, drought, and reduced surface water available for agricultural will increase the need to conserve water. One method for prolonging the High Plains aquifer and surface water supplies is conservation of agricultural water use. Solley (1997) estimated that the irrigation and livestock water use was approximately 92% of all water use in Colorado and agricultural water will use 86% in 2030. The decline will be due to municipalities and industries buying agricultural water (Thorvaldson and Pritchett 2006). Although many conservation measures are available to local producers, there is usually an economic impact of using new technology or equipment, instituting new programs, or reducing the amount of irrigation. The economic impact to eastern Colorado communities and agricultural producers is vital to the success of conservation measures.

The 2007 Census of Agriculture (2009) reported that there are 970 farm operations in Yuma County with an average size of 556 ha totaling 540,034 ha in farmland. The total production was $711,391,000 with 27% ($191,624,000) due to crop sales and 73% ($519,767,000) to livestock sale with the average farm market value sold of $733,393. The total crop land is 52.3% of the total land with acreage of 282,384 ha. The main crops produced in Yuma County are corn for grain at 89,058 ha, wheat grain at 55,079 ha, forage for 12,322 ha, dry edible beans with 4,725 ha, and proso millet with 4,610 ha.

Agriculture is one of the Colorado’s most significant economic sectors, encompassing 47% of the land in the state (USDA 2009). In the Republican River Basin, the agricultural industry comprises 44% of the total economy (Thorvaldson and Pritchett 2006a). A viable and healthy agricultural industry is essential to maintaining the economics, social, and cultural integrity of eastern Colorado. Seventy-five percent of the total values of Colorado's crops derive from the irrigated land which highlights the importance of conservation (Thorvaldson and Pritchett 2006b). Therefore, it is very important for local producers and decision makers to know the potential impacts of conservation measures to the region.

The Republican River basin has an interstate compact with Nebraska and Kansas that requires certain amounts of water to leave Colorado. The groundwater development in Colorado has decreased the flow in the Republican River and its tributaries such as the Arikaree River. Colorado will have to supplement the reduced flow and may have to reduce groundwater pumping to meet compact requirements. Pritchett and Thorvaldson (2008) estimated that 12,545 ha of irrigated land would need to be fallowed in order to meet the Republican River Compact requirements. Eastern Colorado and the Arikaree River basin have few economic alternatives to agriculture and rely heavily on irrigated agriculture for economic activity (Pritchett and Thorvaldson 2008). Since the region depends on irrigated agriculture so exclusively, the region could experience greater economic impacts due to the loss of irrigated agriculture (Pritchett and Thorvaldson 2008). Pritchett and Thorvaldson (2008) analyzed the economic impacts of converting 2525 ha of alfalfa and 10,100 ha of corn to grassland. The total economic impact was estimated at over $25 million or $2,036 per ha of economic activity. Table 2.13 shows the direct, indirect, and induced economic impacts to individual sectors in the region with the highest being irrigated crops as expected. Changing crop production activity leads to altered demand for labor inputs referred to as induced impacts.

Table 2.13: Output Impacts by Sector in the Republican River Basin (Pritchett and Thorvaldson 2006b)



Sector	Direct	Indirect	Induced	Total
Irrigated Crops	-$22,086,480	-$241,494	-$3,435	-$22,331,410
Wholesale trade	$0	-$527,852	-$124,193	-$652,045
Agriculture and forestry support activities	$0	-$381,775	-$355	-$382,130
Owner-occupied dwellings	$0	$0	-$289,686	-$289,686
Cattle ranching and farming	$0	-$178,934	-$15,922	-$194,856
Monetary authorities and depository credit interme	$0	-$87,350	-$69,675	-$157,024
Oil and gas extraction	$0	-$99,453	-$16,793	-$116,246
Other State and local government enterprises[2]	$0	-$74,476	-$23,578	-$98,053
Real estate	$0	-$87,127	-$9,278	-$96,405
Food services and drinking places	$0	-$4,600	-$88,317	-$92,916
Total	**-$22,086,480**	**-$2,279,164**	**-$1,326,600**	**-$25,692,245**

Thorvaldson and Pritchett (2006b) analyzed the economic impacts to the four river basins in Colorado. In this analysis, the estimate projected 8093 ha of irrigated agriculture would be removed in the next 30 years based on the reduction required by the Conservation Reserve Enhancement Program. This reduction of irrigated agriculture will have an economic impact of $13.55 million and lost economic activity of $1,675 per ha (Thorvaldson and Pritchett 2006b). Based on these economic estimates, the value of the potential loss of irrigated agriculture would be $1,675 to $2,036 per ha.

2.7.1 Economy of Field Practice Conservation

Typically, any economic savings from field practices is in the reduced pumping costs and the potential for higher yields. Klocke et al. (2008) estimate the pumping costs at $22 per ha for each 2.54 cm pumped and no-till water savings ranging from 10.2 to 12.7 cm annually. The total water savings potential with 12.7 cm would be $111 per ha.

It was also estimated that corn yields increase by 628 kg/ha for each 2.5 cm of irrigation that is transferred from evaporation to transpiration (Klocke et al. 2008). That means that corn priced at $0.18 per kg and 12.7 cm of water transferred from evaporation to transpiration will have a savings of $556 per ha. There is a significant economic savings achieved in reduction of fuel usage and labor cost by implementing no-tillage field practices as shown in Table 2.14 and Table 2.15.

Table 2.14: Tillage System Diesel Fuel Requirements liters/ha (Meese 2008)

Moldboard Plow	Chisel	Disk	No-Till
8.04	5.05	4.68	2.25

Table 2.15: Tillage System Labor Requirements min/ha (Meese 2008)

Moldboard Plow	Chisel	Disk	No-Till
29.65	23.97	18.04	11.86

Archer et al. (2008) found that conversion from conventional tillage to no-till field practices could reduce erosion, reduce greenhouse gas emissions, conserve water, and have positive economic returns. They found that for irrigated cropland no-till field practices had a net return of $46 to $74 per ha when compared to conventional tillage. The reason for the savings was the reduction in operating costs of $57 to $114 per ha and reduction of machinery ownership costs of $87 to $90 per ha (Archer et al. 2008). The initial capital costs for a new no-till drill (30’ Crustbuster 4000) would range from $84,000 to $90,000 (Farm Power & Equipment Inc, Personal Communication, April 15, 2010). The minimum tillage drill will have very similar costs since the only modification is a less heavy-duty splitter on the drill. This cost does not consider any return costs of selling other machinery. The operational savings were largely due to fuel and labor reductions of 75% and 72%, respectively. Economic saving was still possible with the increased N fertilizer required for the no-till of 16 to 55 kg per ha when compared to conventional tillage. These authors concluded that no-till, irrigated, continuous corn rotation could be economically viable for replacing conventional tillage (Archer et al. 2008). Archer and Reicosky (2009) found that average yields over 7 year study period remained the same for no-till, strip-tillage, fall residue management with strip tillage, spring residue management with strip tillage, and conventional moldboard plow. But the economic returns were \$85, \$92, and \$53 per ha higher for no-till, fall residue management with strip tillage, and spring residue management with strip tillage, respectively, when compared to conventional moldboard plow based on 2007 crop prices and 2008 input prices (Archer and Reicosky 2009). No significant differences in net returns were detected between chisel plow and no-till or any of the strip tillage alternatives given 2007 crop prices and 2008 input prices (Archer and Reicosky 2009). Table 2.16 shows the individual results from Archer and Reicosky's (2009) research.

Table 2.16: Corn and Soybean Average Annual Production Costs for 1997–2003 Based on 2008 Input Prices (Archer and Reicosky 2009)

	NT†	MP	CP	Fall RM	Fall RM + ST	Spring RM	Spring RM + ST	Fall RM + Subsoil
	$\$$ ha^{-1}							
Corn costs								
Labor	17	28	24	20	21	20	21	21
Repairs	19	29	23	20	22	20	22	22
Diesel fuel	31	65	50	35	49	35	49	53
Seed, fertilizer, herbicide	734	734	734	734	734	734	734	734
Interest	19	22	21	20	21	20	20	21
Drying fuel	158	151	140	155	151	147	152	152
Total operating cost	979	1030	992	985	999	976	999	1004
Machinery depreciation	49	79	68	52	70	52	70	78
Machinery overhead	36	62	52	39	53	39	53	60
Total cost	1064	1171	1112	1076	1121	1067	1121	1142
Soybean costs								
Labor	16	30	26	19	20	19	20	20
Repairs	16	28	23	18	19	18	19	19
Fuel	28	66	54	31	45	31	45	49
Seed, fertilizer, herbicide	251	251	251	251	251	251	251	251
Interest	7	11	10	8	9	8	8	9
Drying fuel	4	3	3	6	3	4	3	3
Total operating cost	322	389	365	333	347	330	346	352
Machinery depreciation	40	75	66	43	61	43	61	68
Machinery overhead	30	61	53	33	46	33	46	54
Total cost	392	525	485	408	454	406	453	474
Rotation average costs								
Labor	16	29	25	20	21	20	21	21
Repairs	17	28	23	19	20	19	20	20
Fuel	29	66	52	33	47	33	47	51
Seed, fertilizer, herbicide	493	493	493	493	493	493	493	493
Interest	13	17	15	14	15	14	14	15
Drying fuel	81	77	71	81	77	75	77	78
Total operating cost	650	709	679	659	673	653	673	678
Machinery depreciation	44	77	67	47	65	47	65	73
Machinery overhead	33	61	53	36	49	36	49	57
Total cost	728	848	798	742	787	736	787	808
Total cost (2003–2007 prices)	506	609	569	519	558	515	558	577

† NT, no-till; MP, moldboard plow; CP, chisel plow; Fall RM, fall residue management; Spring RM, spring residue management; ST, strip-tillage.

2.7.2 Economics of Irrigation System Conservation

Torell et al. (1990) estimated the cost of water from the Ogallala Aquifer as the differential between irrigated and dry land farm sales using 7,200 farm sales as a data set. This study found that the value of water in the marketplace has declined 30% in New Mexico and 60% in both Nebraska and northern Colorado. The study considered the value of water from 1979 to 1986 and determined that the average value of water as a percent of irrigated farmland price was 66% in northern Colorado. The average value of water per ha of irrigated farmland is $1,754 and the average value of water per thousand cubic meters of saturated thickness was found to be $4.41 (Torell et al. 1990). In 1981, the in-use marginal water value was $35.6 per thousand m^3 for the northern and central Ogallala and $16.2 per thousand m^3 for the southern Ogallala (Torell et al. 1990). When considering the costs required of extracting water, the new costs would be $30.9 per thousand m^3 and $9.3 per thousand m^3 for northern and central Ogallala, respectively (Torell et al. 1990). Improving pumping performance and efficiency can greatly affect total energy demands. According to Zilberman et al. (2008), energy for groundwater irrigation accounted for between 4% and 25% of groundwater system production cost.

In areas pumping from deep groundwater aquifers, economic incentives for water conservation exist because practices that result in increased application efficiency are frequently justified because of decreased pumping costs (Smith et al. 1996). In addition, institutional incentives in the form of restrictions on the rate of aquifer depletion encourage the adoption of irrigation water conservation practices. Economic benefits are difficult to project on a general basis because of the large number of variables involved require that potential gains have to be evaluated on a case-by-case basis (Smith et al. 1996). Table 2.17 shows the costs associated with each type of irrigation method for installation and the average annual costs for maintenance.

Table 2.17: Estimated Costs of Irrigation Methods in Colorado (Colorado Agriculture Water Alliance 2008)

Type of Irrigation	Average Capital $/ha	Average Annual $/ha
Flood Furrow	$91	$74
Gated Pipe	$440	$126
Center Pivot Circle	$1070	$158
Center Pivot with Corner	$1403	$198
Subsurface Drip Irrigation	$2470	$296

2.7.3 Economics of Management Practice Conservation

The top management practices could have minimal economic impacts to the community and the farmer. During field trials in the Western Great Plains, drought-tolerant corn showed a 6% to 10 % yield increase (Monsanto Company 2009). These drought tolerant crops project to increase yields by 2012. Other research comparing hybrid yields showed that genetic improvements have increased yields 2.6% per year for the last three decades (Tollenaar 1989). The increased yields will allow higher farmer incomes per acre and save water in the process. Hillyer (2005) discussed the increased cost of genetically engineered and transgenic traits in seeds with each input adding approximately $25 to $50 a trait (corn borer, herbicide resistance, Bt rootworm protection). The assumption that the high performing drought tolerant crops would also demand costs similar to other traits is reasonable. This can have a significant costs when the ideal seeding rate of approximately 79,000 seeds per hectare and approximately 80,000 seeds per bag (Elmore and Abendroth 2006).

The shorter season corn did reduce the total water usage but there was also a reduced yield (Howell et al. 1998). Other research showed that hybrids that mature five days earlier than the traditional full season hybrids produced the same grain yield and higher silage yield with better quality (Xu 2007). This shows that current research in short season hybrids and stress-tolerant hybrids are feasible to reduce irrigation without yield penalty. The research by Xu (2007) supports the conclusion that yields are increasing each year, which includes short season crops.

Reducing irrigation early in the season, but fully irrigating later in the season has shown no yield decreases. Farre and Faci (2008) found that corn under mild irrigation deficit extracted more water than under severe deficit irrigation and concluded that less stressed plants developed deeper and more dense rooting systems. The proper application of deficit irrigation practices can generate significant savings in irrigation water allocation. The crops that are ideally suited for drier environments and deficit irrigation are crops that have lower water stress sensitivity (Stone and Schlegel 2006). Nielsen et al. (2002) found that with corn, water reduced by 15.24 cm during the vegetative development had no yield reductions in Akron, Colorado.

2.7.4 Economics of Conservation Programs

The goal of all water conservation programs is to maximize the net benefits of conserving water and minimizing the cost of conserving any given quantity of water (Wilkins-Wells et al. 2002). The High Plains Associates (1982) study found that under the most effective water conservation programs, more than a 405,000 ha of farmland then irrigated by the Ogallala Aquifer would return to dry land production by the year 2020. Investment in irrigation water conservation programs by the Bureau of Reclamation showed that the average payment for the programs was \$284 per ha of irrigation treated and \$88.3 per thousand m^3 of water saved. This report also said that the highest paid capital for conservation was in the Lower Colorado region at \$501 per ha and the least was in the Great Plains region with \$175 per ha (Wilkins-Wells et al. 2002). Water conservation in Goshen County, Wyoming found that reducing irrigation application involves minimizing investment of producers. The average producer investment for conservation would be about \$28.4 per thousand m^3 and the public investment for cost sharing would be on average of \$48.6 per thousand m^3 (Wilkins-Wells et al. 2002).

Water rights have a price range of \$243 to \$324 per thousand m^3 with South Platte wells typically producing 308.5 to 370.3 million m^3 of water each year (Pritchett and Weiler 2003). The current Conservation Reserve Enhancement Program establishes payments based on distance from the tributaries of the Republican River and shown in Table 2.18. Payments made for the retirement of irrigation wells range from \$247 to \$1605 per ha. The goals of the project are to conserve agricultural irrigation water use in the basin by five percent that will include dry land of 2,023 ha and irrigated land of 12,140 ha (RRWCD 2006).

Table 2.18: Republican River CREP Payments \$/ha (RRWCD 2006)

Payment Type	**Surface**	**<1.6 km (<1 mi)**	**<3.2 km (<2 mi)**	**<6.4 km (<4 mi)**	**<6.4+ km (<4+ mi)**
Annual RRWCD Rent Payment	\$124	\$62	\$37	\$25	-
Total Water Retire (Yrs 5, 10, 15)	\$1,483	\$988	\$618	\$432	\$247
Bonus Payment (Yr 1)	\$297	\$86	\$62	\$37	\$25

Another program currently used in Colorado is the Environmental Quality Incentive Program (EQIP) that seeks to provide a voluntary conservation program for farmers and ranchers that promotes agricultural production and environmental quality as compatible goals. The 2009 RRWCD (2009) EQIP is through the Natural Resource Conservation Service (NRCS), a program in that the water right is retired for a period in time but the land remains in production for dry land farming or grazing throughout the contract period. The 2009 program only offers funding from RRWCD for permanent retirements; however, NRCS will offer payments for either a 5-year or a permanent retirement. The permanent well retirement payments are \$1927 per ha with the farmer still allowed to dry land farm or pasture as shown in Table 2.19 (RRWCD 2009).

Table 2.19: Environmental Quality Incentives Programs (EQIP) Payments of Retire Irrigation Wells in the Republican River Basin, $/ha (RRWCD 2009)

Retirement Type	RRWCD	NRCS	Total
5-year	0	$556	$556
Permanent	$963	$963	$1,927

The lease-fallow programs are popular among farmer in the South Platte with a 63% participation rate if adequately compensated (Pritchett et al. 2008). Most farmers say the compensation range of $679 to $1,420 per ha per year is adequate. Pritchett et al. (2008) say that irrigated cropland rents for $741 per ha and dry land cropland only nets $124 per ha. Pritchett et al. (2008) concluded that if irrigated land is leased for $741 per ha and 1.6 per thousand m^3 of water is leased, then the cost of $124 per ha is $0.81 per thousand m^3. If a long-term lease (15 years) was completed then the value of water could be $2432 per thousand m^3 with a 5% average rate of return (Pritchett et al. 2008). The Lower Ark consortium has also created the first leasing agreement with Pikes Peak Regional Water Authority to lease one share of 1621 per thousand m^3 of water for $500 from the Super Ditch Company (Vickers 2009).

2.7.5 Economics of Conservation Crop Selection

Use of alternative crops that have a lower evapotranspiration or alternative irrigation management strategies will reduce water consumption from the Ogallala Aquifer, thus extending the economic life of irrigation within the region. These strategies will also help improve the Arikaree River stream flow and therefore, help Colorado with compliance of the Republican River Settlement. Corn is the primary irrigated crop in the High Plains of Colorado where approximately 74% (2007 Census of Agriculture 2009) is grown. Acreage of lower water use crops (wheat, beans, soybeans, sunflower, etc.) was approximately 13% of the irrigated acres. Irrigated corn has an evapotranspiration (ET) of 63.5 to 68.6 cm. Lower water use crops can have water uses of 45.7 to 61.0 cm. Farmers have primarily chosen corn due to the potential for high returns with the price increasing approximately 9.5% from 1990's to the 2000's. Yuma County produced an average corn yield of 11,541 kg/ha (2007 Census of Agriculture 2009). Due to corns high production potential the average income was $1,211 per ha for the 2000's (National Agricultural Statistic Services 2010). The farmers in eastern Colorado identify the potential lower water use crops as winter wheat, dry beans, and soybeans. The economics shows that winter wheat's price has increased approximately 23% from 1990's to the 2000's. In Yuma County, the average winter wheat production is 2,966 kg/ha (2007 Census of Agriculture 2009). Based on the average data, winter wheat has the potential income average of $447 per ha for the 2000's (National Agricultural Statistics Service 2010). The economics shows that the dry beans price has increased approximately 10.9% from 1990's to the 2000's and Yuma County averaged yields for dry beans of 2,735 kg per ha (2007 Census of Agriculture 2009). Based on the average data, dry beans have the potential income average of $1,221 per ha for the 2000's. The economics shows that soybean price has increased approximately 13.8% from 1990's to the 2000's. Yuma County soybeans yields on average are 3738 kg/ha (2007 Census of Agriculture 2009). Based on the average data, soybeans have the potential income average of $941 per ha for the 2000's (National Agricultural Statistics Service, 2010). Table 2.20 shows total sale value, total production, and cost per unit of the top producing crops in the Republican River basin.

Table 2.20: Value of Sales by Irrigated Crop for Republican River Basin Counties (Thorvaldson and Pritchett 2006b)

Crops	**Total Production of Irrigated Crops**	**Value of Irrigated Crop Sales (Millions)**	**Value ($/Unit)**	**Percent of Total Value**
Total		$ 367.06		100.0%
Corn Grain (BU)	99,125,600	$ 206.18	$ 2.08	56.17%
Hay (TON)	838,715	$ 75.48	$ 89.99	20.56%
Sugerbeets (TON)	44,825,000	$ 15.24	$ 0.34	4.15%
All Wheat (BU)	5,106,250	$ 13.79	$ 2.70	3.76%
Sunflower (LBS)	120,104,600	$ 12.61	$ 0.10	3.44%
Dry, Edible Beans (LBS)	74,898,000	$ 11.98	$ 0.16	3.26%
Corn Silage (TON)	552,500	$ 11.33	$ 20.51	3.09%
Potatoes (LBS)	731,000	$ 6.80	$ 9.30	1.85%

Changes in cropping practices can be challenging, have substantial changes (fertilizers, herbicides, management, et.), and economic barriers to the transition in cropping practices. For example, shifts from feed crops (corn or alfalfa) to melons in the Arkansas River basin can result in significant water savings because of the seasonal consumptive use of melons is much lower than that of either corn or alfalfa. However, this type of cropping change involves making wholesale modifications in farm operations and entering a more dynamic marketing environment (Smith et al. 1996). Thus, this change in cropping practices is not likely to occur on a widespread basis. Economic incentives, education of alternative farming practices, and field demonstrations to area farmers overcome the economic barriers to water savings through changing cropping practices.

CHAPTER 3 SURVEY OF POTENTIAL WATER CONSERVATION IN EASTERN COLORADO

3.1 SURVEY OF EASTERN COLORADO PRODUCERS

To implement preservation and restoration programs successfully, it is imperative that the stakeholders within the community acknowledge the need to protect and preserve the Arikaree River. Collectively, these stakeholders must decide that options are feasible for them to both endorse and facilitate the "buy in" of the programs that are set forth. Informational meetings informed stakeholders of past research completed and potential conservation practices that would be practical for use locally. These meetings were also ideal opportunities to distribute opinion surveys on possible future conservation measures. The surveys conducted at the informational meetings allowed stakeholders the ability to provide feedback, make suggestions, and express concerns. The surveys identified the most feasible conservation methods. Appendix 8.1 explains the survey entitled "A Survey of Potential Water Conservation in eastern Colorado". The survey also identified economic parameters used in selecting feasible conservation methods. The economic parameters will help to show how farmers evaluate different conservation alternatives based upon differing perspectives such as farm size, knowledge, and experience. It was critical to the research that the communities completely engage in the research in order to successfully gain local insight into the feasible conservation measures. On the reciprocal side, the research results will help the watershed stakeholders make good decisions on how to protect and preserve the Arikaree River without negatively affecting a fragile rural economy.

3.1.1 Survey Contents

The survey, developed from multiple sources, included general farm information, economic information, consultations with local agricultural experts, and a comprehensive literature review of conservation methods. The survey was broken into seven sections: General Farm Information, Field Practices, Irrigation System Information, Management Practices, Programs, Crop Selection, and Demographic Information. The general farm information and the demographic information provide general farm size as well as the existing practices in order to assist in identifying feasibility of the conservation measures. The middle five sections of the survey focused on the different conservation measures to consider for development in eastern Colorado. Farmers identified the top three conservation practices that they would be willing to implement on their farms. Of the water conservation surveys distributed to 227 farmers in eastern Colorado, forty-one surveys returned for an 18% response rate providing the basis of the research for this project.

Research completed by Pritchett et al. (2006) sent surveys to 2,500 farmers selected from Agriculture Census database included 948 small farms, 785 medium farms and 767 large farms (Pritchett et al. 2006). The mailed surveys had 33 surveys returned due to insufficient/inaccurate address with 713 (29%) surveys completed and returned (Pritchett et al. 2006). Pritchett et al. (2006) surveys were completed in three steps: initial mailing of survey, followed by a postcard reminder two weeks later, and a second survey mailing to non respondents two weeks later (Pritchett et al. 2006). The Arikaree research response rate of 18% is close to other agricultural response rates in Colorado as noted before. The higher response rate of the surveys conducted by Pritchett et al. (2006)

could be due to multiple mailings and reminders. The researcher made considerable effort in the Arikaree River basin survey to establish rapport with local farmers during presentations in order to maximize the number of survey responses.

The possible water conservation methods and practices identified in the survey originated from a comprehensive literature review of agricultural research conducted throughout the country and in the arid western United States under conditions similar to the Arikaree River basin. The literature review identified practical and effective conservation methods used in other basins considered for implementation in Yuma County. The conservation methods focused on the methods compatible with center pivot irrigation and the grain crops grown in the project area. The literature review results for water conservation can be broken into five different categories, including field practices, irrigation systems, management practices, programs, and crop selection. These are the field practices identified in this research: no tillage, minimum tillage, strip or zone tillage, mulch and conservation tillage, land leveling, management of crop residue, and bench terraces. Each of these methods utilizes unique techniques to maintain water in the soil profile, to reduce water evaporation, to reduce water runoff, and to utilize the infiltration of rainfall.

The second section of conservation considered is the current irrigation systems. In eastern Colorado, where many consider irrigation a necessary requirement for successful farming, primarily the farmers use the center pivot systems. The conservation methods include use of a multi-functional irrigation system for fertigation and chemigation, the installation of low-pressure heads on drop tubes, to retrofit wells with smaller and more efficient pumps, the replacement of malfunctioning underground piping, and installation of low-pressure sprinkler packages such as MESA, LPIC, LESA, and LAPA. Other methods include the installation of a drip irrigation system, air injection into a drip system, to remove the end gun, and the installation of a remote or automated control system. These methods can reduce water usage by applying water at the right time, in the correct location, and with the appropriate pressure for each individual field's soils and conditions. Improvement of the irrigation systems requires applying water uniformly, using higher efficiency systems, and reducing water losses and energy.

The third section of conservation is the management practices used to conserve water. These practices include planting crops that use less water (i.e. drought tolerant crops), planting crops with a shorter growing season, using deficit irrigation throughout the season, use of deficit irrigation early in the season and fully irrigate later in the season, and ending the irrigation season earlier than is currently practiced. Other management practices include: scheduling irrigation based on crop requirements, monitoring system performance, incorporating a fallow period into the crop rotation, growing dry-land crops as part of the crop rotation, fallowing a portion of a formerly irrigated field, convert to non-irrigated crops, switching to cool season crops, and splitting pivots between crops that use irrigation at different times.

The fourth conservation methods are potential and existing programs possibly implemented in eastern Colorado. The existing programs are permanent voluntary well retirement, federal land retirement programs, voluntary conservation incentives, and financial incentive for conservation irrigation equipment upgrades. Potential programs used in other regions and concept idea programs are temporary well retirement, rotational fallow incentives, water use limits over certain period incentive, tax or payment incentive for ceasing to irrigate less productive land, and incentive for conservation to less water intensive crops.

The final section of the survey is crop selection that would be planting a lower water use crop to replace the corn predominantly grown on approximately 52% of all croplands in Yuma County. The lower water use crops, barley, oats, dry beans, hay millet, proso millet, sorghum grain, soybeans, Sudan grass for hay, sunflowers, perennial forage crops, and wheat, all are options to consider. Although each of these crops uses less water than corn, each of these crops has unique growing requirements needing consideration when choosing an appropriate crop for eastern Colorado. Also, the economics of producing these crops and the potential for income from these crops needs to be weighed carefully.

3.1.2 Survey Results

The total irrigated crops in Yuma County are 106,766 ha with a total harvest land of 169,917 ha. The operators of these farms are predominantly male (84%) at the average age of 56.0 (2007 Census of Agriculture 2009). The total cropland is out of the total land acreage of 282,504 ha. The main crop produced in Yuma County is corn for grain (52%) of all the crops produced on 89,096 ha. The second highest crop produced is wheat grain at 55,103 ha, then forage for 12,328 ha, dry edible beans with 4,727 ha, and proso millet with 4,612 ha (2007 Census of Agriculture 2009).

3.1.3 General Farm Information

Residences in Yuma County, predominately received the surveys because the project area is entirely in Yuma County. Although the public and open meetings invited all residences located throughout eastern Colorado, there was only a small representation of survey respondents from other counties. Figure 3.1 shows the respondent farm location according to each county in eastern Colorado.

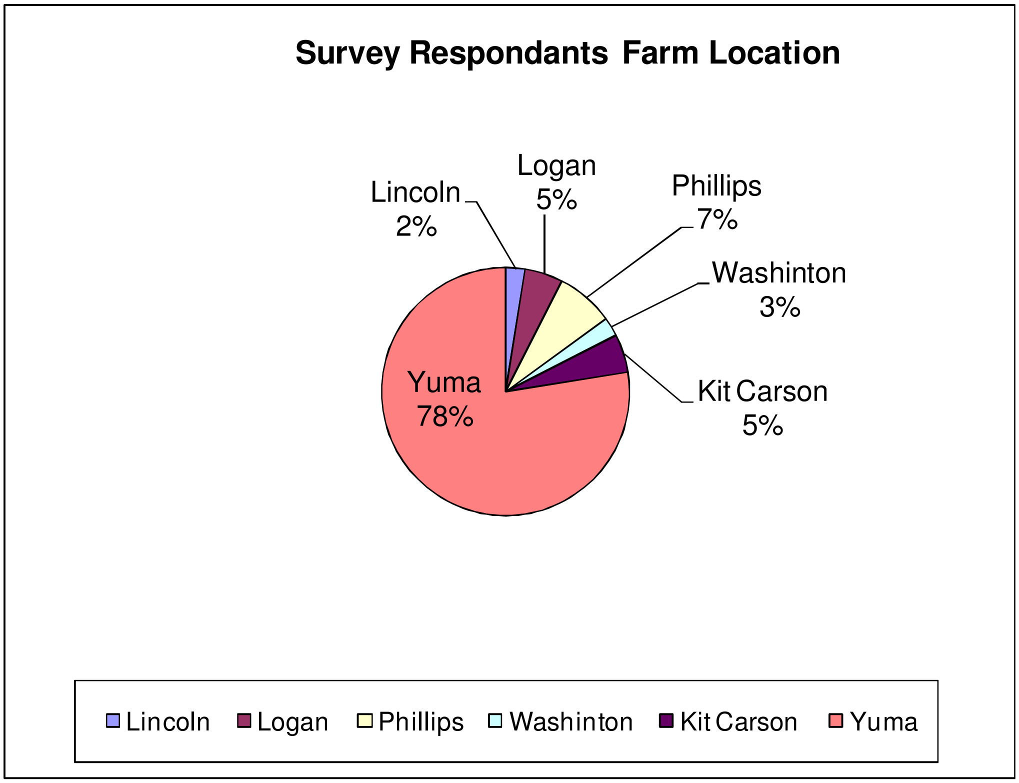


Figure 3.1: Survey Respondent Farm Location

The general farm information from the survey identified that the average farm size of survey respondents to be 1,304 ha, that was larger than the Yuma County average farm size. The 2007 Census of Agriculture (2009) found that 970 farms operation are in Yuma County with an average size of 557 ha and total land in farms is 540,046 ha. Figure 3.2 presents the frequency of farmland size histogram. The survey also requested that the farmers project their estimated 2009 irrigated land and crop breakdowns, which are shown in Figures 3.3, 3.4, 3.5, and 3.6. The highest projected irrigated crops for 2009 were corn at 74.5% and dry beans at 8.02%. The corn projections were 22.5% higher than the 2007 Census data that identified that only 52% of Yuma harvested land was corn (2007 Census of Agriculture 2009). This could be due to the higher average corn price of $0.19/kg for 2008 and $0.15/kg in 2009 when compared to 2006 and 2007 price of $0.09/kg and $0.13/kg, respectively (USDA National Agricultural Statistics Service 2010).

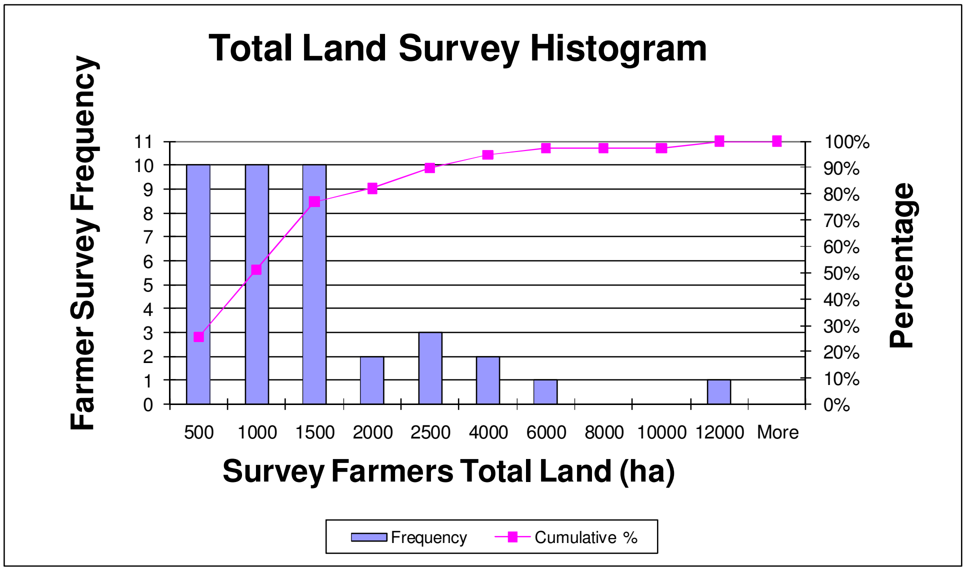


Figure 3.2: Survey Results of Total Land

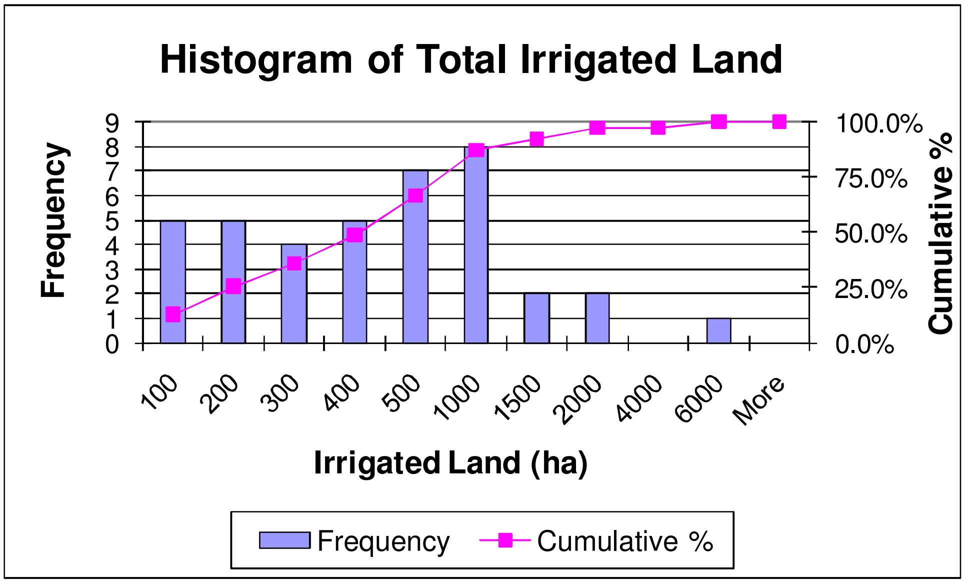


Figure 3.3: Total Irrigated Land by Survey Respondents

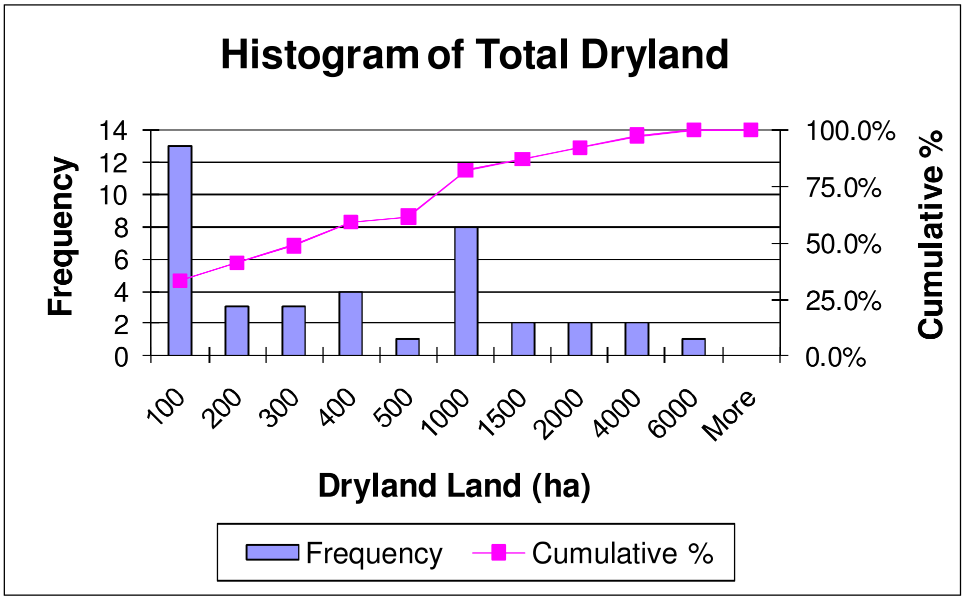


Figure 3.4: Total Dry Land by Survey Respondents

The survey requested that farmers' project estimated 2009 dry-land acreage and crop breakdowns, which Figures 3.5 and 3.6 shows. The highest projected dry-land crops for 2009 were wheat at 47.2% and grass hay/pasture at 17.1%. The dry-land corn projection of 10.1% was very similar to the 2007 Yuma County dry-land corn of 10.9% (2007 Census of Agriculture 2009).

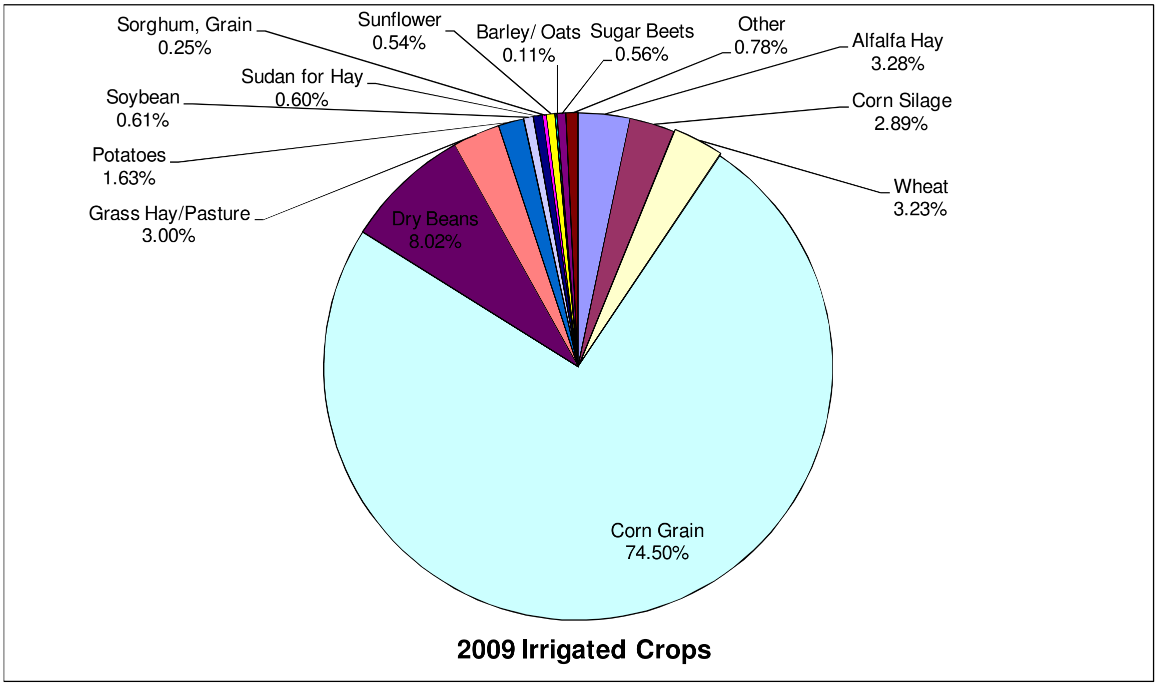


Figure 3.5: Survey Projected 2009 Irrigated Crops

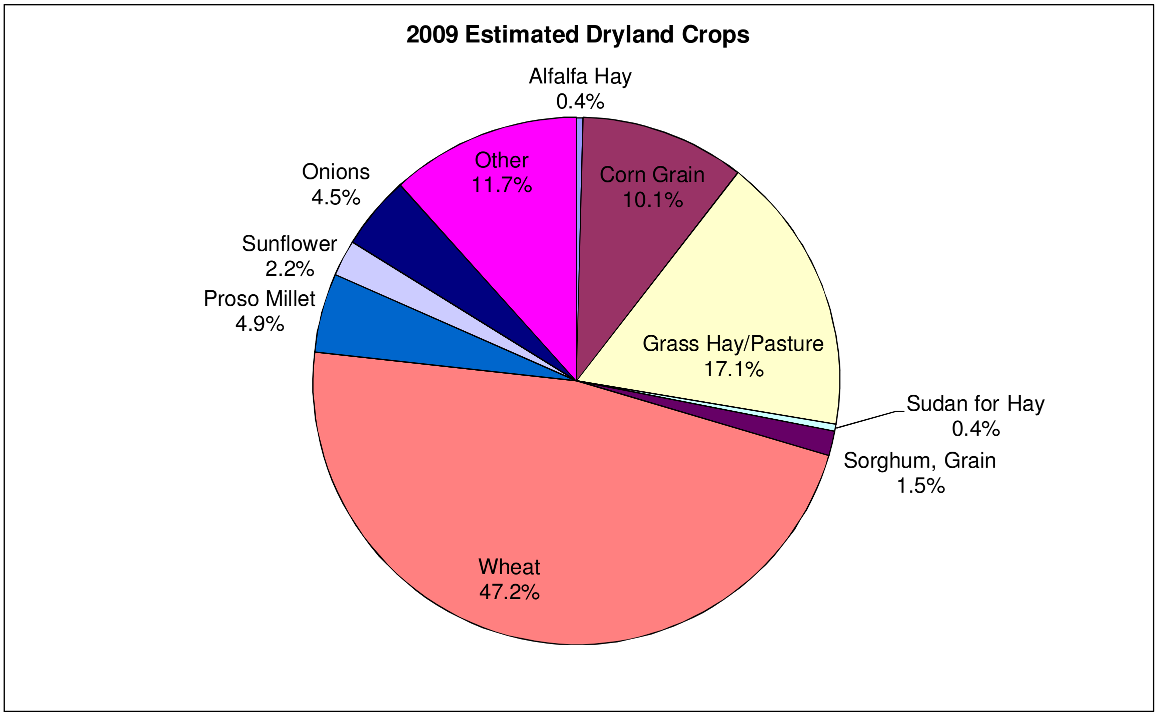


Figure 3.6: Survey Identified 2009 Dry-land Crop

The survey asked respondents: "Colorado farmers may have to reduce irrigation supplies as part of compact compliance, drought conditions, and where well capacity cannot meet crop water requirements. How many cm of water could you voluntarily reduce pumping from your well?" The responses indicated a range of voluntary reduction from 1.3 to 91.3 cm with an average reduction of 16.3 cm. Figure 3.7 shows the frequency of responses to possible water reductions.

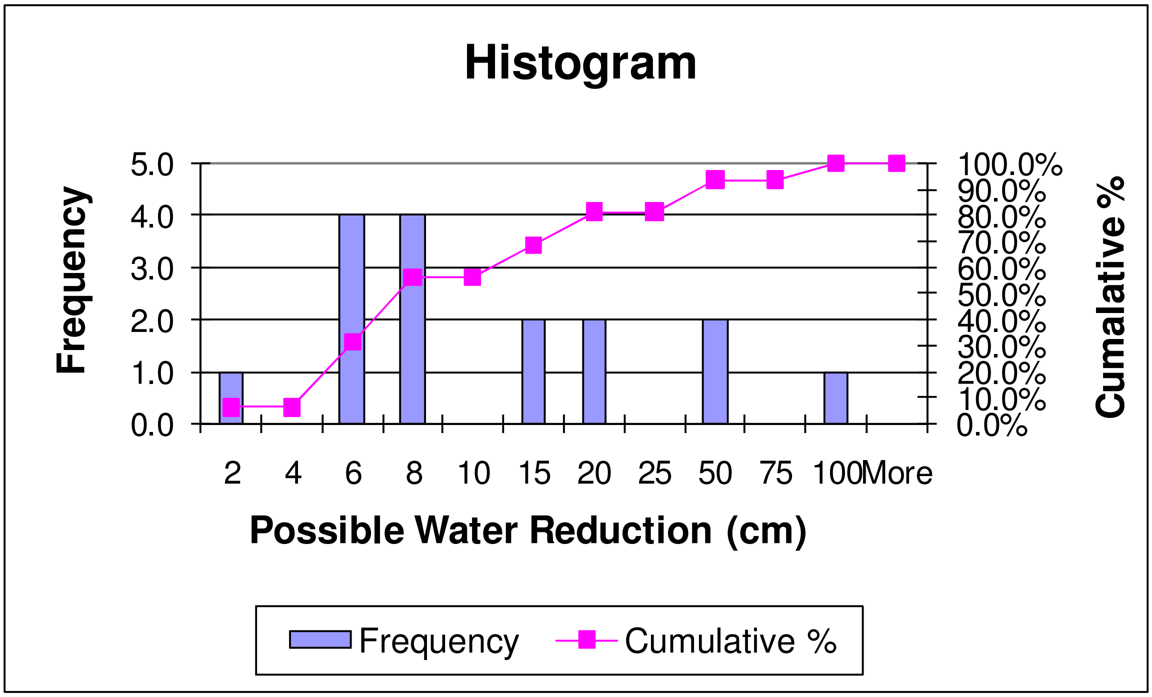


Figure 3.7: Survey Identified Potential Water Reduction if Required

3.1.4 Farm Demographics

The farm demographics characterize the survey respondents (farmers) by the type of operator, age, gross income, education, and income due to irrigation. The majority of respondents were owner/operators (85%). The next group was the absentee owners at 7% as shown in Figure 3.8. Distribution of the respondents' ages was very even as shown in Figure 3.9. The largest age bracket among respondents was ages 61 to 70 years old at 32%. The next bracket was those who are 51 to 60 years old at 24%.

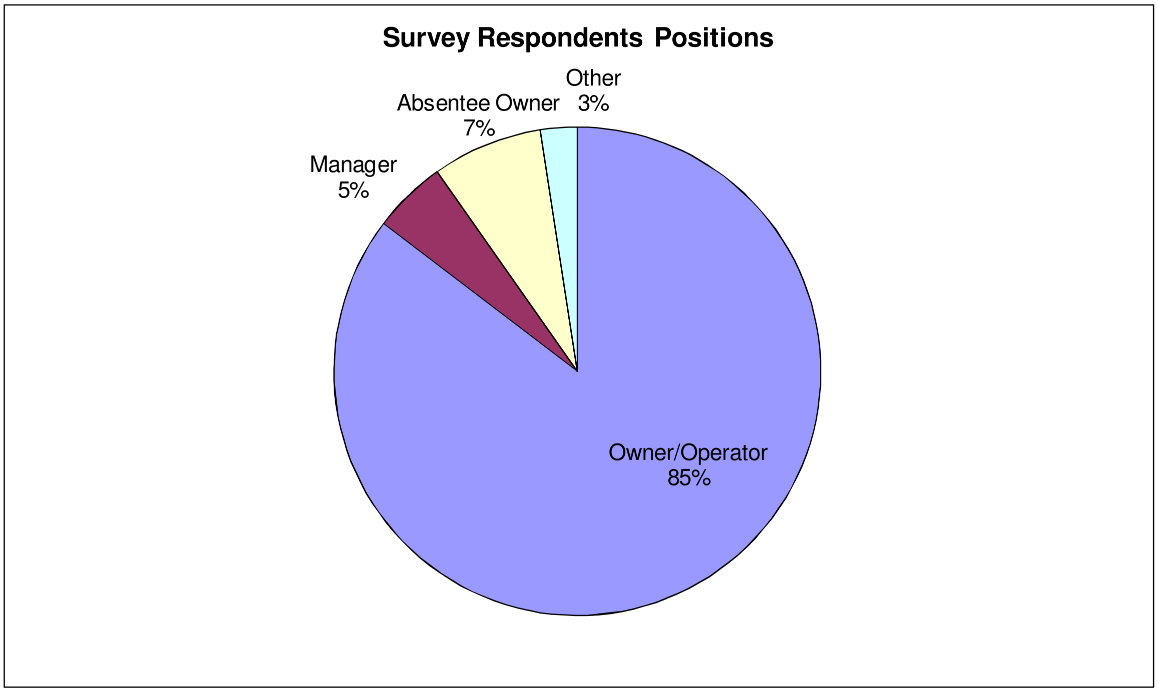


Figure 3.8: Survey Respondent Positions

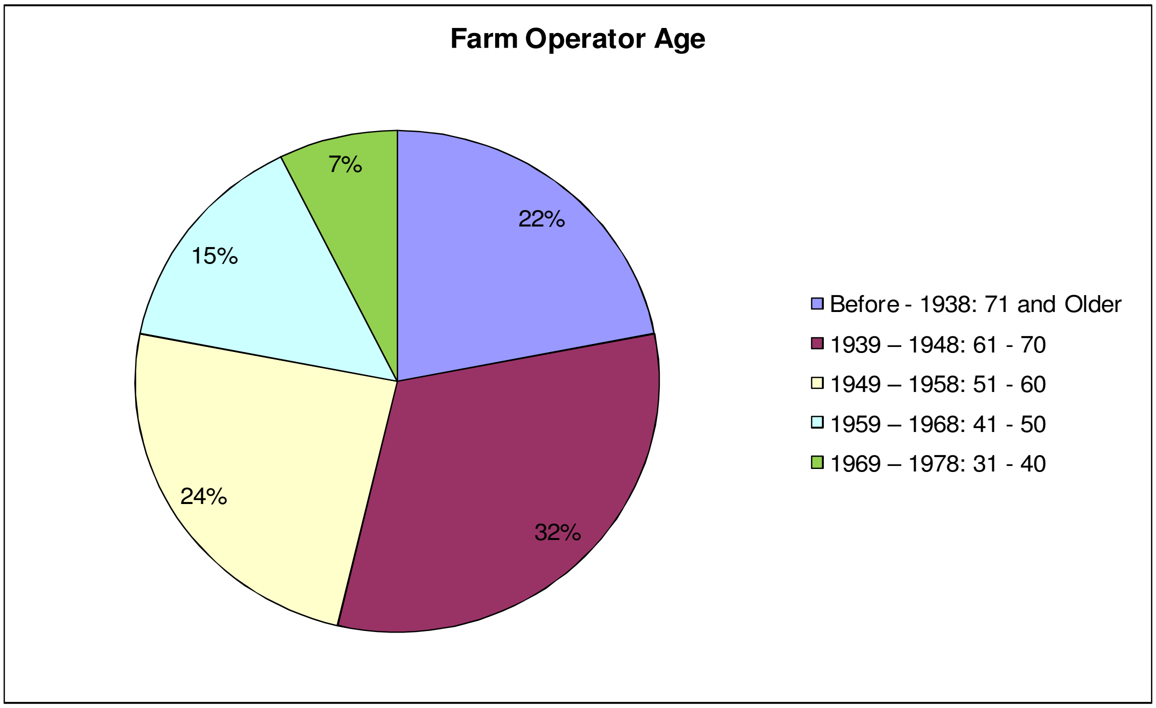


Figure 3.9: Survey Respondent Age

The educational level of respondents varied with the bachelor's degree at the highest percentage of 38% as shown in Figure 3.10. Note that 71% of the respondents had some post-secondary experience as compared to 29% who had no further education beyond high school. These education results imply that the more educated farmers is more likely to respond to surveys. The results could also be bias towards farmers with higher education levels, which could correspond to higher potential implementation of conservation alternatives.

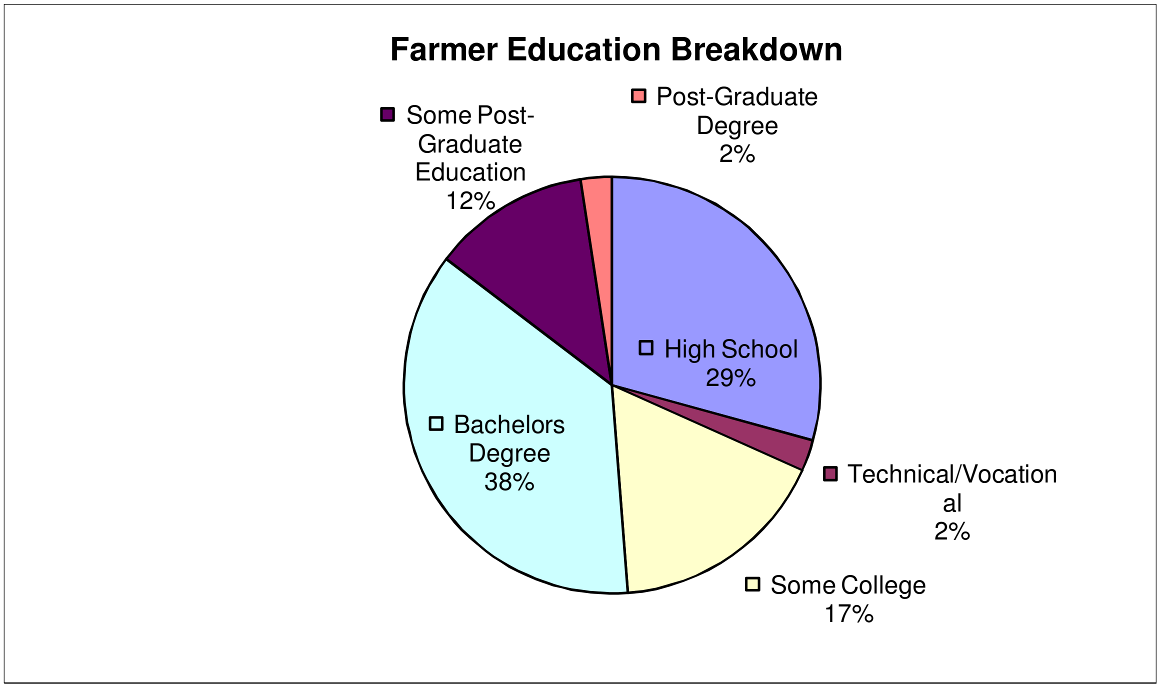


Figure 3.10: Survey Respondent Education

The survey respondents reported that 32% have an annual gross income of $500,000 to $1,000,000 while 28% have a gross income of $1,000,000 to $5,000,000. Figure 3.11 shows the annual gross income of eastern Colorado farmers. These results showed that higher gross income ($500,000 to $5,000,000) farmers were more likely to fill out the survey. The higher response rate among the higher gross income farmer could be due to the availability of more time to fill out the survey, that they have more stake invested in continued access to water and irrigated farming, and possibly have more progressive attitudes about preserving agriculture. The survey respondents showed that on average, irrigated agriculture represented approximately 69% of the gross income with a range from 10% to 100%. Figure 3.12 illustrates the distribution of the income from irrigation.

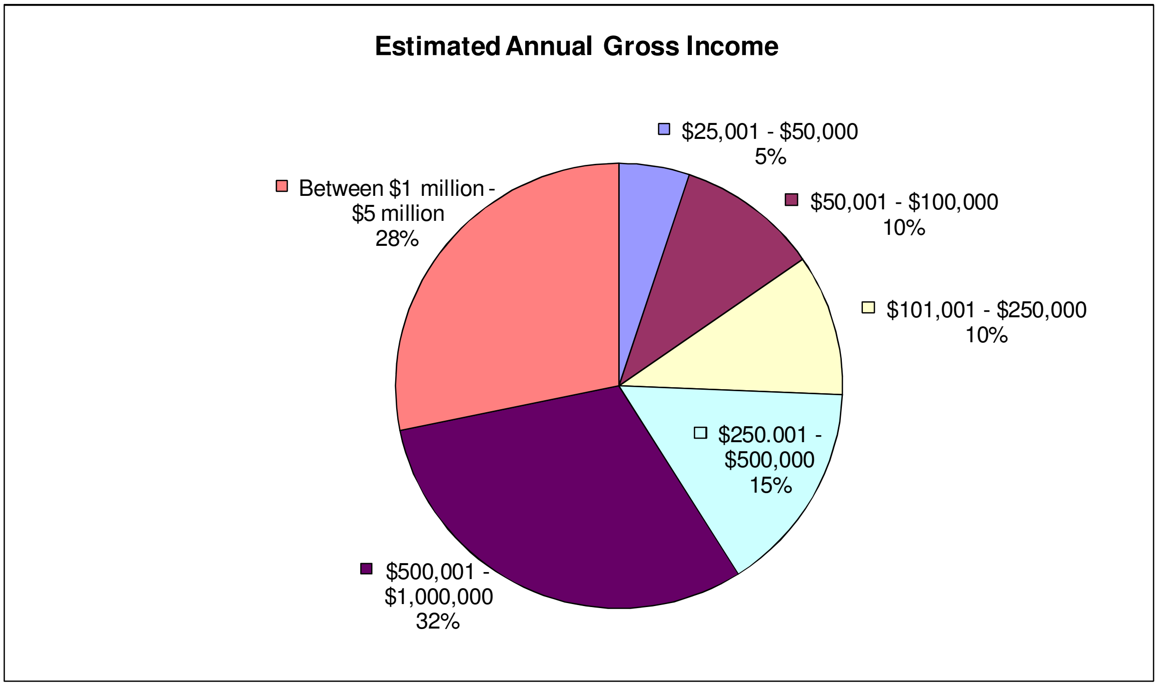


Figure 3.11: Survey Respondent Annual Gross Income

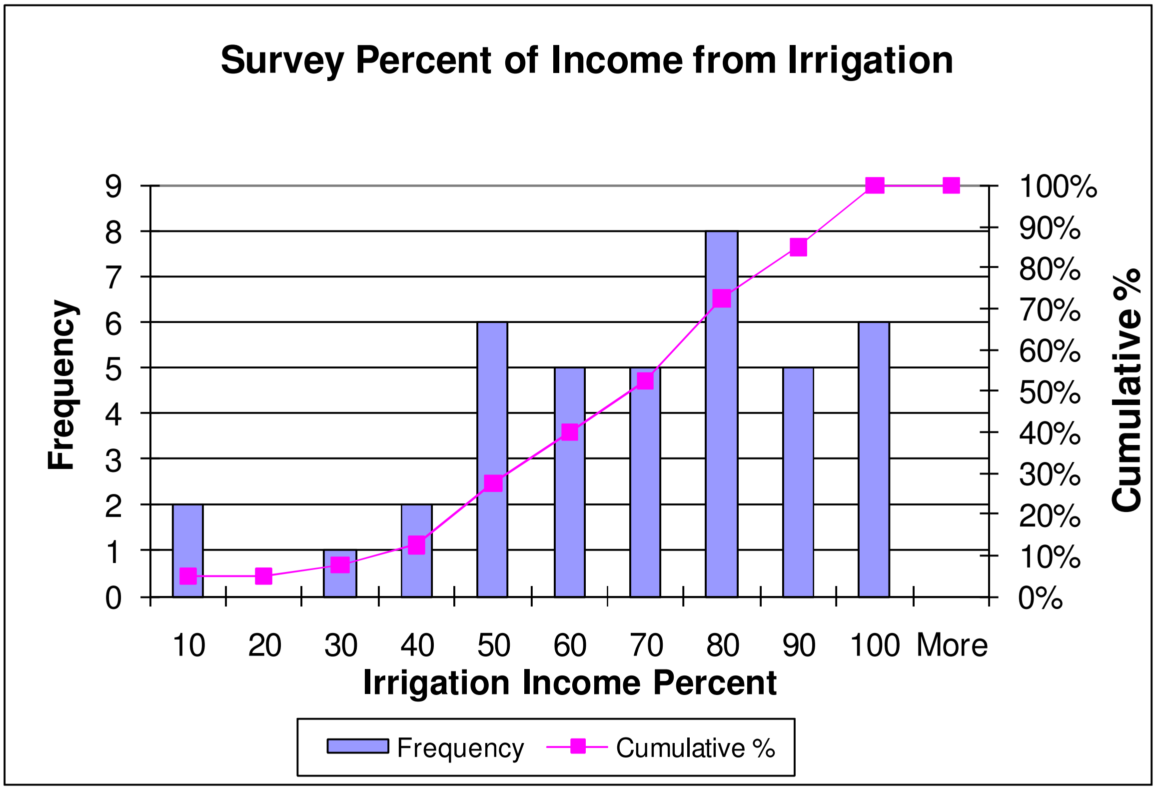


Figure 3.12: Survey Respondent Gross Income from Irrigated Agriculture

3.1.5 Survey Conservation Methods

The results of these sections of the survey are of key importance to implementing feasible water conservation practices that will be manageable for farmers in eastern Colorado. It is in the long-term interests of eastern Colorado for the agricultural community to take a proactive approach to reducing water usage so that this precious resource is available for future agricultural production and for sustaining the local river systems. The results of the surveys have identified water conservation techniques and methods that farmers in eastern Colorado could implement practically on their individual farms. Using a relative importance, the researcher compiled the top three ranked survey conservation alternatives from each section. The relative importance combines the frequency of an identified practice and the ranking of that practice. The rank of the conservation practices (1, 2, and 3) as identified by survey responses recognized their preferred conservation alternatives. The benefit of using relative importance values is the ability to compare the respondents' responses and the significance of their answers (Leuschner et al. 1988). The relative importance provides users with a better qualitative understanding of the distance between response items. The relative importance provides an understandable interpretation of the importance respondents place on an item that remains correct regardless of varying response rates for each item (Leuschner et al. 1988). The sum of all relative importance values should be equal to 100. The formula for calculating relative's importance is given in Equation 3.1.

$$\mathrm{RI} = \frac{\sum_{i=1}^{m} * \sum_{k-1}^{N} \omega_{ijk}}{\sum_{i=1}^{m} * \sum_{j=1}^{n} * \sum_{k-1}^{N} \omega_{ijk}} * 100 \quad \text{(Leuschner et al. 1988)} \quad (3.1)$$

Where: ω_{ijk} = weight for rank I assigned to item j by respondent k
= 0 if items j is unranked
= m-i-1 if item j has rank i
i = 1, ….m, number of ranks requested
k = 1, ….N, number of respondents to the question

Within each section, the survey asked respondents if the conservation practices were in use in order to identify possibility of improved participation for each conservation practice. If the practice was not in use, then the respondents needed to explain why not. These were the answers received: reduced profits too much, do not have the funds to implement this practice, do not know how to implement this practice, the farm's soils are not compatible with this practice, and a lack of the equipment needed to execute this practice. The final question for each conservation practice was to identify the top three most likely practices that the farmer would implement in the next five years.

3.1.5.1 Field Practices

The results of the field practice section identified that approximately 50% of the respondents already use no-tillage, minimum tillage, strip tillage, mulch tillage, and/or crop residue management. The survey respondents currently using conservation field practices are in Table 3.1. These responses indicate that the farmers are seeking methods of conserving water and are conscientious in their field practices. The survey showed that the main reason for not currently using no-tillage, minimum tillage, and strip tillage was due to lack of the equipment to carry out the practice with 42.1%, 21.1%, and 47.4%, respectively. These results suggest that additional programs or assistance of purchasing equipment could increase water conservation field practices. The field practices sections of the survey identified the three most preferred field practices to consider implementation. Those three field practices with the highest relative importance are no tillage (27.97), minimum tillage (23.78), and strip or zonal tillage (23.08) as shown in Table 3.2.

Table 3.1: Field Practices Currently Used by Survey Respondents (%)

No Tillage	48.7%
Minimum Tillage	51.4%
Strip Tillage or Zone Tillage	54.1%
Mulch Tillage or Other Conservation Tillage	48.7%
Land Leveling	2.7%
Manage Crop Residue/Tillage to Reduce Evaporation	56.8%
Build Conservation Bench Terraces	5.4%

Table 3.2: Top Field Practices Identified in Survey and Relative Importance (RI)

No Tillage	27.97
Minimum Tillage	23.78
Strip Tillage or Zone Tillage	23.08
Mulch Tillage or Other Conservation Tillage	4.20
Land Leveling	0.70
Manage Crop Residue/Tillage to Reduce Evaporation	16.08
Build Conservation Bench Terraces	4.20

3.1.5.2 Irrigation System Information

The results of the irrigation system information section identified that many farmers have already performed water conservation measures on their irrigation systems. Table 3.3 shows the breakdown of the use of conservation measures. The percentage total is not 100% since farmers were to check all that apply. Note that only 26% of the respondents used remote and automated control systems. This conservation measure could have significant water savings throughout the basin; therefore, there should be an increased awareness of the participation rate of this practice. These responses would indicate that farmers are seeking methods of conserving water and are being conscientious in their application of water and use of their irrigation systems. 37% of all respondents made obvious the main reason for not installing water conservation irrigation equipment is lack of funds to implement the practice. The survey identified the top irrigation practices with the highest relative importance that can conserve water are using a multi-function irrigation system (16.79), retrofit well with smaller or more efficient pump or motor (13.87), installation of drip irrigation (13.14), and low pressure sprinkler packages (13.14) as shown in Table 3.4. The relative importance values are close together indicating that there was not a clear preference for a particular irrigation system upgrade. These closely ranked results are most likely due to the farmers' existing irrigation equipment, the crops grown, and the soil types.

Table 3.3: Irrigation Conservation Measures Being Practices in Yuma County (%)

Use Multi-function Irrigation System	71.1%
Install Low Pressure Heads on Drop Tubes	84.2%
Retrofit Well with Smaller or More Efficient Pump	52.6%
Replace Old or Leaking Underground Pipe	42.1%
Low Pressure Sprinkler Packages (MESA, LPIC, LESA, and LEPA)	60.5%
Use Drip Irrigation	2.6%
Recover Water from Air Injection in Drip Systems	5.3%
Remove End Gun	68.4%
Remote and Automated Control Systems	26.3%

Table 3.4: Top Irrigation System Practices Identified in Survey and Relative Importance (RI)

Use Multi-function Irrigation System	16.79
Install Low Pressure Heads on Drop Tubes	10.95
Retrofit Well with Smaller or More Efficient Pump	13.87
Replace Old or Leaking Underground Pipe	2.92
Low Pressure Sprinkler Packages (MESA, LPIC, LESA, and LEPA)	13.14
Use Drip Irrigation	13.14
Recover Water from Air Injection in Drip Systems	7.30
Remove End Gun	9.49
Remote and Automated Control Systems	12.41

3.1.5.3 Management Practices

The management practices section identified that many farmers are already using water conservation management practices. Table 3.5 shows the breakdown of the use of each conservation measure. These responses indicate that farmers are in search of methods to conserve water and are being careful in their application of water. The survey demonstrates that the main reason for not performing some management practices is that the practice reduces profits per acre too much. The survey identified the management practices that can conserve water are planting crops that use less water, i.e. drought tolerant crops (26.61), planting crops with a shorter growing season (9.70), and reducing irrigation early in season but fully irrigating later in the season (9.70) as shown in Table 3.6. The relative importance of drought tolerant crops was strongly preferred over other management practices.

Table 3.5: Management Practices Currently in Use by Respondents (%)

Plant Crops That Use Less Water or Drought Tolerant Crops	52.8%
Plant Crops with Shorter Growing Season	55.6%
Reduce Irrigation (Deficit Irrigate) Throughout the Season	27.8%
Reduce Irrigation Early in the Season, but Irrigate Fully Later in the Season	44.4%
End the Irrigation Season Earlier than Usual	36.1%
Schedule Irrigation Based on Crop Requirement (Monitor Soil Moisture, Rainfall, ET)	75.0%
Schedule Irrigation Based on Crop Requirements (Crop Consultant)	69.4%
System Performance (Well Water Meter, Routinely Checking Pumping Efficiency)	58.3%
Incorporate a Fallow Period into the Crop Rotation	16.7%
Grow a Dry-land Crop as Part of a Crop Rotation that Includes Irrigated Crops	16.7%
Fallow a Portion of a Formerly Irrigated Field and Fully Irrigate the Remainder	11.1%
Convert to a Non-Irrigated Crop or Pasture	11.1%
Switch to Cool Season Crops (e.g. Wheat)	36.1%
Splitting Pivots Between Crops that Use Irrigation at Different Times	41.7%

Table 3.6: Top Management Practices Identified by Respondents (RI)

Plant Crops That Use Less Water or Drought Tolerant Crops	27.61
Plant Crops with Shorter Growing Season	9.70
Reduce Irrigation (Deficit Irrigate) Throughout the Season	6.72
Reduce Irrigation Early in the Season, but Irrigate Fully Later in the Season	9.70
End the Irrigation Season Earlier than Usual	1.49
Schedule Irrigation Based on Crop Requirement (Monitor Soil Moisture, Rainfall, ET)	8.96
Schedule Irrigation Based on Crop Requirements (Crop Consultant)	8.21
System Performance (Well Water Meter, Routinely Checking Pumping Efficiency)	8.21
Incorporate a Fallow Period into the Crop Rotation	3.73
Grow a Dry-land Crop as Part of a Crop Rotation that Includes Irrigated Crops	2.24
Fallow a Portion of a Formerly Irrigated Field and Fully Irrigate the Remainder	2.99
Convert to a Non-Irrigated Crop or Pasture	3.73
Switch to Cool Season Crops (e.g. Wheat)	3.73
Splitting Pivots Between Crops that Use Irrigation at Different Times	2.99

3.1.5.4 Water Conservation Programs

The results of the programs section documented that many farmers currently participate in water conservation programs. Table 3.7 shows the breakdown of the participation in the conservation programs. Observe that the programs with 0% participation are not programs currently in operation in Yuma County; however, they have been implemented in other states and groundwater districts. These responses would indicate that farmers are seeking methods of conserving water and participating in programs to upgrade equipment. The most preferred programs currently participated in are the voluntary conservation incentive to implement conservation practices. The highest number of responses in indicated that the respondents are willing to participate in both water use limits and incentives to convert to a less water use crop as shown in Table 3.8. The survey identified the top relative importance programs that can conserve water are an incentive for conversion to less water intensive crop (25.00), an incentive for water use limits over certain period (16.18), and a rotational fallow incentive (14.71) as shown in Table 3.9. The results indicate the most preferred program is an incentive to convert to a less water intensive crop. State agencies and the natural resources community will greatly benefit from this knowledge gathered regarding the conservation programs and those most preferred by producers.

Table 3.7: Programs Currently Participating by Respondent (%)

Permanent Voluntary Retirement of Irrigation Well	11.1%
Temporary Well Retirement Program (3, 5, 10, or 15 years)	3.7%
Rotational Fallow Incentive	0.0%
Federal Land Retirement Program (e.g., CRP, CREP, WRP, GRP)	7.4%
Voluntary Conservation Incentives to Implement Conservation Practices	33.3%
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	0.0%
Financial Incentives for Conservation Irrigation Equipment Upgrades	22.2%
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dry-land Farming or Environmental Easements	0.0%
Incentive for Conversion to Less Water Intensive Crop	14.8%
Other	7.4%

Table 3.8: Programs Respondents Would be Willing to Participate In (%)

Permanent Voluntary Retirement of Irrigation Well	10.0%
Temporary Well Retirement Program-Varied Period (3, 5, 10, or 15 years)	14.3%
Rotational Fallow Incentive	10.0%
Federal Land Retirement Program (e.g., CRP, CREP, WRP, GRP)	8.6%
Voluntary Conservation Incentives to Implement Conservation Practices - (e.g. EQIP and CSP)	8.6%
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	11.4%
Financial Incentives for Conservation Irrigation Equipment Upgrades	12.9%
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dry-land Farming or Environmental Easements	8.6%
Incentive for Conversion to Less Water Intensive Crop	14.3%
Other (Listed Above)	1.4%

Table 3.9: Programs Relative Importance of Responses

Permanent Voluntary Retirement of Irrigation Well	11.76
Temporary Well Retirement Program-Varied Period (3, 5, 10, or 15 years)	10.29
Rotational Fallow Incentive	14.71
Federal Land Retirement Program (e.g., CRP, CREP, WRP, GRP)	4.41
Voluntary Conservation Incentives to Implement Conservation Practices - (e.g. EQIP and CSP)	4.41
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	16.18
Financial Incentives for Conservation Irrigation Equipment Upgrades	8.82
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dry-land Farming or Environmental Easements	4.41
Incentive for Conversion to Less Water Intensive Crop	25.00

In addition to the preferred program identified, the survey asked respondents about minimum payment to participate and the percentage of the land possibly installed in the program. This section of the survey had very little participation with only six respondents that reduces the accuracy of these responses. It was also observed that some respondents' minimum payments were exceedingly high that increased averages as shown in Table 3.10. The same respondents also would commit 100% of their land to the noted programs that indicates the respondents could be retiring or providing false data. The outlier data eliminated from the minimum program payment was $3,000 since this value was 10 times the next minimum payment. The outlier data for the maximum percent of irrigated land committed to the eliminated program were values of 100%. The purpose of these program payments and questions are to incentive the conversion to reduce irrigation practices and crops, but not forcing farmers to retire. These responses could provide inaccurate information for this research as shown in Table 3.10 and 3.11 without the outliers.

Table 3.10: Respondents Average Minimum Payment for Program ($/Acre/year)

Programs	Average All Data	Average Without Outliers
Permanent Voluntary Retirement of Irrigation Well	$1,200	$300
Temporary Well Retirement Program (3, 5, 10, or 15 years)	$780	$225
Rotational Fallow Incentive	$200	$200
Federal Land Retirement Program (e.g., CRP, CREP, WRP, GRP)	$1,125	$188
Voluntary Conservation Incentives to Implement Conservation Practices	NR	NR
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	$92	$92
Financial Incentives for Conservation Irrigation Equipment Upgrades	$10	$10
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dry-land Farming or Environmental Easements	$125	$125
Incentive for Conversion to Less Water Intensive Crop	$75	$75

NR – No Response

Table 3.11: Respondents Maximum Percent of Irrigated Land Committed to Program (%)

Programs	Average All Data	Average Without Outliers
Permanent Voluntary Retirement of Irrigation Well	72%	15%
Temporary Well Retirement Program (3, 5, 10, or 15 years)	50%	37.5%
Rotational Fallow Incentive	50%	25%
Federal Land Retirement Program (e.g., CRP, CREP, WRP, GRP)	55%	10%
Voluntary Conservation Incentives to Implement Conservation Practices	NR	NR
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	67%	50%
Financial Incentives for Conservation Irrigation Equipment Upgrades	100%	NR
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dry-land Farming or Environmental Easements	25%	25%
Incentive for Conversion to Less Water Intensive Crop	75%	50%

3.1.5.5 Crop Selection

The crop selection section illustrated that many farmers would be willing to plant lower water use crops. Table 3.12 shows the breakdown of possible crops that respondents are willing to plant. The main reason for not planting lower water intensive crops was that these crops were not profitable enough. The survey identified the top relative importance crops for conversion as winter wheat (23.66), dry beans (23.66), and soybeans (17.56) as shown in Table 3.13.

Table 3.12: Respondents Willing to Plant this Crops (%)

Barley/Oats	37.14%
Beans, Dry	54.29%
Hay Millet	51.43%
Proso Millet	40.00%
Sorghum, Grain	25.71%
Soybeans	54.29%
Sudan for Hay	48.57%
Sunflowers	57.14%
Irrigated Wheat, Winter	82.86%
Irrigated Wheat/Barley, Spring	22.86%
Perennial Forage Crops	25.71%
Other (Please List)	2.86%

Table 3.13: Top Lower Water Use Crops Identified by Respondents (RI)

Barley/Oats	5.34
Beans, Dry	23.66
Hay Millet	5.34
Proso Millet	5.34
Sorghum, Grain	4.58
Soybeans	17.56
Sudan for Hay	1.53
Sunflowers	9.92
Irrigated Wheat, Winter	23.66
Irrigated Wheat/Barley, Spring	1.53
Perennial Forage Crops	0
Other (Please List)	1.53

CHAPTER 4 HIGH PLAINS AQUIFER AND ARIKAREE RIVER ALLUVIAL MODEL: WATER BALANCE

A water balance model was developed for the Arikaree River to compare pre-development (before pumping), post-development (after pumping), and future conditions. Base flows from groundwater and storm events supplied by the Arikaree River maintain habitat pools. As a groundwater derived stream, water level elevation in the surrounding High Plains Aquifer control the base flows into the Arikaree River. The interaction between the Arikaree River alluvium and the High Plains Aquifer has changed over time from a system in equilibrium (prior to irrigation pumping) to a system with declining water levels. The previous research completed in the region has provided a general understanding of the interaction of the system as shown in Figure 4.1.

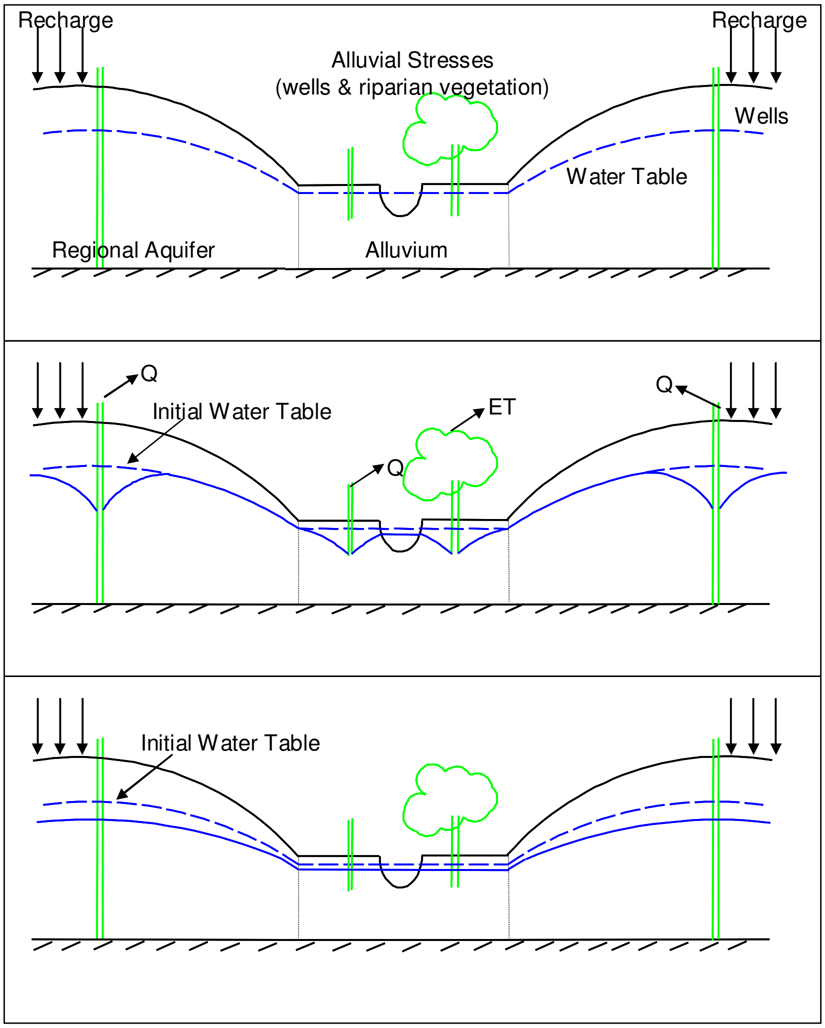


Figure 4.1: Conceptualization of the High Plains Aquifer and the Alluvial Aquifer at the Beginning of the Season, During the Season, and at the Beginning of the Following Season Before Pumping and Evapotranspiration Begins (Squires 2007).

When precipitation falls on the dune sands in the area, a portion recharges the High Plains aquifer. Eventually, the groundwater flows to the alluvial aquifer and then discharges to the river. Along that path, water is lost from the subsurface to the atmosphere through evapotranspiration, particularly in the riparian corridor along the Arikaree River where the water table is closest to the land surface. Figure 4.2 show a schematic diagram of the dynamics in the regional aquifer and the alluvium.

The High Plains aquifer and the alluvial aquifer affect the river on different time scales. The withdrawals from the High Plains aquifer affect the river annually while withdrawals from the alluvial aquifer due to irrigation pumping and riparian use affect the river daily throughout the growing season in a similar pattern as shown in Figure 4.2. The radius of influence of the wells pumping from the High Plains aquifer does not intersect the river during one pumping season (Squires, 2007). The cone of depression of these wells fills in by a change in storage in the High Plains aquifer.

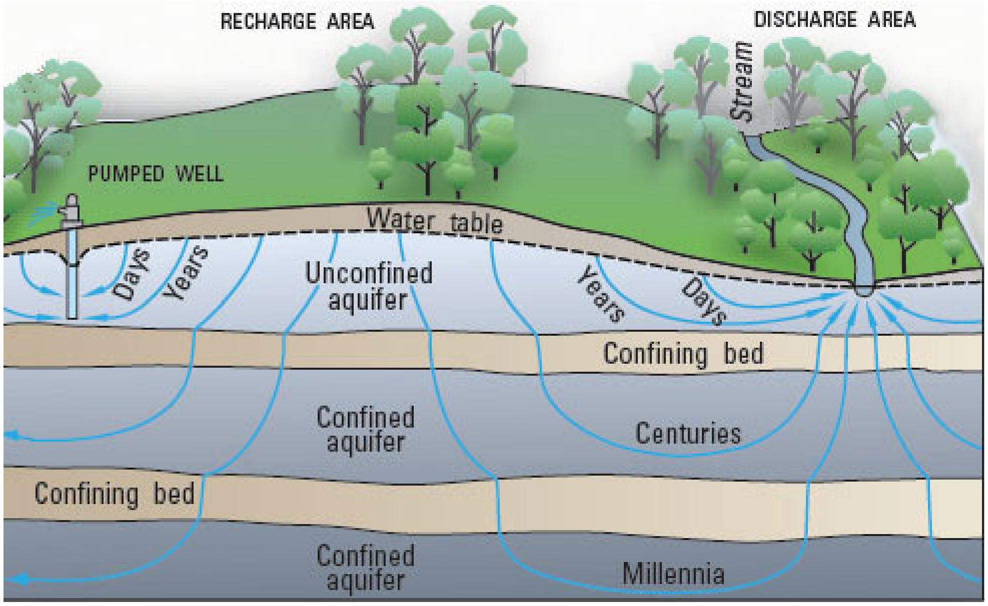


Figure 4.2: Schematic Diagram of Groundwater Flow Timeline (USGS 2010)

This change in storage causes a relatively constant decline in the High Plains aquifer water table elevation from year to year. As the High Plains aquifer water table elevation declines, there is less groundwater flux from the High Plains aquifer to the alluvial aquifer. This reduction in groundwater flux causes a deficit water balance in the alluvium that reduces the alluvial water table elevation and river stage at the beginning of each season in comparison to the elevations at the beginning of the previous season. The dramatic reduction in the alluvium water table and river stage of the annual river discharge shows in Figure 1.6. Alluvial stresses such as riparian evapotranspiration and pumping from the alluvium affect the river throughout the growing season. Fluctuations in the river stage are a result of alluvial stresses and precipitation events only. The water table elevation in the alluvium is lower than the water table elevation in the regional aquifer. The dune sand recharge areas in the High Plains aquifer maintain this head difference.

4.1 MODEL DEVELOPMENT

This water balance does not account for spatial and temporal variability in parameters such as recharge, evapotranspiration, and pumping, but provides the initial step in understanding and modeling of the aquifer and river hydrologic system.

4.1.1 Water Balance Model

The western boundary is the County line between Yuma County and Washington County and the eastern boundary is the border between Colorado and Kansas. The north and south boundaries constitute the groundwater divide as shown in Figure 4.3. The data used in the development of the model were bedrock elevations, groundwater contour maps, and geological data from Weist (1964). Based on geological data, Weist (1964) represented the groundwater flux from the regional High Plains aquifer to the alluvium by a flux boundary specified along the north and south edges of the alluvium.

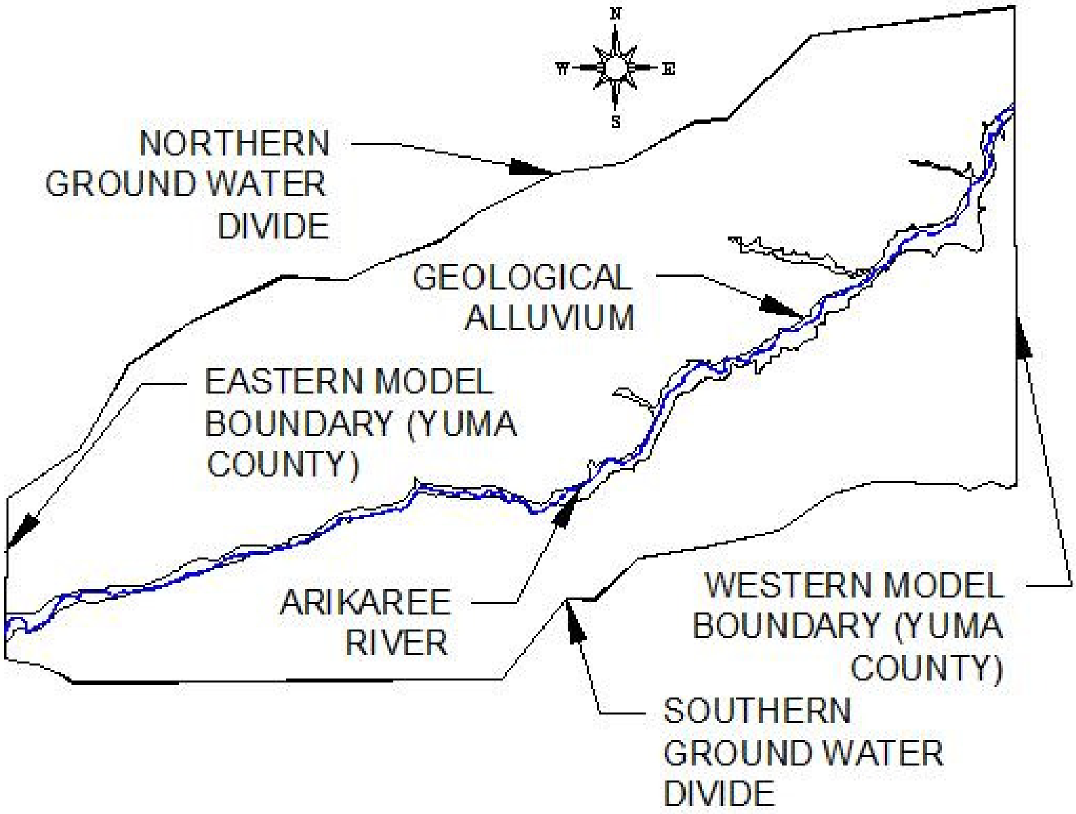


Figure 4.3: Water Balance Boundaries

4.1.1.1 Model Inputs

The model is broken into three distinctive model areas that include the regional High Plains aquifer, the alluvium model, and a complete model combining the High Plains aquifer and alluvium. Figure 4.4 and 4.5 illustrate schematically the inputs and outputs of the modeled regions.

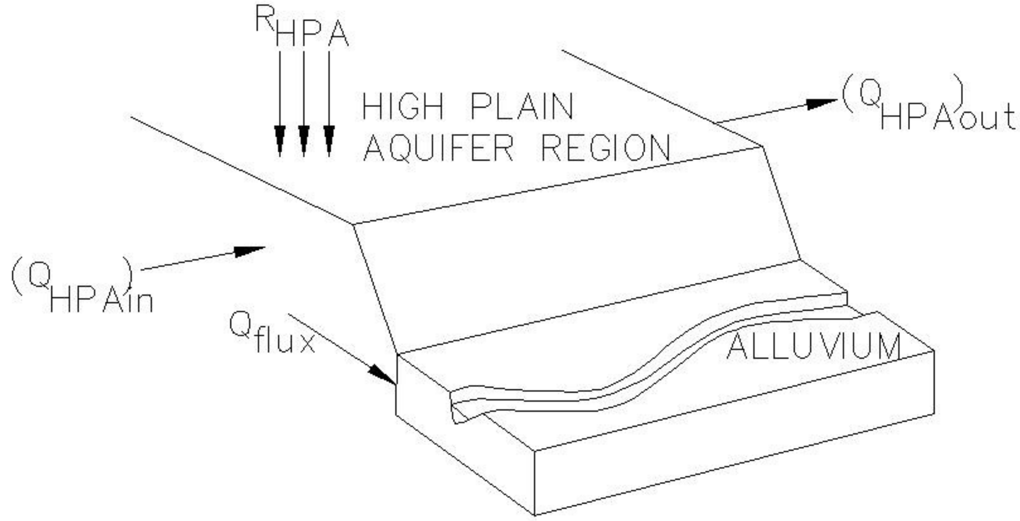


Figure 4.4: High Plains Aquifer Region Model Inputs and Outputs

The inputs for the regional High Plains aquifer model are groundwater flow from the western boundary, $(Q_{HPA})_{in}$, into the High Plains aquifer model boundary. The other inputs would recharge across the entire High Plains aquifer model area. The outputs from the model are groundwater flows out of the eastern High Plains aquifer model boundary into Kansas, $(Q_{HPA})_{out}$, groundwater flow from High Plains aquifer into the alluvial aquifer, Q_{flux}, and wells pumping from the alluvium, $(Q_w)_{HPA}$.

The inputs for the alluvium aquifer model are flows from the regional High Plains aquifer to the alluvial aquifer, Q_{flux}, inflow from the up gradient alluvium at the eastern boundary, $(Q_{alluv})_{in}$, river inflow on the eastern boundary, SF_{in}, and recharge R_{alluv}. The outputs are river outflow at the western boundary, SF_{out}, alluvial groundwater flow leaving the study area on the eastern boundary, $(Q_{alluv})_{out}$, riparian and grass evapotranspiration, ET, and wells pumping from the alluvium, $(Q_w)_{alluv}$.

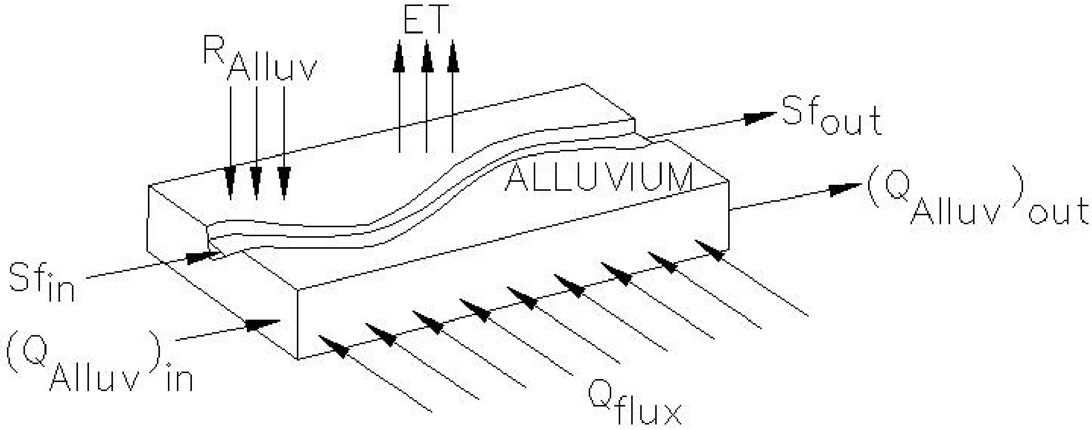


Figure 4.5: Alluvial Aquifer Inputs for Water Balance

Initial values for initial model setup were determined from available data and the calibrated regional model developed by Squires (2007), and (R. Magelky, personal communication, April 2009). Throughout the project, as the water balance was analyzed and the transient model calibration performed, these initial parameter estimates changed. Tables 4.1 and 4.2 shows the pre-development model parameters used before pumping began in the High Plains aquifer and alluvial aquifer with their respective data sources.

Table 4.1: Pre-development Inputs and Outputs to the Alluvial Groundwater Model

Parameter	Notation	Data Source	Units
Stream inflow	SF_{in}	10% of USGS gauging station #6821360-Arikaree River at Haigler,NE	m^3/yr
Stream outflow	SF_{out}	USGS gauging station #6821360-Arikaree River at Haigler, NE	m^3/yr
Inflow from up gradient alluvium	$(Q_{alluv})_{in}$	1958 Head Contour Map (Weist 1964)	m^3/yr
Outflow to down gradient alluvium	$(Q_{alluv})_{out}$	1958 Head Contour Map (Weist 1964)	m^3/yr
Flow into the alluvium from the HPA	Q_{flux}	Estimated from the pre-development regional model	m^3/yr
Riparian Evapotranspiration	ET_R	Average Seasonal ET of 89.2 cm from Riley (2009)	m^3/yr
Grass Evapotranspiration	ET_G	Calibration parameter	m^3/yr
Recharge to the alluvium	R_{alluv}	≈15% of precipitation (Willard Owens Consultants 1988; Squires 2007)	m^3/yr

Stream inflow was assumed to be 10% of the average stream flow data measured at USGS gauging station #6821360 (Haigler, NE) from 1933 to 1960. Squires (2009) established the estimated inflow 10% from previous research. Stream outflow was the average stream flow data measured at USGS gauging station #6821360 (Haigler, NE) (Squires, 2007). The constant flux boundaries specified at the upstream boundary and at the downstream boundary of the alluvium estimations came from the 1958 head contour map shown in Figure 4.6 (Weist 1964). The hydraulic conductivities used in the groundwater boundaries illustrated in Figure 4.7 (Borman et al. 1983) indicate that the alluvium hydraulic conductivities are three times higher than in the surrounding areas (Squires 2007). The groundwater flux estimations between the High Plains aquifer and the alluvial aquifer from the pre-development calibrated regional models matched well data and determined balance to each region. Riparian evapotranspiration researched by Riley (2009) established an average value of 89.2 cm in the 2006 growing season. This riparian evapotranspiration value affected an area of 909 ha as delineated by Wachob

(2006). The alluvium grass evapotranspiration was a calibration constant used to balance the alluvial water balance. The alluvium grass evapotranspiration area was the remaining area in the alluvium outside the riparian area for an area of 27,621 ha (28,530 ha – 909 ha). Recharge to the alluvium was determined to be approximately 15% from research completed by Willard Owens Consultants (1988) and from calibration; regional water balances (Squires 2007). For the alluvial aquifer, the estimation of the recharge was to be 6.6 cm, 15% of the average precipitation of 44 cm based on a lysimeter in the alluvium along the South Platte in Fort Morgan County, Colorado (Willard Owens Consultants 1988).

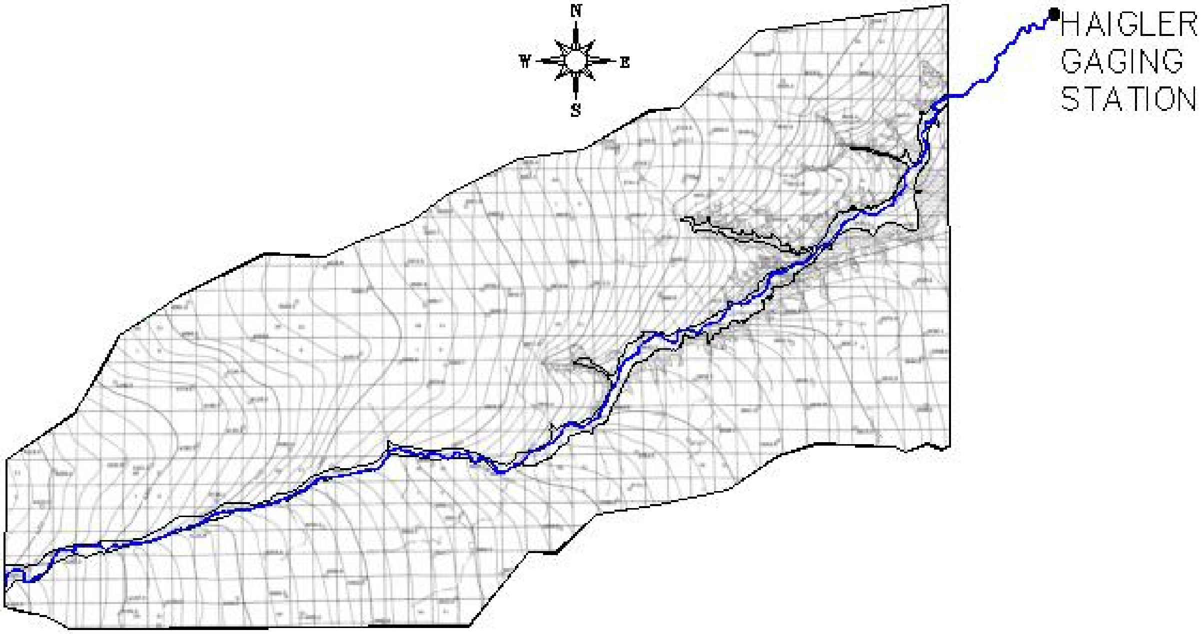


Figure 4.6: Water Balance Model with Water Table Contours and Haigler Gauging Station (Weist 1964)

Table 4.2: Pre-Development Inputs and Outputs to the High Plain Aquifer Groundwater Model

Parameter	Notation	Data Source	Units
Recharge to the HPA	R_{HPA}	≈7% (Reddell1967; Sophocleous 1992)	m^3/yr
Upstream groundwater inflow to the HPA	$(Q_{HPA})_{in}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr
Groundwater outflow from the HPA	$(Q_{HPA})_{out}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr
Flow out from the HPA to the alluvium	Q_{flux}	Estimated from the pre-development regional model using the zone budget feature	m^3/yr

The specified constant flux boundaries at the upstream boundary and at the downstream boundary of the High Plains aquifer estimates came from the 1958 head contour map (Weist 1964). Since the stream flow gauging station is approximately 11,300 meters downstream of the Yuma County boundary, the water balance did not use all of the groundwater flow leaving the boundary. The Weist (1964) contours shows the groundwater entering the river prior to the gauging station and were not used in calculations to avoid double water flows. The water balance as shown in Figure 4.6 used the Weist (1964) groundwater contour map. Figure 4.8 illustrates the groundwater flux profile entering the western boundary of the water balance basin. Figure 4.9 shows the groundwater flux profile leaving the eastern boundary. The groundwater flux out of the High Plains aquifer and into the alluvial aquifer was estimated from the pre-development calibrated regional models to match well data and to balance each region. Recharge to the High Plains aquifer was determined to be approximately 7% from research by Reddell (1967) and Sophocleous (1992) and previous regional water balance research (Squires 2007). For the High Plains aquifer, the estimated recharge was 3.1 cm, 7 percent of the average precipitation of 44 cm from 1932 to 1960 (Reddell 1967).

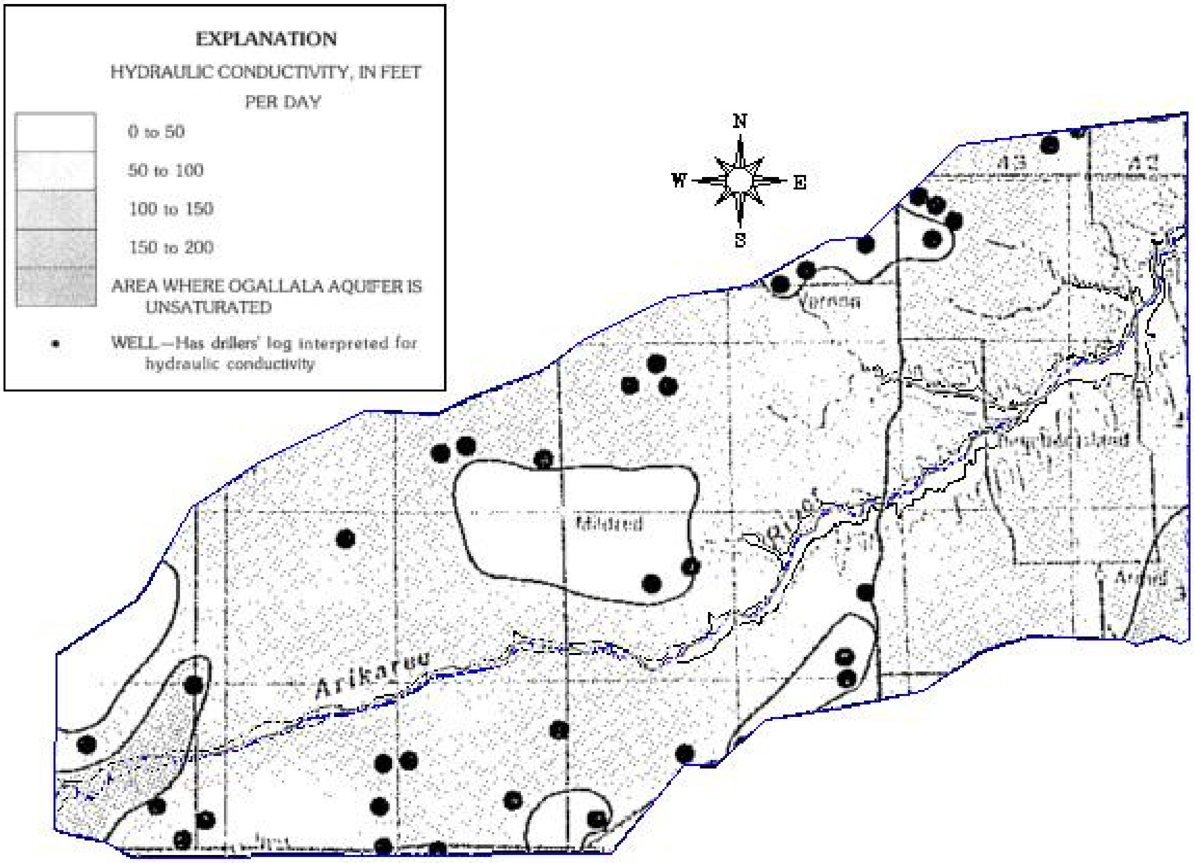


Figure 4.7: Hydraulic Conductivities Used in Water Balance (Borman et al. 1983)

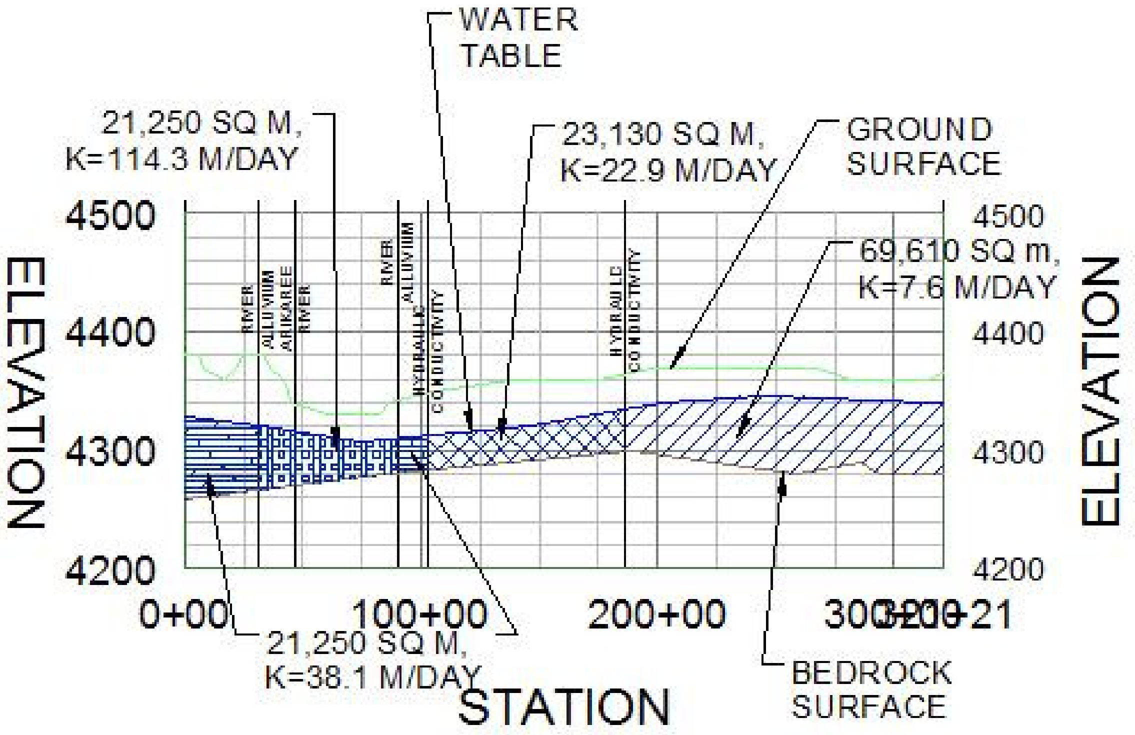


Figure 4.8: Western Boundary Groundwater Profile

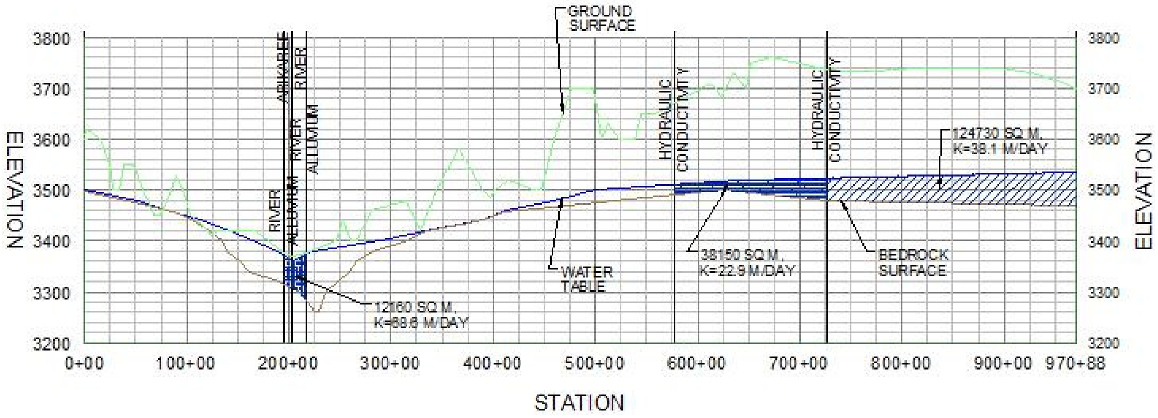


Figure 4.9: Eastern Boundary Groundwater Profile

A second water balance was developed by utilizing the pre-development water balance and current irrigation pumping rates. The pre-development model assumed that the wells did not begin pumping until after 1960. Therefore, the trial of the model tested without the wells for model calibration prior to 1960. Finally, the post-development water balance estimated the amount of reduction of pumping needing in order to maintain current alluvial groundwater stage and fish habitat. To complete this estimation, the researcher simply reduced the amount of irrigation pumping until the change in storage equaled zero and updated the balance with current stream flow and aquifer outflow conditions. Table 4.3 shows the calculated irrigation pumping from 2002 to 2006 for the project area by previous researchers. With the outliers removed from the calculation, the researcher used the average irrigation pumping in the post-development water balance. These outliers were significantly higher and lower than the other irrigation pumping estimates. The outliers of pumping water use estimates did not correlate with the precipitation each year. The average (2002-2006) irrigation wells pumping of the previous research was 71.2 million cubic meters.

If the 71.2 million cubic meters of irrigation water spread over the irrigated area of 12,268 ha (Wachob 2006), the results would be 58.0 cm. If planting corn in the entire basin, the crop water requirement would be 67.2 cm and the water usage would be 82.45 million cubic meters. According to the 2007 Census of Agriculture (2009) identified that approximately 74.3% of the irrigated crops being corn. This would agree with the estimated irrigation pumping of 71.2 million cubic meters used for the water balance model. Table 4.4 shows the post-development water balance inputs.

Table 4.3: Total Groundwater Used for Irrigation in Water Balance Model (Crossed Out Outlier Data Excluded) (Riley 2009)

Study	Year	Source	Number of Farmers	Land Accounted For Ha (ac)	Number of Wells Included	Water Used (million m^3)	Rainfall measured (m)
Fardal, 2003	2002	Personal Interviews	6	2,042 (5,044)	31	69.4	0.32
Griffin, 2004	~~2003~~	~~Surveys~~	4	~~1,134 (2,800)~~	~~12~~	~~52.2~~	0.36
Wachob, 2006	2004	Surveys	4	900 (2,224)	14	75.4	0.47
Wachob, 2006	2005	YW Well Test Ass.	15	885 (2,185)	15	57.6	0.48
Riley, 2007	~~2006~~	~~Surveys~~	~~10~~	~~2,321 (5,734)~~	~~39~~	~~88.5~~	0.33
	2006	YW Well Test Ass.	15	917 (2,266)	19	82.4	
					Average	**71.2**	

Table 4.4: Post-Development Water Balance Inputs

Wells pumping from the alluvium	$(Q_w)_{alluv}$	Assumed 18 of the 192 wells pumping from alluvium	m^3/yr
Wells pumping from the HPA	$(Q_w)_{HPA}$	Assumed 174 of the 192 wells pumping from alluvium	m^3/yr

4.1.1.2 High Plains Aquifer and Alluvial Aquifer Interaction

The relationship between the High Plains aquifer and the alluvial aquifer is important when looking at long term drying trends in the Arikaree River. The regional aquifer primarily recharge in the dune sands. Groundwater flux that occurs from the High Plains aquifer to the alluvium significantly affects the water balance in the alluvium and the consequent water table elevation in the alluvium. The groundwater flux between the High Plains aquifer and alluvium aquifer was studied by combining the water balance data and Darcy's Law for groundwater flow. Groundwater modeling and analyses examine flows at specific locations within the basin, but the modeling does not account for spatial and temporal variations in parameters around the research area.

An initial water balance quantifies water inputs and outputs to a control volume for a system in equilibrium. Table 4.5 illustrates the parameters used for the water balance calculations for the pre and post development models. A major assumption of the initial (before the wells were installed, pre-1960) water balance is that the change in groundwater storage is zero, that is, the groundwater table recovers after each growing season. Each of the three control volumes; the regional control volume, the High Plains aquifer control volume, and the alluvial aquifer control volume, used the previously stated assumption. The regional control volume includes both the High Plains aquifer control volume and the alluvial aquifer control volume. Figure 4.10 shows the initial water balance parameter average values for the three water balances models.

Table 4.5: Pre and Post Development Water Balance Parameters

Parameter	Notation	Data Source	Units	Notes
Recharge to the HPA	R_{HPA}	≈7% (Reddell 1967; Sophocleous 1992)	m^3/yr	a
Recharge to the Alluvial Aquifer	R_{alluv}	≈15% to 20% of precipitation (Willard Owens Consultants 1988)	m^3/yr	a
Upstream groundwater inflow to the HPA	$(Q_{HPA})_{in}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr	a
Groundwater outflow from the HPA	$(Q_{HPA})_{out}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr	a
Upstream groundwater inflow to the alluvial aquifer	$(Q_{alluv})_{in}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr	a
Groundwater outflow from the alluvial aquifer	$(Q_{alluv})_{out}$	1958 Groundwater Contour Map (Weist 1964)	m^3/yr	a
Stream Outflow	SF_{out}	USGS Stream Gage #06821500 at Haigler, NE	m^3/yr	b
Stream Inflow	SF_{in}	10% of outflow (Squires 2007)	m^3/yr	b
Riparian Evapotranspiration	ET_R	Average Seasonal ET of 89.2 cm from Riley (2009)	m^3/yr	a
Grass Evapotranspiration	ET_G	Calculated in the initial water balance with $\Delta S = 0$	m^3/yr	a
Groundwater Flux from the HPA to the alluvial aquifer	Q_{flux}	Calculated in the initial water balance with $\Delta S = 0$	m^3/yr	
Pumping in the HPA	$(Q_w)_{HPA}$	Assumed 18 of the 192 wells pumping from alluvium	m^3/yr	c
Pumping in the alluvium	$(Q_w)_{alluv}$	Assumed 174 of the 192 wells pumping from alluvium	m^3/yr	c
Change in water level in the alluvium	Δy_{alluv}	Calculated in the post well installment water balance	m/yr	d
Change in water level in the HPA	Δy_{HPA}	Calculated in the post well installment water balance	m/yr	d

Notes:
a. Value assumed constant for both the initial and final water balance
b. The initial stream outflow assumed to be an average value at Haigler from 1933-1960. From 1968 to 2010, stream outflows used from the average annual Haigler gauging station.
c. Values only used in the post-development water balance and assumed constant.
d. Average values from 1968 to 2010.

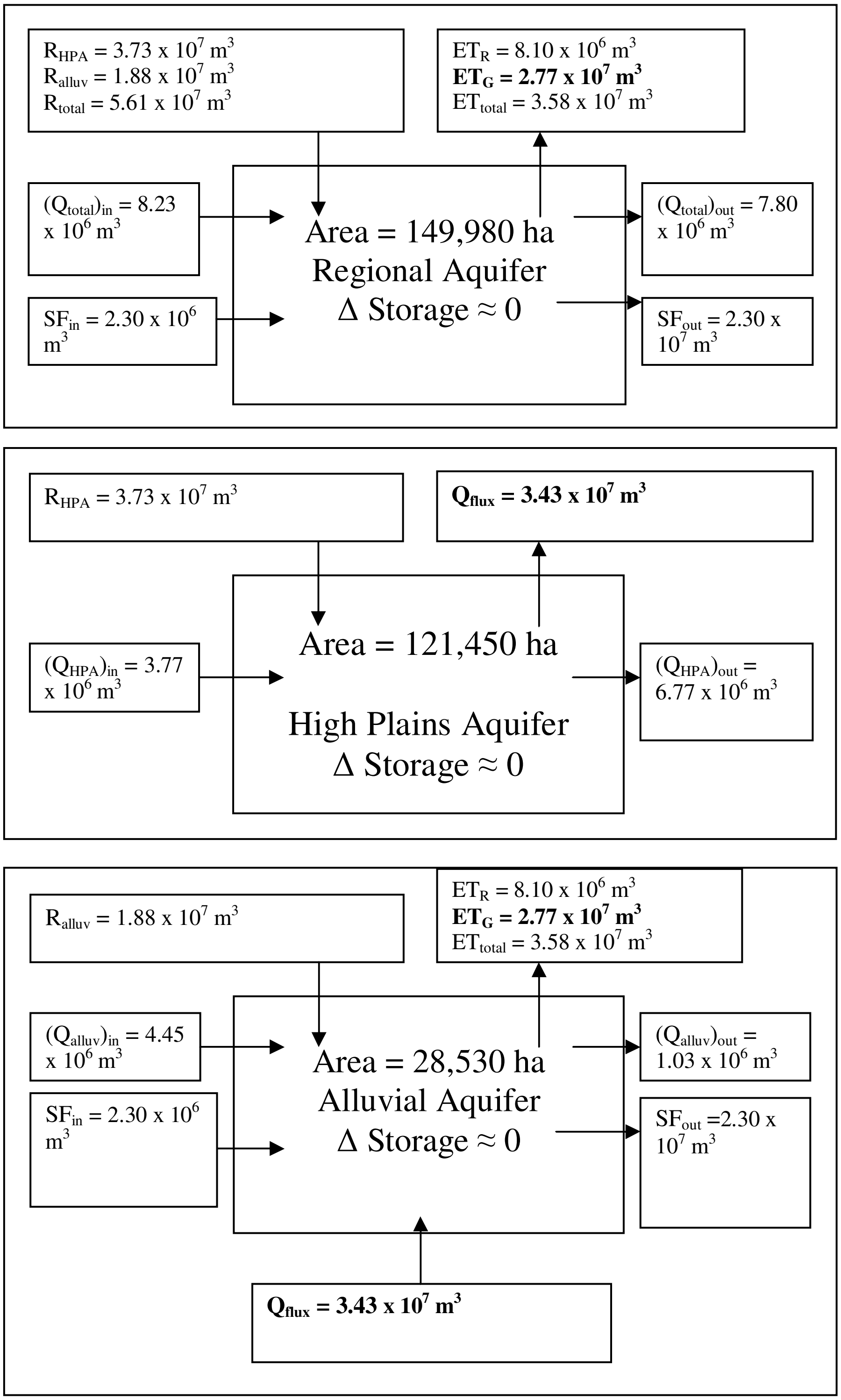


Figure 4.10: Initial Water Balance for the Regional Aquifer, High Plains Aquifer, and the Alluvial Aquifer (Terms in Bold Solved in the Pre-Development Water Balance)

4.1.1.3 Post Well-Installation Water Balance

Figure 4.11 illustrates the average water balance for the post well-installation period (post-1968). In these balances, the groundwater inflows, groundwater outflows, and ET are understood to be the same as in the initial water balance. The recharge for the alluvium will increase from 15% to 20% because of the increase capacity for infiltration in the alluvium. Historically, the main discharge out of the basin was the stream flow out that significantly decreases after the installation of irrigation wells. The additional water entering the alluvium will either be recharge to the aquifer or evapotranspiration out of the basin. Therefore, the recharge is linearly increased for 1968 to 1974 to a recharge rate of 20%. The recharge rate adjusted with changing participation rate each year. Other parameters that change based on year averages were stream flow in and out. The alluvium groundwater flow out decreased due to reduced saturated thickness of the alluvium aquifer.

On Figure 4.11, the change in water table elevation per year in the High Plains aquifer control volume was set equal to the average water table decline (approximately 0.24 m/year). Assuming other inputs and outputs to the High Plains aquifer control volume, the Q_{flux} is calculated. Then insert the calculated Q_{flux} into the water balance for the alluvial aquifer to calculate the average decline in the water table in the alluvium. This was about 0.0415 m/year on average from 1968 to 2010.

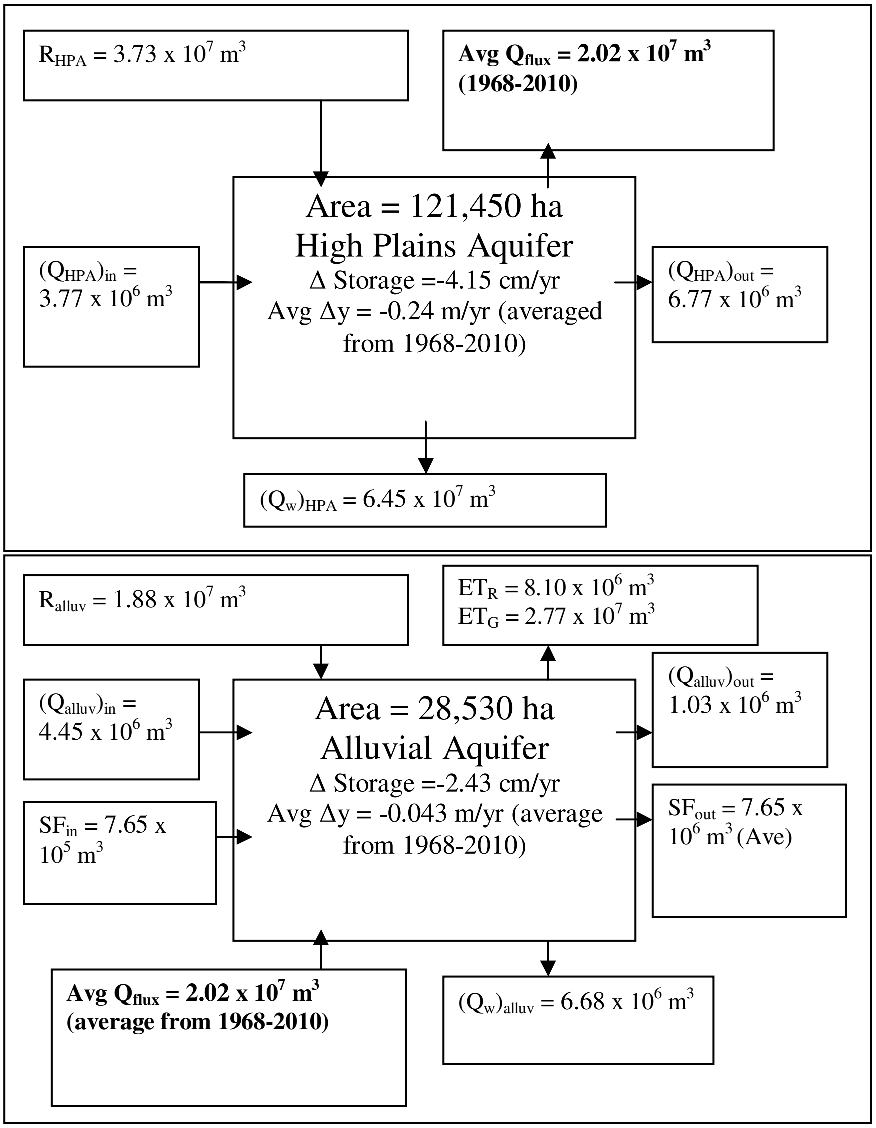


Figure 4.11: Post-Development Water Balance for the High Plains Aquifer and the Alluvial Aquifer (Terms in Bold Solved for in Post-Development the Water Balance)

4.1.1.4 Water Balance Calculations

This section will give insight in the application by applying Darcy's law and water balances on a yearly time step. Figure 4.12 shows a two-dimension diagram of the High Plains aquifer and the alluvial aquifer interaction. This diagram shows the different variables used in the Darcy's Law calculations as discussed in the following section.

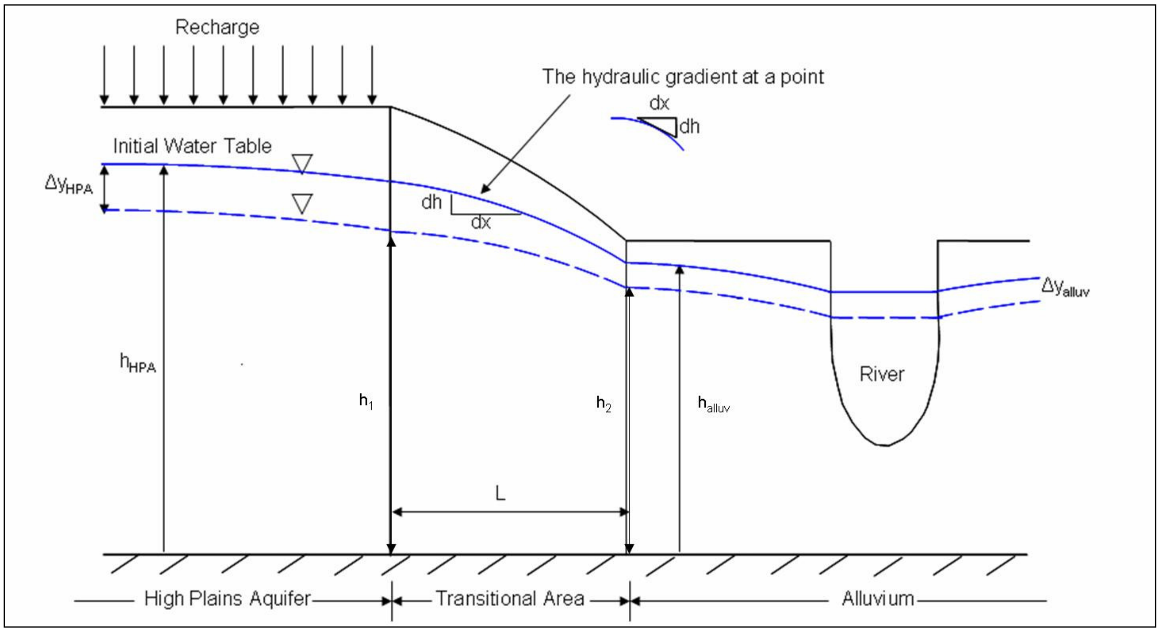


Figure 4.12: 2-D Schematic Showing the Relationship Between the High Plains Aquifer and the Alluvial Aquifer (Squires 2007)

To estimate the groundwater flux into the alluvium throughout time, a one-dimensional form of Darcy's Law calculated the flow in the x-direction per unit width as shown in Equation 4.1:

$$Q_{flux} = Q_x = -Kh\frac{dh}{dx} \qquad (4.1)$$

Where: Q_{flux} = groundwater flux from the HPA to the alluvium (L^2/t)
K = hydraulic conductivity (L/t)
h = h(x,t) = the saturated thickness of the aquifer at x at time t (L)
dh/dx = hydraulic gradient (L/L)

Irrigation efficiencies are relatively high under the center-pivot systems in the basin so that a zero net recharge in irrigated areas is reasonable. Equation 4.2 also assumed the Dupuit-Forcheimer assumptions (McWhorter and Sunada 1977) are valid. Integrating Equation 4.2 with the boundary conditions:

at $x = 0$, $h(0,t) = h_1$
at $x = L$, $h(L,t) = h_2$

Results in

$$Q_{flux} = \frac{K}{2L}\left(h_2^{\,2} - h_1^{\,2}\right) \qquad (4.2)$$

Where: L = length of the transitional area (L)
$h_1(x,t) = h_1(0,t)$ saturated thickness in the HPA at x= 0 at year t
$h_2(x,t) = h_2(L,t)$ saturated thickness in the alluvial aquifer at x=L at year t
t = time in years, t = 0 is 1968

The hydraulic head in the High Plains aquifer is larger than in the alluvium because the High Plains aquifer has a large recharge area in the dune sands north of the river while the river and alluvium are discharge areas, particularly in predevelopment. Hydraulic head in the High Plains aquifer (h_1) and hydraulic head in the alluvial aquifer (h_2) both change with time due to the change in aquifer storage and precipitation levels. The decline in the High Plains aquifer due to irrigation pumping will result in a decrease flux into the alluvium aquifer over time. Application of Darcy's law would suggest that the change in groundwater flux from the High Plains aquifer to the alluvium is not linear over time.

The hydraulic conductivity in the alluvium is approximately three times the hydraulic conductivity in the transition area. Therefore, by continuity, the water table slope in the transition area is three times the water table slope in the alluvium. The analysis assumed that the water table slope towards the river in the alluvium is reasonably flat from each boundary of the alluvium. The research study assumed the changes in the alluvial water table elevation occurred uniformly across the entire alluvium. In reality, the water table in the alluvium gradually slopes to the river and water table declines would vary spatially.

To have confidence in the changes in water table elevations over time, both Darcy's law and the yearly water balance must be satisfied. These are both inexact calculations, but the advantage gained from the exercise is an understanding of the system. From a yearly water balance:

$$\Delta y(t) = \frac{Out - In}{Area(Sya)}$$

For convenience, this equation is written so that a positive value of $\Delta y(t)$ implies a decline in the water table. For the High Plains aquifer:

$$\Delta y_{HPA}(t) = \frac{Q_{flux}(t) + (Q_{HPA})_{out} + (Q_w)_{HPA} - R_{HPA} - (Q_{HPA})_{in}}{121{,}450 Sya} \qquad (4.3)$$

The units in equations 4.3 and 4.4 are m^3/yr in the numerator and m^2 in the denominator. For the alluvial aquifer:

$$\Delta y_{alluv}(t) = \frac{ET + SF_{out} + (Q_{alluv})_{out} + (Q_w)_{alluv} - R_{alluv} - (Q_{alluv})_{in} - SF_{in} - Q_{flux}(t)}{28{,}530 Sya} \qquad (4.4)$$

Also, wells were installed over a period of years so that Q_w for both the alluvium and the High Plains aquifer increase from 60% in 1968 to final constant pumping value in 1975.

The water table elevation at the beginning of each season is determined by subtracting the change from the water table elevation at the beginning of the previous season as shown:

$$h_1(0,t) = h_{HPA}(t) - \Delta y_{HPA}(t) \qquad (4.4a)$$

$$h_2(L,t) = h_{alluv}(t) - \Delta y_{alluv}(t) \qquad (4.4b)$$

Where: $h_{HPA}(t)$ = saturated thickness in the HPA at the beginning of the previous season (L)
$h_{alluv}(t)$ = saturated thickness in the alluvium at the beginning of the previous season (L)

Equations 4.1 through 4.4 used yearly changes in water table levels to estimate. In the first year, the groundwater flux was from the initial water balance and entered into equations 4.3 and 4.4 to determine the water table elevation changes for the following year. Then the water table elevation changes were entered into equations 4.4a and 4.4b to determine the saturated thickness in both aquifers. At that point, equation 4.2 worked to determine the new groundwater flux. Introducing this new groundwater flux into the next equation enabled the calculation of the water table changes for the following year. Repeating this process for each year from 1968 to 2010 resulted in a yearly groundwater flux, yearly water table elevation in the High Plains aquifer, and yearly water table elevation in the alluvial aquifer seen in Appendix 8.2. This water balance model calibrated to match alluvium well data and High Plains aquifer well data. The water balance model projections beyond 2010 appear in future sections.

The length of the transitional area, L, in Equation 4.2 is unknown, but calibrated based on Q_{flux} from the water balance model. However, let ℓ = the planar length of the intersection of the two aquifer, L is the length of transition region, K = 22.86 m/day, $h_1(0,0)$= 32 m and $h_2(L,0)$ = 9 meters. Then $L/\ell = 0.15$ if Q_{flux} equals the predevelopment flux of 3.36 x 10^7 m^3/year. This is reasonable. If ℓ = 85,000 m (42,500 m planar length on each side of the river where the High Plains aquifer is in contact with the alluvial aquifer), then L is approximately 12940 m, that would correspond to the average distance from the edge of the alluvium to the monitoring wells in the High Plains aquifer.

Calculations of the decline in water levels in the High Plains aquifer using the method described in this section compared very well to measured data. Figure 4.13 shows calculated water table elevation in the High Plains aquifer compared to data measured at Well #9380. The calculations of the water table elevations started at the initial water table elevation that occurred at Well #9380. This well was chosen for this research because it was used in previous research by Squires (2007) and had water levels elevations for the entire post-development modeling (1968 to 2009).

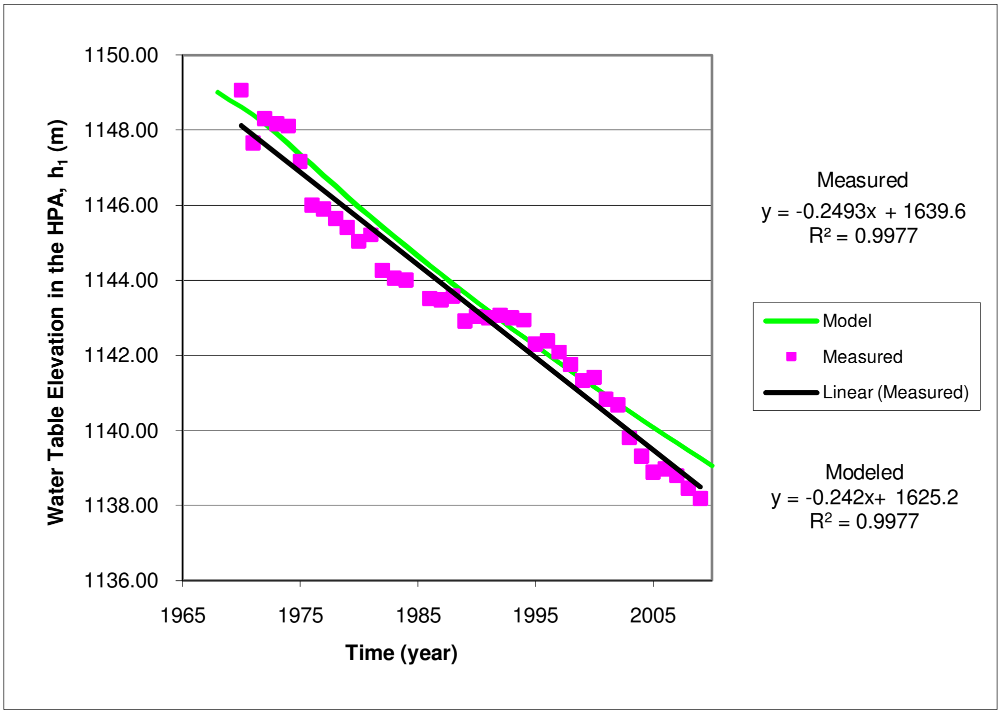


Figure 4.13: Measured and Calculated Water Table Elevation Declines in the High Plains Aquifer

Results for the alluvial aquifer are more uncertain and variable due to many factors discussed in later sections. Figure 4.14 shows the calculation and measured yearly water table decline data in the alluvium. These wells are located throughout the basin and one well upstream approximately 8,140 m of the western boundary as shown in Figure 4.15.

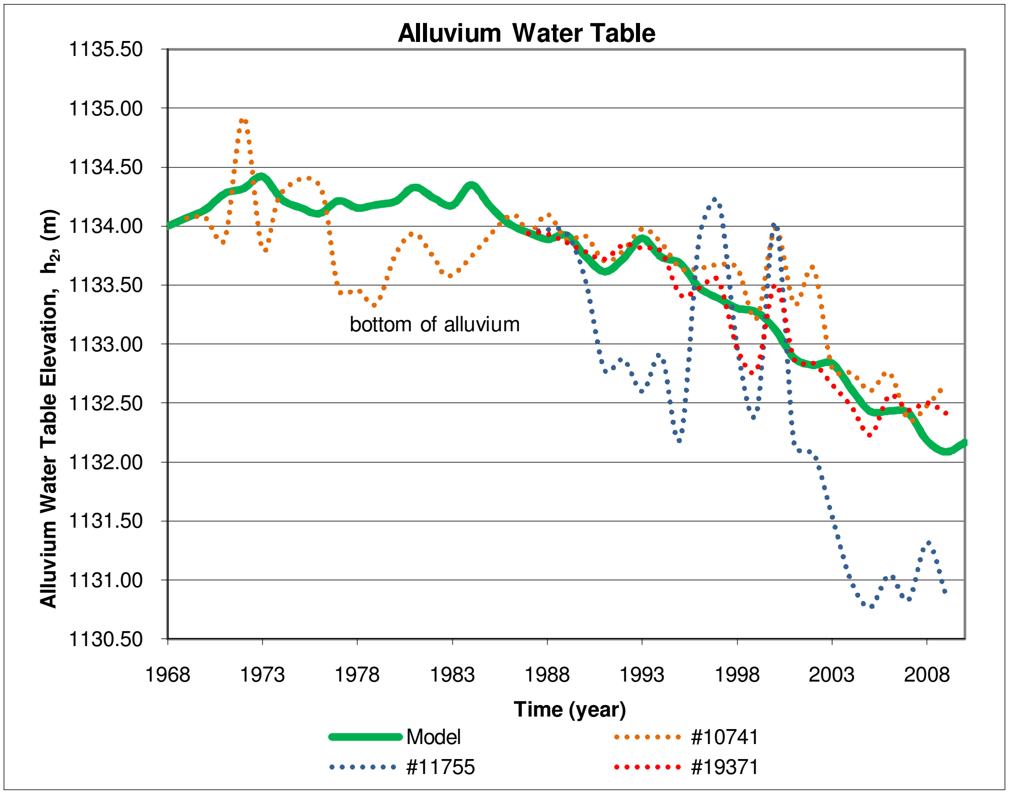


Figure 4.14: Calculated and Measured Alluvial Water Table Declines

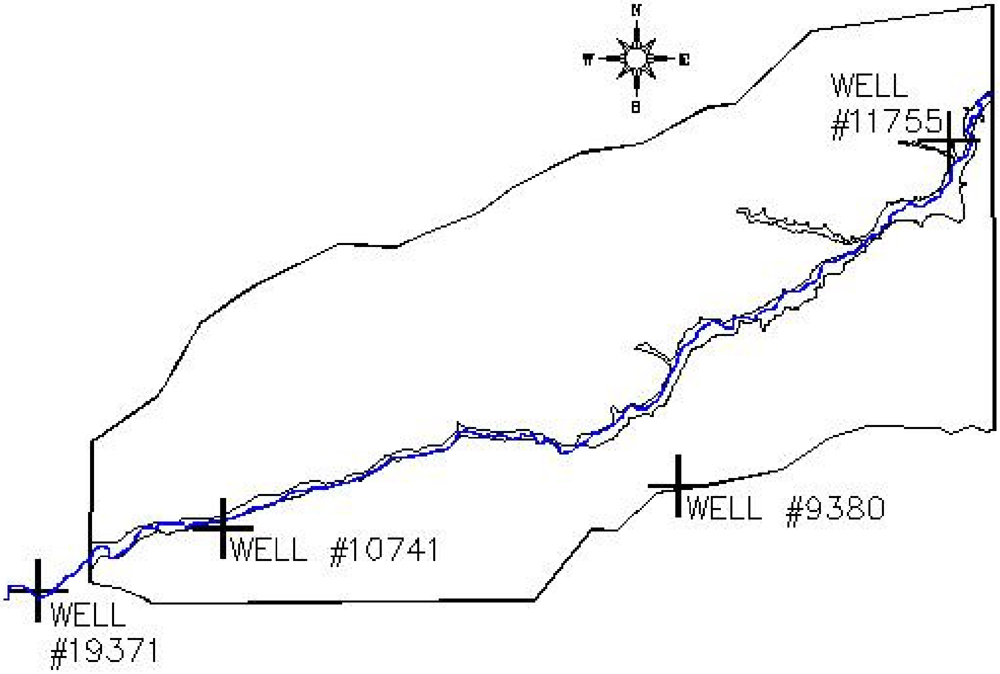


Figure 4.15: Water Balance Calibration Well Locations

4.1.2 Water Conservation Model

Opportunities to address the water needs of irrigators and the stream flow requirements for habitat maintenance are many and diverse. For our discussion, water conservation defines a long-term increase in the productive use of water supply without compromising the desired water services. Water conservation in agricultural production can also mean more efficient water use, transmission and distribution system efficiency, reduced evaporation and runoff, and the production of crops with reduced water requirements. A comprehensive literature review studied the conservation methods and practices used throughout the country and in the arid western United States under conditions similar to the Arikaree River basin.

The goals of this research were to identify feasible measures to reduce water usage and increase flows to the Arikaree River and alluvial aquifer. The best process of identifying these methods is working with local farmers and irrigators in the eastern Colorado. The surveys of local farmers directed our research based on the results. Estimates were made of the potential water saving for each of the identified top three conservation methods.

The tillage practices sections of the survey identified the three most preferred tillage practices for future implementation. The three tillage practices chosen are no tillage, minimum tillage, and strip or zonal tillage. The next section of the survey identified the irrigation practices that can effectively conserve water: using a multi-function irrigation system, the installation of low-pressure heads on drop tubes, installation of drip irrigation, and low pressure sprinkler packages. The third section of the conservation survey explored management practices. The survey recognized the most feasible practices are to plant crops that use less water or drought tolerant crops, to plant crops with shorter growing season, and to reduce irrigation early in the season while irrigating fully later in the season. The next section studies conservation programs that are the most practical and manageable for producers. The survey results show that farmers preferred a rotational fallow incentive, incentive for conversion to less water intensive crop, and water use limits over a certain period. The final method of conservation identifies the less intensive water use crops, possibly to replace corn; which predominantly is grown throughout eastern Colorado. The preferred crops for production by farmers in eastern Colorado are soybeans, dry beans, and winter wheat. The water conservation model evaluates these top conservation alternatives.

The dominant variables used in the analysis of water conservation measures were the literature review of other research and crop water usage within Yuma County. The crop data was a collection of ET from the Colorado Agricultural Meteorological Network (CoAgMet 2010). CoAgMet (2010) is a network of automatic weather stations distributed across the state. Weather records date back to 1992. The weather stations selected for this research were locations throughout the research area characterized as an irrigation area. Weather stations were categorized using site characteristics as well as detailed analyses of historical weather data from each site (USDA 2010). The CoAgMet stations selected were located in Yuma (yum02), Wray (wry01) and Idalia (idl01) for all research calculations.

CoAgMet provides daily crop water use or evapotranspiration (ET) reports for Colorado farmers and water users. The ET report from CoAgMet suggests alternatives to improve irrigation management and conserve limited water resources by fine-tuning the irrigation timing and the amount. The reference crops ET commonly used are cool-season grass (short reference) and alfalfa (tall reference) fully covering the ground. Historically, the reference crop in Colorado was alfalfa. Estimations of the actual ET (Eta) of other crops were determined by multiplying reference crop ET (ETr) by a crop coefficient (Kc). At any given point in the growing season, the Kc for a crop is simply the ratio of its ETa over reference crop ETr. Previously, CoAgMet used the 1982 Kimberly Penman equation. However, the American Society of Civil Engineers (ASCE) Standardized Penman-Monteith equation is another option for CoAgMet users (USDA 2010).

$$ET_a = K_c \times ET_r \qquad (4.5)$$

The ET equations most often used in Colorado are the Kimberly-Penman and Jensen-Haise models. The Jensen-Haise equation uses temperature and solar radiation measurements, while the Penman equation uses temperature, solar radiation, wind run, and humidity (Al-Kaisi and Broner 2009, Mohammad 1997). In a recent analysis at an independent site near Bushland, Texas, the 1996 Kimberly Penman performed equally well as the recommended ASCE standardized reference ETr equation in predicting measured ETa (Wright et al. 2000). The 1982 Kimberly Penman equation demonstrated a high predictive accuracy in other regions of the U.S. and worldwide (Allen et al. 2009). The Jensen-Haise equation represents a temperature-radiation method of calculating a daily ETr (Dockter 1994). The Jensen-Haise equation resulted from about 3,000 measurements of the ET taken in the Western Regions of the United States for a 35-year period.

$$ET_r = C_T(T_{mean} - T_X)R_S \qquad (4.6)$$

Where: C_T = Temperature coefficient
T_{mean} = Daily mean temperature
T_X = Intercept of the temperature
R_S = Measured global solar radiation

$$ET_r = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}W_f(e_S - e_d) \qquad (4.7)$$

Where: Δ = Slope of the Saturation vapor pressure and temperature curve
γ = Psychrometric constant
R_n= Net radiation
G = Soil heat flux
W_f = Wind function dependent on daily wind travel
(e_S-$e_{d)}$ = Mean daily saturation vapor-pressure deficit

The CoAgMet calculated Kimberly Penman to estimate crop water use for corn, dry beans, and winter wheat. CoAgMet did not have soybean ETa data available and for that reason, calculations of the ETa for soybeans used the Jensen-Haise equation. Figure 4.16 illustrates the crop coefficient curve used for the crop water requirements calculations for soybeans. The starting dates and termination dates shown in Table 4.6 and 4.7 estimated the season water usage at each site. Collection of the ET data used to estimate the crop water requirements came from 1997 to 2008 in order to help eliminate fluctuation in the climatic conditions.

Table 4.6: Start Dates for Colorado Crops and Calculation Parameters for Jensen-Haise Equation (NCWCD 2010)

	Average Calendar Dates			Average Summation of Jensen-Haise Etr		
Crop	Plant	Cover	Terminate	Plant to Green Line	Green Line to Cover	Cover to Terminate
Pasture grass		4/4	10/15		2.0	43.3
Turf grass		3/15	10/15			45.3
Alfalfa 1st		5/7	6/1		6.0	6.0
Alfalfa 2nd		6/23	7/14		6.0	6.0
Alfalfa 3rd		8/5	8/29		6.0	6.0
Alfalfa 4th		9/30	10/15		6.0	1.9
Alfalfa new	4/15			2.0	9.0	6.0
Corn for silage	4/28	7/22	9/5	2.4	18.8	11.3
Corn for grain	4/28	7/22	10/15	2.4	18.8	17.7
Spring grains	4/1	6/1	7/20	1.0	10.9	13.6
Winter wheat		5/16	7/4		10.5	13.0
Dry beans	5/31	7/20	9/1	1.0	12.9	11.0
Sugar beets	3/22	7/10	10/15	1.1	22.7	21.0
Potatoes early	4/15	7/4	8/8	1.2	17.9	9.7
Potatoes late	6/3	8/7	9/11	1.3	16.7	8.1
Onions from seed	3/15	7/23	9/1	1.1	27.0	10.1
Onions from sets	4/1	7/23	9/1	0.8	21.2	8.4
Cucumbers	5/30	8/5	9/4	1.3	17.2	7.2
Carrots	4/1	7/2	8/1	0.9	19.5	19.5
Sorghum	6/1	8/20	9/15	1.8	20.0	5.6
Soybeans	5/25	8/10	9/25	1.3	19.9	9.8

Table 4.7: Crop Start and Termination Dates for Conservation Calculations

	Average Calendar Dates	
Crop	Plant	Terminate
Corn	4/20	10/15
Beans, Dry	5/31	9/1
Soybeans	5/25	9/25
Wheat, Winter	3/1	7/4

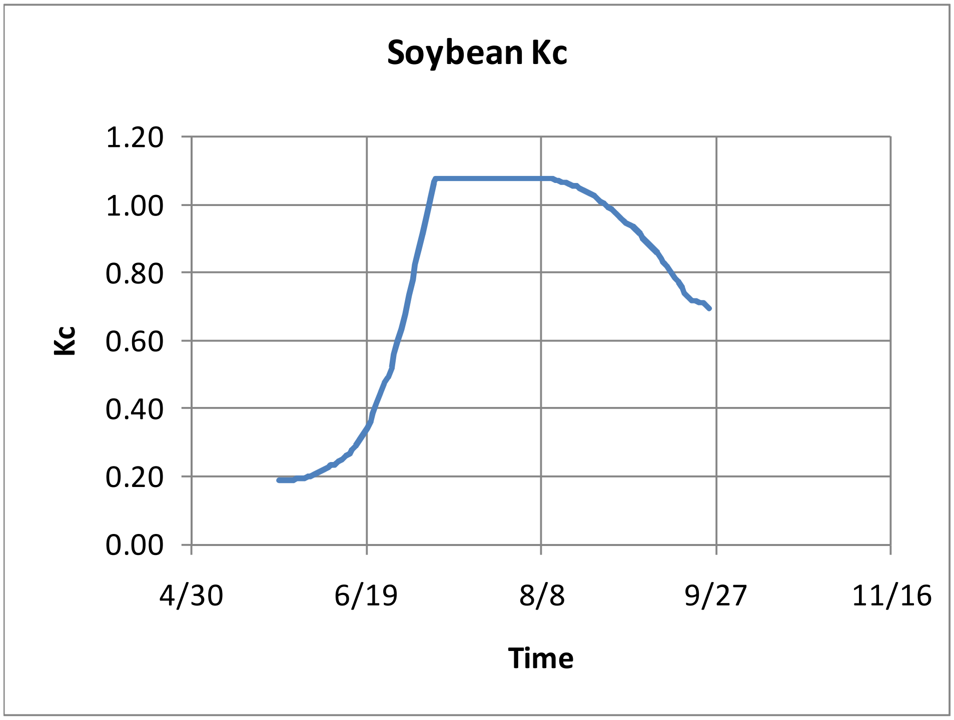


Figure 4.16: Calculated Soybean Crop Coefficient Curve

All the water conservation calculations used the estimations as shown in Table 4.8 of the final crop water requirements. In the 2007 Census of Agriculture (2009), approximately 52% of all the crops harvested and 75% of all the irrigated crops are corn providing the baseline for conservation measures. The calculations of water conservation in the irrigation practices, management practices, programs, and crop selection used this corn baseline. The conservation irrigation practices typically increase the application efficiency with the water savings calculated based on the corn crop water requirements. The conservation management practices typically conserve a certain percent of the dominant corn crop water requirements to calculate the total water savings. The programs section and the crop selection water savings calculations are based on corn being generally grown throughout Yuma County.

Table 4.8: Calculated Season Crop Water Requirements in Project Area

	Crop Water Requirements	
Crop	**cm**	**Inch**
Corn	64.2	26.46
Beans, Dry	55.8	21.97
Soybeans	64.4	25.36
Wheat, Winter	47.7	18.77
Average	**58.0**	**23.14**

Other data used in the water conservation model were the current participation of local farmers in the noted conservation alternatives. Calculations of the current participation use data utilize the results of survey responses when possible. When not possible, as in the crop conversion section, the 2007 Census of Agriculture (2009) provided the basis to estimate of the current harvesting rates of each crop.

The final water conservation model parameter was the future participation of local farmers that provided the constant for all alternatives. Modifying this parameter determined what impacts all the participation levels (1% to 100%) would have on the groundwater balance models. Discussed in the Results sections are these modifications of the future participation projections, based on different result scenarios.

4.1.3 Economic Impacts Model

The success of any of the conservation alternatives is developing feasible and realistic alternatives for future implementation throughout eastern Colorado. The identified list of conservation alternatives can achieve these goals: to protect and preserve the river, to reduce groundwater usage, and minimize economics effects on the local farming community. The top three conservation alternatives in each section identified in the survey evaluated the potential economic impact of implementing these conservation alternatives. The economic parameters evaluated are water value, pumping costs, potential yield reduction, any capital costs, annual maintenance costs, and economic values identified in the surveys. These were the economic parameters used to estimate potential impacts to eastern Colorado's economics.

Generally, the calculations of the economic models use per hectare of irrigated land, but these calculations were not appropriate with these modeling requirements. Instead, the economic impacts used per cubic meter of water pumped to correlate the quantity of water savings and economic impacts of each alternative. Shown in the following Tables are the parameters for the economic model. Table 4.9 shows the parameters used in each section of the water savings return and the reduced pumping costs. These economic analyses were not comprehensive of all the economic factors, but do provide a general idea of the costs and saving of each alternative.

Table 4.9: Economic Model Parameters for All Sections

Section	Alternative	Parameters	Value	Units	Source
All	All	Savings Water Return	356	$/ha-m	(Torell et al. 1990)
All	All	Savings of Pumping Return	48.6 to 68.9	$/ha-m	(Torell et al. 1990)

The major drawback to implementing new field practices is the initial capital cost to purchase new equipment at approximately $90,000. The capital costs assumed a 20-year period per standard loans and using only one new planter per farm. The final two rows of Table 4.10 show estimated returns per hectare based on other economic research.

Table 4.10: **Economic Model Parameters for the Field Practices Section**

Section	Alternative	Parameters	Value	Units	Source
Field	No-Till/Minimum Tillage	Capital Cost (No till Planter)	90,000	$	(Farm Power & Equipment Inc., Personal Communication, April 15, 2010)
Field	No-Till/Minimum Tillage	Capital Cost (No till Planter)	557	ha/farm	(2007 Census of Agriculture 2009)
Field	No-Till/Minimum Tillage	Production Return	46, 74, 85	$/ha	(Archer et al. 2008)
Field	Strip	Production Return	53, 92	$/ha	(Archer and Reicosky 2009)

These costs are for the complete installation of new irrigation systems. This could lead to inaccurate cost projections since predominantly irrigation systems are already center pivots and would only require modifications to the existing systems. Therefore, these capital costs are worst-case scenarios and the costs could be significantly less depending on existing infrastructure. The costs for retrofitting wells are variable depending on the extent of the retrofit. The wells in some circumstances would only require modification to the impellers that is a relatively low cost. In other situations, it may require replacement of the pump and motor for ideal operation efficiency. In hilly terrain, the optimal system would require a variable frequency drive that has an approximate cost of $10,000.

Table 4.11: **Economic Model Parameters for the Irrigation Practices Section**

Section	Alternative	Parameters	Value	Units	Source
Irrigation	Multi-Functional System/Low Pressure Packages	Capital Cost	1,070	$/ha	(Colorado Agriculture Water Alliance 2008)
Irrigation	Retrofit Well	Capital Cost	20,000	$/Center Pivot	
Irrigation	Drip Irrigation	Capital Cost	2,470	$/ha	(Colorado Agriculture Water Alliance 2008)
Irrigation	Multi-Functional System/Low Pressure Packages	Annual Cost	158	$/ha	(Colorado Agriculture Water Alliance 2008)
Irrigation	Retrofit Well	Annual Cost	74	$/ha	(Colorado Agriculture Water Alliance 2008)
Irrigation	Drip Irrigation	Annual Cost	296	$/ha	(Colorado Agriculture Water Alliance 2008)

The top management practices have many factors that change with time and per manufacturer. Producers need to be critical consumers when buying hybrids with seed treatments and transgenic because these biotech traits are not vital for every farming operation (Hillyer 2005). The prices of hybrids in the mid-1990s sold for $65 to $70 a bag in comparison to prices currently being around $200 per bag. Superior genetics along with transgenic traits and new seed-treatment options have helped to increase U.S. corn yields by some 30 bushels per acre since 1997 (Hillyer 2005). "Certainly farmers have experienced a pretty significant price-point increase in seed corn because of transgenic traits and seed treatments over the last five years", says Steve Klein, Garst Seed Co. marketing director (Hillyer 2005). Note that future hybrids may not experience any decrease in the yields and these calculations included some yield decreases. Therefore, this model may overestimate the costs of yield reductions. Table 4.12 shows the economic model parameters used for the management practices.

Table 4.12: Economic Model Parameters for the Management Practices Section

Section	Alternative	Parameters	Value	Units	Source
Management	Drought Tolerant Crop/Shorter Growing Season	Seed Capital	50	$/Bag	(Hillyer 2005)
Management	Drought Tolerant Crop/Shorter Growing Season	Seed Capital	79,000	Seeds/ha	(Elmore and Abendroth 2006)
Management	Drought Tolerant Crop/Shorter Growing Season	Seed Capital	80,000	Seeds/Bag	(Elmore and Abendroth 2006)
Management	Reduce Irrigation Early	Yield Cost	11,521	kg/ha	(2007 Census of Agriculture 2009)
Management	Reduce Irrigation Early	Yield Cost	0.15	$/kg	(USDA, 2010)
Management	Reduce Irrigation Early	Yield Cost	0, 15	%	(Lytle et al. 2008; Nielsen et al. 2002)
Management	Drought Tolerant/Shorter Growing Season	Yield Return	6, 10	%	(Monsanto Company, 2009)

The programs section of the model includes theoretical and actual programs that have very little economic data. The rotational fallow program calculations assume there is no payment to farmers for the fallowing period. The basis of the program is that farmers would receive an incentive to participate. Most likely, the incentive payments would reduce the negative economic impacts to the region because of the re-investment of the incentive into the local economy or other farm operations. Table 4.13 illustrates the economic model parameters used for the programs section.

Table 4.13: Economic Model Parameters for the Programs Section

Section	Alternative	Parameters	Value	Units	Source
Programs	Rotational Fallow	Reduced Irrigation Cost	2,036	$/ha	(Pritchett and Thorvaldson, 2008)
Programs	Water Use Limit	Yield Cost	Average of Top Three Cost of Crops	$/m^3	(USDA 2010)
Programs	Conversion to Less Water Intensive Crop	Yield Cost	11,521	kg/ha	(2007 Census of Agriculture 2009)
Programs	Conversion to Less Water Intensive Crop	Yield Cost	0.15	$/kg	((USDA 2010)
Programs	Conversion to Less Water Intensive Crop	Yield Cost	0, 15	%	(Lytle et al. 2008; Nielsen et al. 2002)

The final section on crop selection examines the difference in potential income when converting from corn to a lower water use crop. The prices used in the analysis were average values from the entire year of 2009. The production rates of each of these crops used as a basis the average data from the 2007 Census of Agriculture (2009) for Yuma County. This analysis will vary significantly based on crop prices and market demands for each crop. Table 4.14 shows the parameters for this section.

Table 4.14: Economic Model Parameters for the Crop Selection Section

Section	Alternative	Parameters	Value	Units	Source
Crop Selection	All	Dominate Crop (Corn)	11,521	kg/ha	(2007 Census of Agriculture 2009)
Crop Selection	All	Dominate Crop (Corn)	0.15	$/kg	(USDA 2010)
Crop Selection	Wheat	Lower Water Use Crop	2,732	kg/ha	(2007 Census of Agriculture 2009)
Crop Selection	Wheat	Lower Water Use Crop	0.18	$/kg	(USDA 2010)
Crop Selection	Beans, Dry	Lower Water Use Crop	2,732	kg/ha	(2007 Census of Agriculture 2009)
Crop Selection	Beans, Dry	Lower Water Use Crop	0.45	$/kg	(USDA 2010)
Crop Selection	Soybeans	Lower Water Use Crop	3,746	kg/ha	(2007 Census of Agriculture 2009)
Crop Selection	Soybeans	Lower Water Use Crop	0.37	$/kg	((USDA 2010)

CHAPTER 5 MODEL RESULTS AND DISCUSSION

5.1 WATER CONSERVATION AND ECONOMIC IMPACTS RESULTS

The conservation alternatives for each section based the evaluation on potential water savings and minimal economic impacts to the local farmers and communities. Both Figures 5.1 and 5.2 show the result of the water savings and of the economic impact for field and irrigation practices. The best alternatives were no-tillage for field practices due mainly to the reduced labor and machinery costs. The top irrigation practice was conversion to a low-pressure package system due to the water savings and the reduced power requirements as shown in Table 3.4. The top management practice is the planting of drought tolerant crops due to lower cost and high potential benefits. Evaluation of the actual results of drought tolerant crops should determine the actual water savings and economic impacts. Figure 5.3 illustrates the water conservation and economic impacts of the management practices.

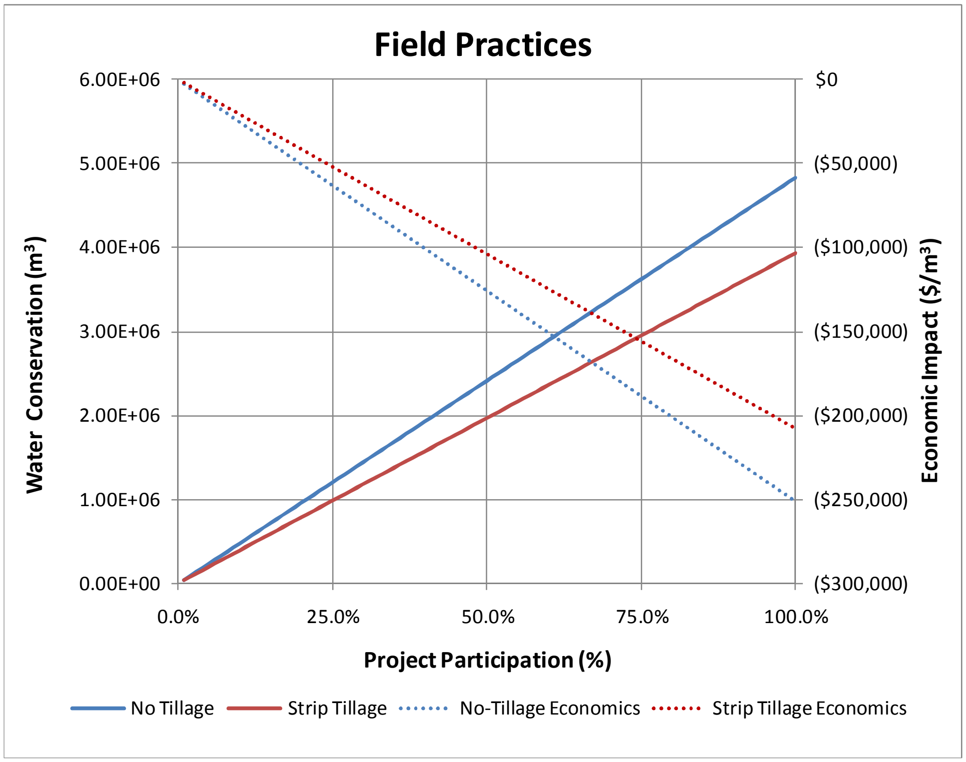


Figure 5.1: Field Practices Water Savings and Economic Impacts Analysis

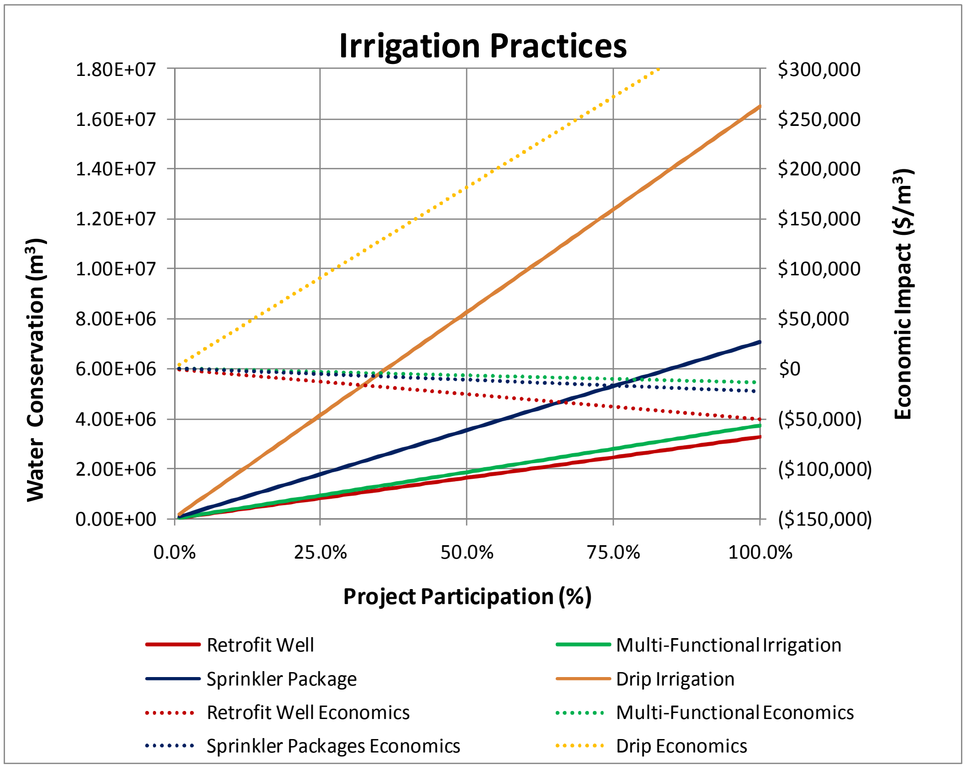


Figure 5.2: Irrigation Program Water Savings and Economic Impacts Analysis

The most effective water conservation program is setting water use limits over a given period as shown in Figure 5.4. This analysis did not evaluate the costs to government or funding agencies that may provide incentives for the limits. The local groundwater districts could implement these water use limits allowing adjustments to the program to meet local variances. If the State of Colorado implemented water limits, it could be detrimental to farming due to the lack of modification to changing conditions throughout the state. The top identified crop for conversion was beans because they had the least economic impact and most water conservation as shown in Figure 5.5. This was mainly due to low water use of 55.8 cm per season and the high yield returns. This crop conversion would still cause potential impacts to farmers due the higher yields and price of corn that farmers would be converting.

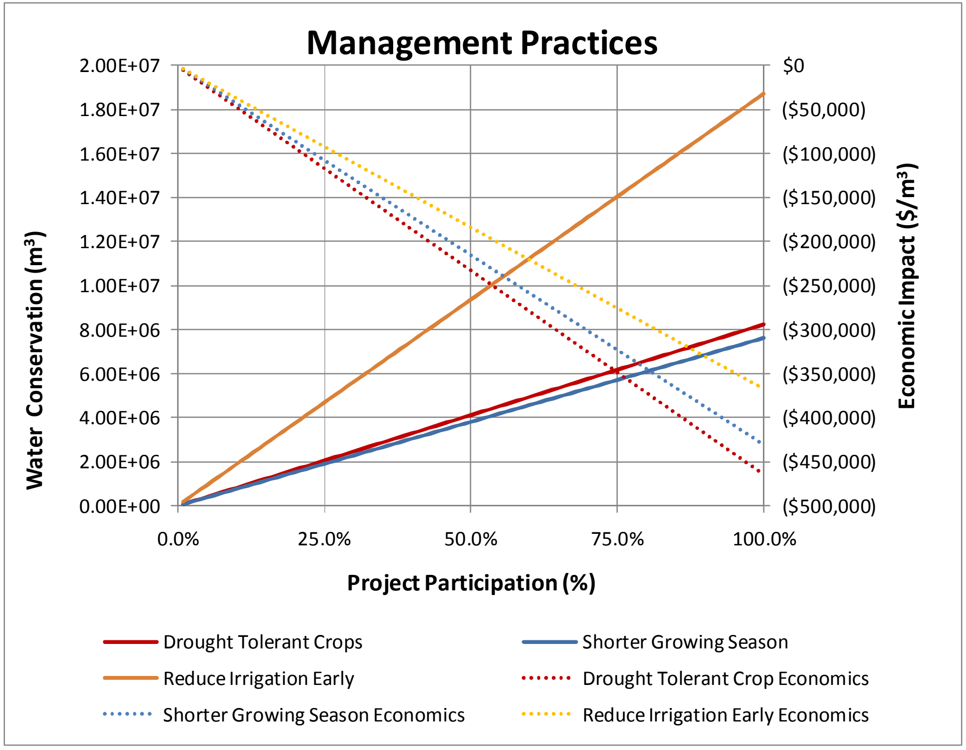


Figure 5.3: Management Practices Water Savings and Economic Impacts Analysis

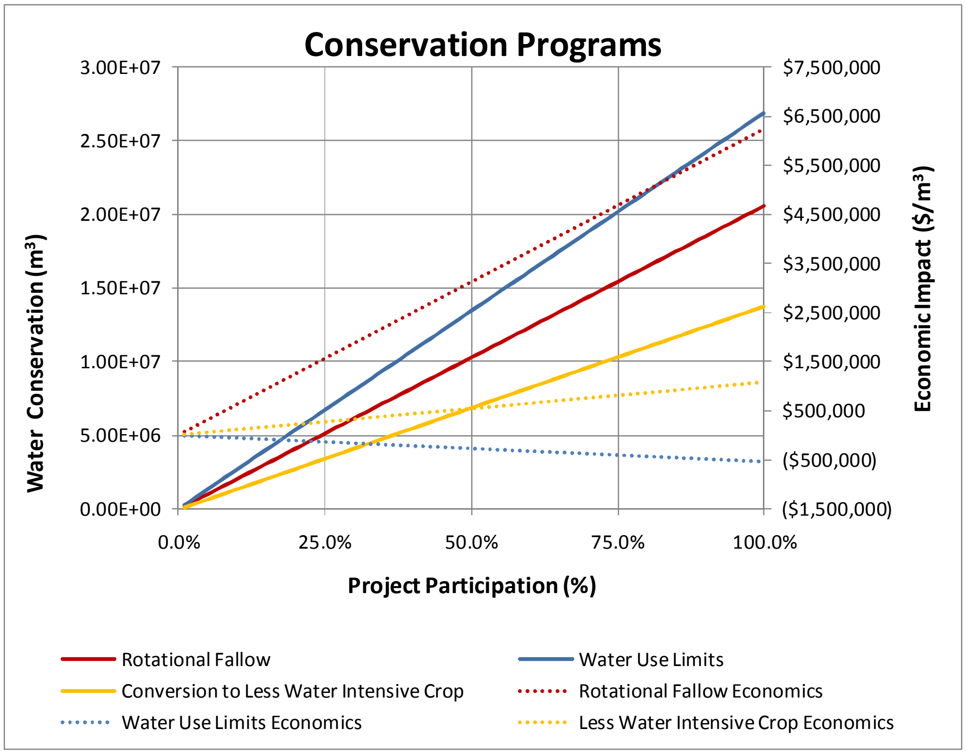


Figure 5.4: Conservation Program Water Savings and Economic Impacts Analysis

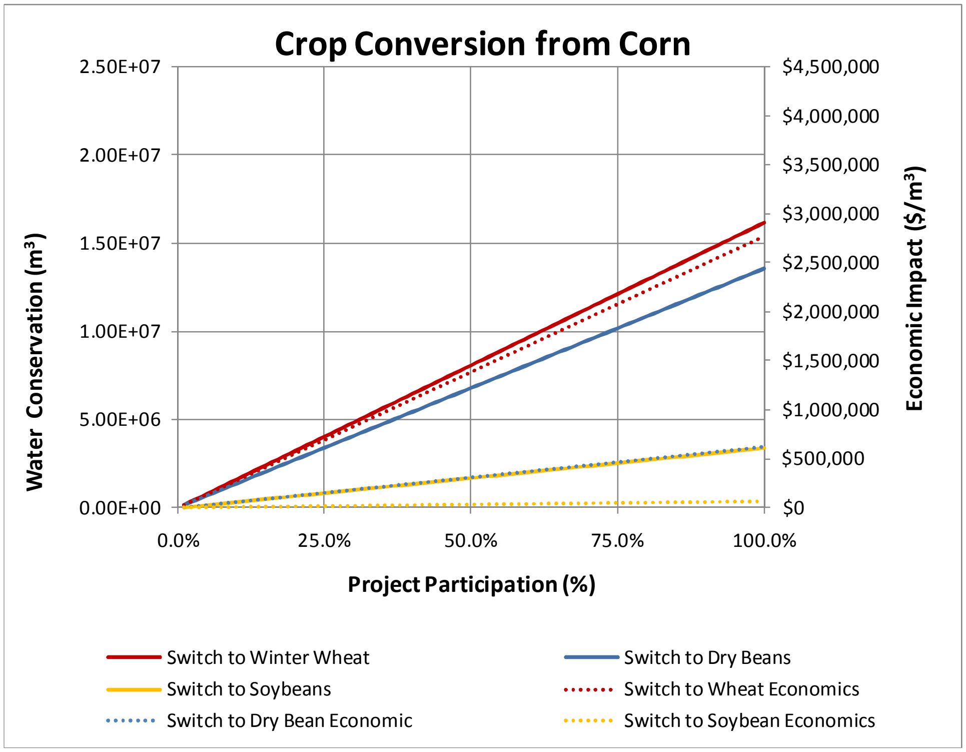


Figure 5.5: Crop Conversion from Corn Water Savings and Economic Impacts Analysis

Both Figures 5.6 and 5.7 show a comparison to each section of the identified water conservation methods. These figures would allow farmers or local agencies to identify the best use of Yuma Counties' water resource and the results of water savings. The shown water use limits could have the most potential water savings and least impacts to farmers. There could also be a negative impact to the funding agency or state to incentives the local farmers. The next highest potential for an effective water conservation method was conversion from corn to dry beans. The following results of the conservation sections are management practices and then followed by irrigation practices.

The field practices had the least potential water savings when compared to the other methods. This method could also have the highest potential participation due to the economic savings and because it is, the natural direction farmers are choosing. No-till systems usually have a learning curve with local farmers and farmers usually do not convert 100% of their land at once.

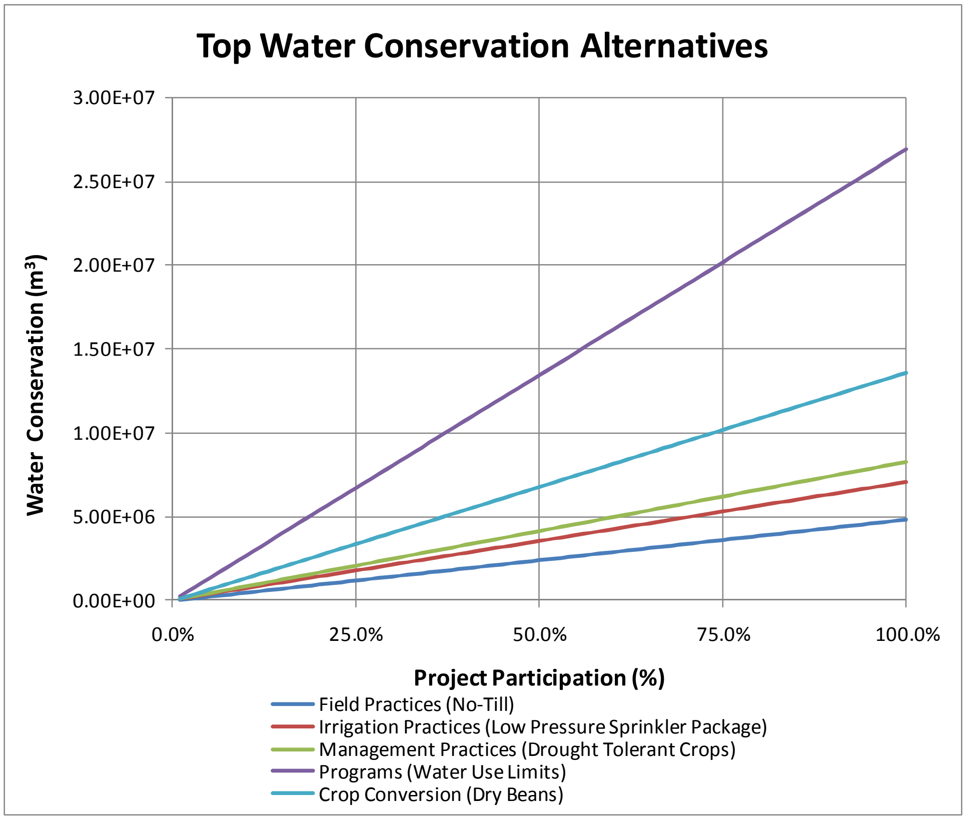


Figure 5.6: **Top Water Savings and Economic Impacts Alternatives**

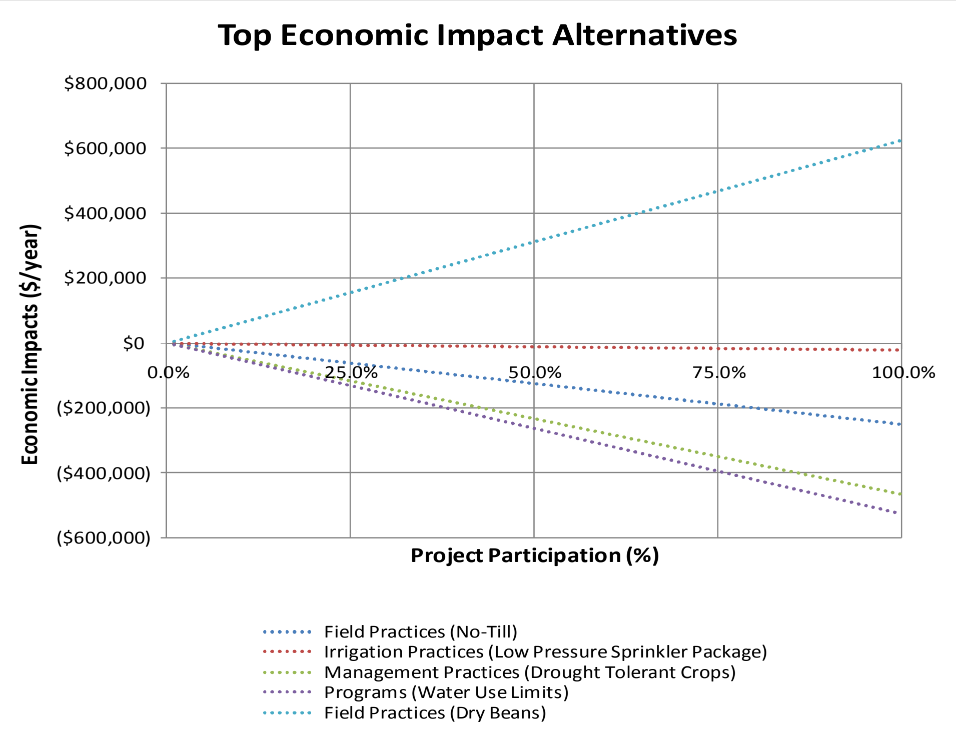


Figure 5.7: **Top Water Savings and Economic Impacts Alternatives**

5.1.1 Water Balance Results

This results section will examine several scenarios for the future of the Arikaree River and possible methods to decrease the decline of the High Plains aquifer and the alluvial aquifer. The results for the High Plains aquifer are relatively straightforward, based on the measured data, and modeled information. The water balance measurements from this study indicate the High Plains aquifer is currently declining at 0.247 m. This water level decline of approximately 0.25 m per year (1 foot per year) matches other research by Squires (2007) and Falke (2009). The water balance modeled High Plains aquifer for post-development (1968 to 2010) groundwater rate of decline was 0.242 m, which is very similar to the measured decline rate.

Although a straight line can approximate the water table decline in the High Plains aquifer, the water table decline in the alluvium appears to be nonlinear. The alluvial aquifer is more complicated to model and it is difficult to predict the future results due to its varying components and changing groundwater flux from the High Plains aquifer.

The previous research by Squires (2007) performed three different modeling methods for the alluvium as shown in Figure 5.8. The previous modeling results from the different assumptions could have significant impacts on the results. Squires (2007) showed the nonlinear decline using the previous water balances and Darcy's Law. The linear decline at 0.08 m/year was calculated by replacing the flux in the water balance in 2006 with the flux calculated in 2006 by the regional groundwater model (R. Magelky, personal communication, April, 2009). The decline in the alluvial water table changed from 0.15 m/year to 0.08 m/year. Figure 5.8 (Squires 2007) illustrates the linear decline of 0.054 m/year.

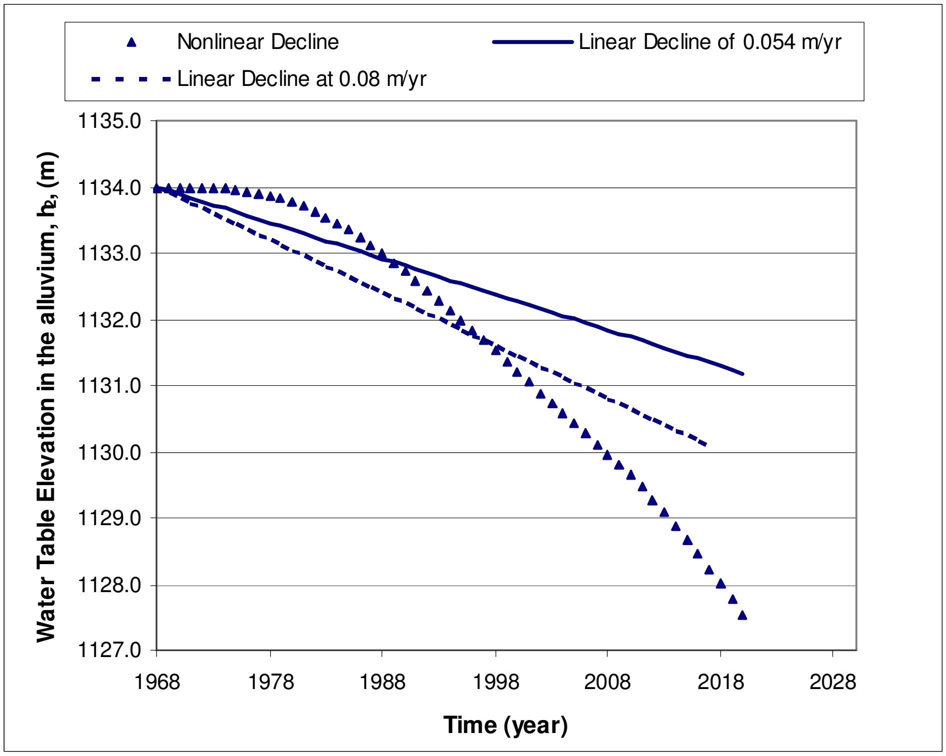


Figure 5.8: Previous Research Calculated Water Table Declines in the Alluvial Aquifer (Squires 2007)

The data (Figure 5.9) suggest that from 1968 to approximately 1985 there was slight decline in the alluvium water levels with fluctuations from climatic patterns. This indicated the water in the alluvial aquifer released from the storage supplement because of the lack of water from the High Plains aquifer flux. In approximately 1985, the possible depletion of the stored water caused the alluvium water table to establish new declining water table equilibrium in order to correspond to the declining High Plains aquifer.

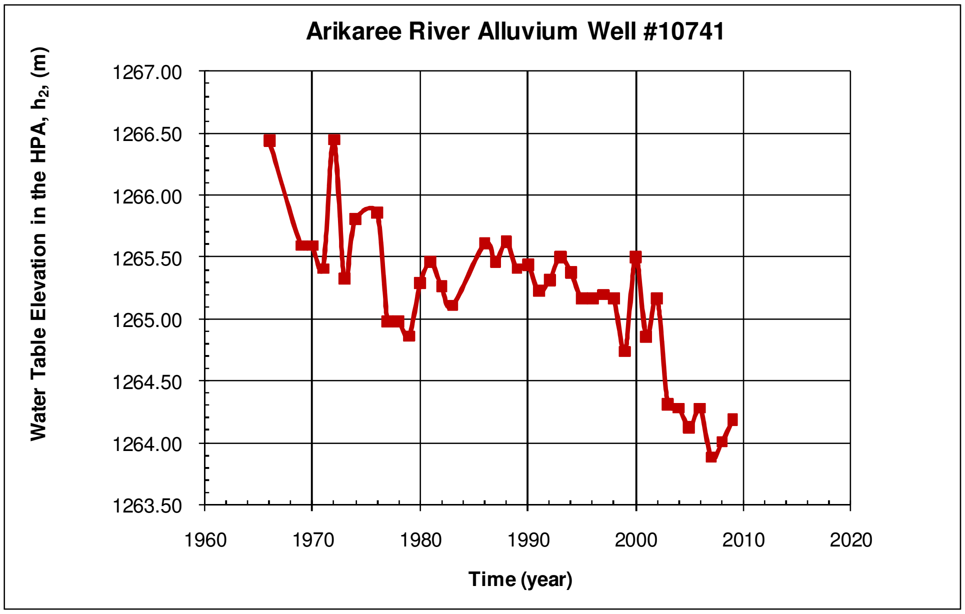


Figure 5.9: Alluvial Well #10741 Water Table Data

The data from well #11755 shows a very dynamic stream that has extreme fluctuations due to climatic changes as shown in Figure 5.10. These extreme fluctuations are most likely due to the alluvium geology in the area that is either sand or other material with high hydraulic conductivity properties to create these types of instability. Because this well is not typical across the basin, it was not used in calibrating the water balance model.

Therefore, the goal of the modeling was matching the alluvial decline from 1985 to 2009. There were only 3 wells with available water table data in the alluvium and only one well (#10741) with data for the entire post-development modeling. The other two wells only had water table data from 1987 to 2009 as shown in Figure 5.10. The well data for #19371 and #10741 had very similar linear declines from 1987 to 2009 so calibration of the model used these wells. The fluctuations of the water table directly relate to the precipitation and stream flow in the Arikaree River Basin. Figures 5.11 and 5.12 show the correlation of the groundwater level to precipitation and to the stream flow.

This knowledge about the water table flocculation allows us to conclude that the alluvium has had a steady decline in water levels since 1985. The average decline of the alluvial water table from 1985 to 2009 was 0.079 m/year using data from wells #10741 and #19371 as shown in Figure 5.13.

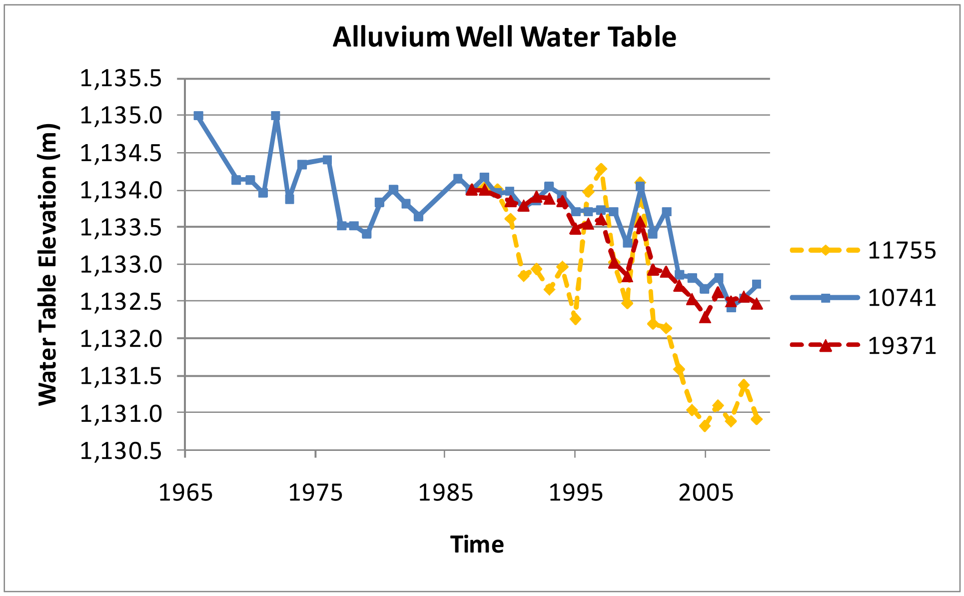


Figure 5.10: Alluvial Well Water Table Data

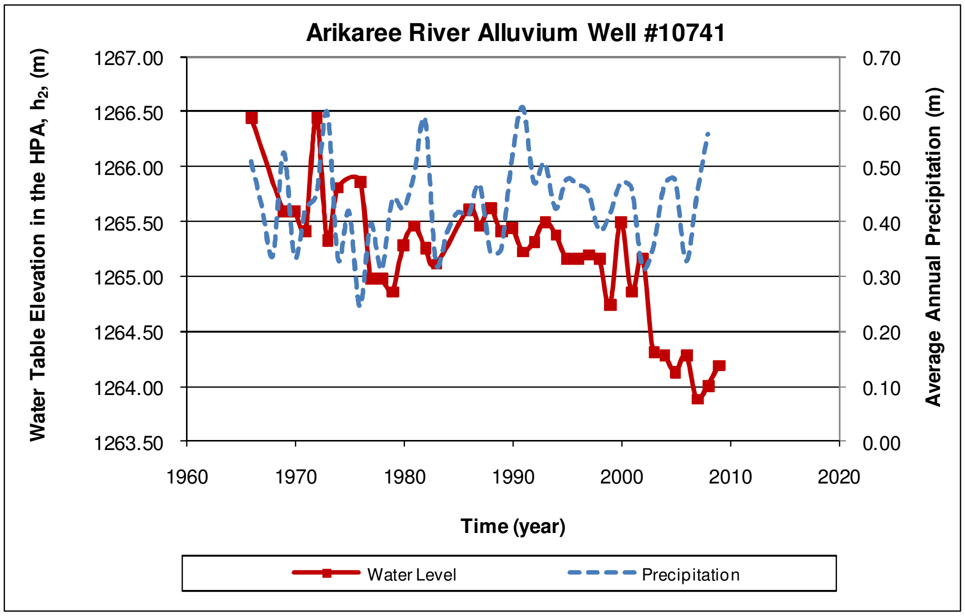


Figure 5.11: Alluvial Water Table Correlation to Precipitation

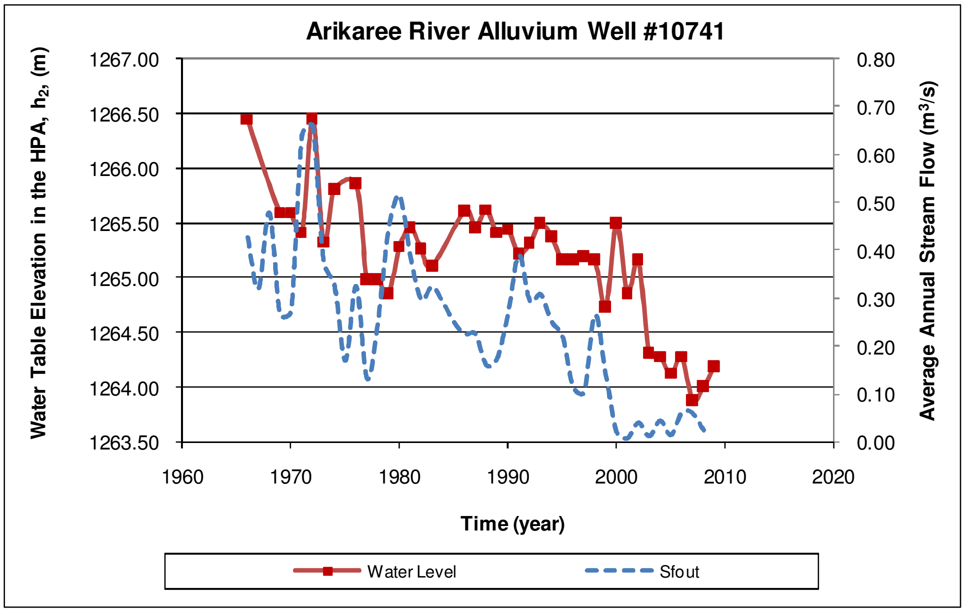


Figure 5.12: Alluvial Water Table Correlation to Streamflow

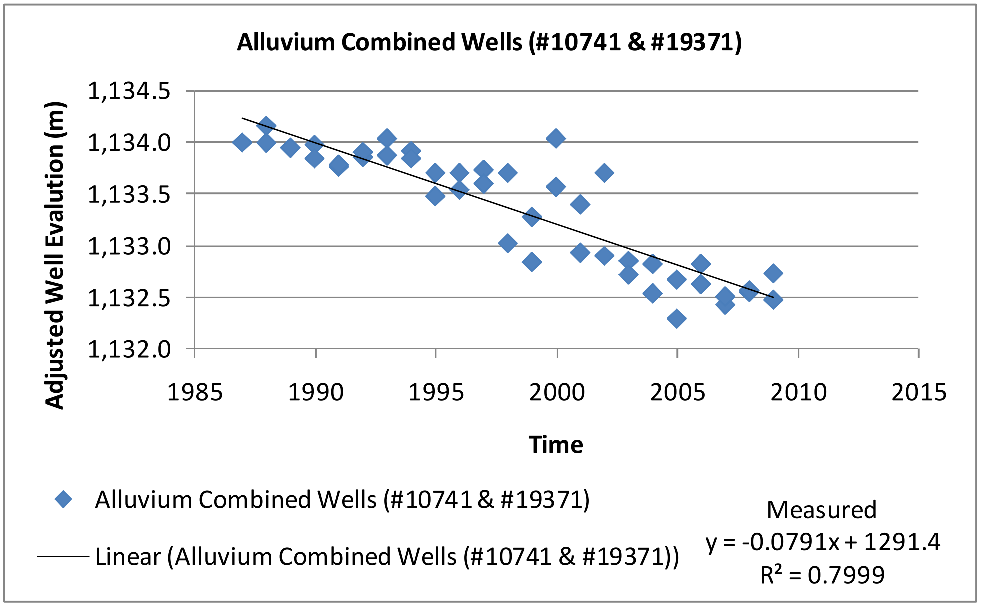


Figure 5.13: Alluvial Linear Water Table Decline

5.1.1.1 Pool Depth Results

Falke (2009) took a census of the total amount of refuge pool habitat within each of the three segments during late July, the period of lowest connectivity, from 2005-2007. No pools were present in the downstream segment during any of the surveys. In that time range, there were 172 to 218 pools identified in the upstream segment as shown in Figure

5.14. The middle segment had between 27 to 35 pools surveyed for habitat (Falke 2009). On the average, the middle segment only had 16.3% as many pools as in the upper segment. Overall, the upstream segment contained significantly more fish habitat pools than the middle segment during the driest portion of the summer 2005 to 2007 (Falke 2009). Given the high incidence of drying in the downstream and middle segments (Scheurer et al. 2003a), it appeared that the habitat would persist primarily in the upstream segment in order to sustain viable populations of native fishes like Brassy Minnow and Orange Throat darter (Falke 2009). Likewise, the decline of the remaining habitat in the middle segment would likely precede that of the upstream segment due to the number of pools. Therefore, we chose to model only the upstream portion of the basin where the alluvial aquifer directly connects to the High Plains aquifer, and where core habitats for fish are most likely to persist into the future.

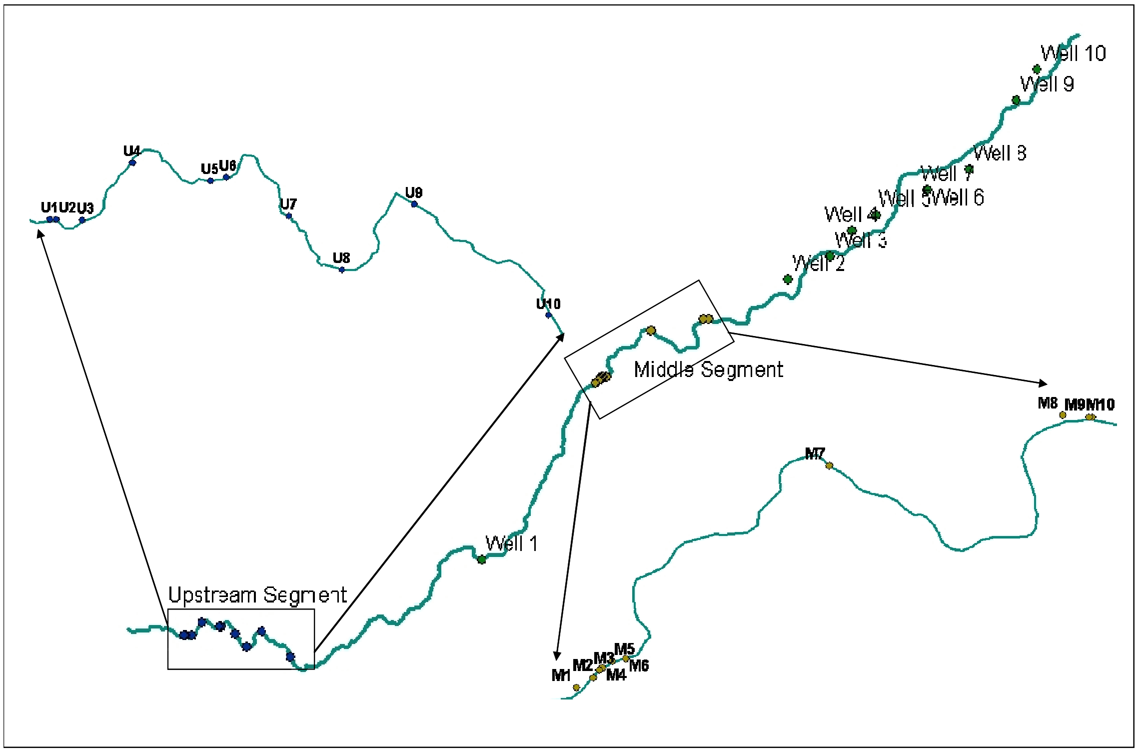


Figure 5.14: Interseasonal Habitat Census Critical Pools (Squires 2007)

Fardel (2003), Griffin (2004), and Falke (2009), showed a strong correlation between the alluvial water table and the pool depths as shown in Figure 5.15. Shallow alluvial groundwater stage directly relates to pool depth across six pairs of wells and pools in the upstream segment from April through October 2007. As the groundwater stage declined during the summer, pool depths also declined. Spikes in the groundwater stage were due to precipitation events and not reflected in pool depths. These observations indicated that the dynamics of pool stage directly related to alluvial groundwater in the Arikaree River (Falke 2009). The deepest pool in the upstream section in 2006 was 1.5 m. Therefore, for these modeling efforts we assume the bottom of the pool was approximately 1.5 m below the water table elevation in 2006.

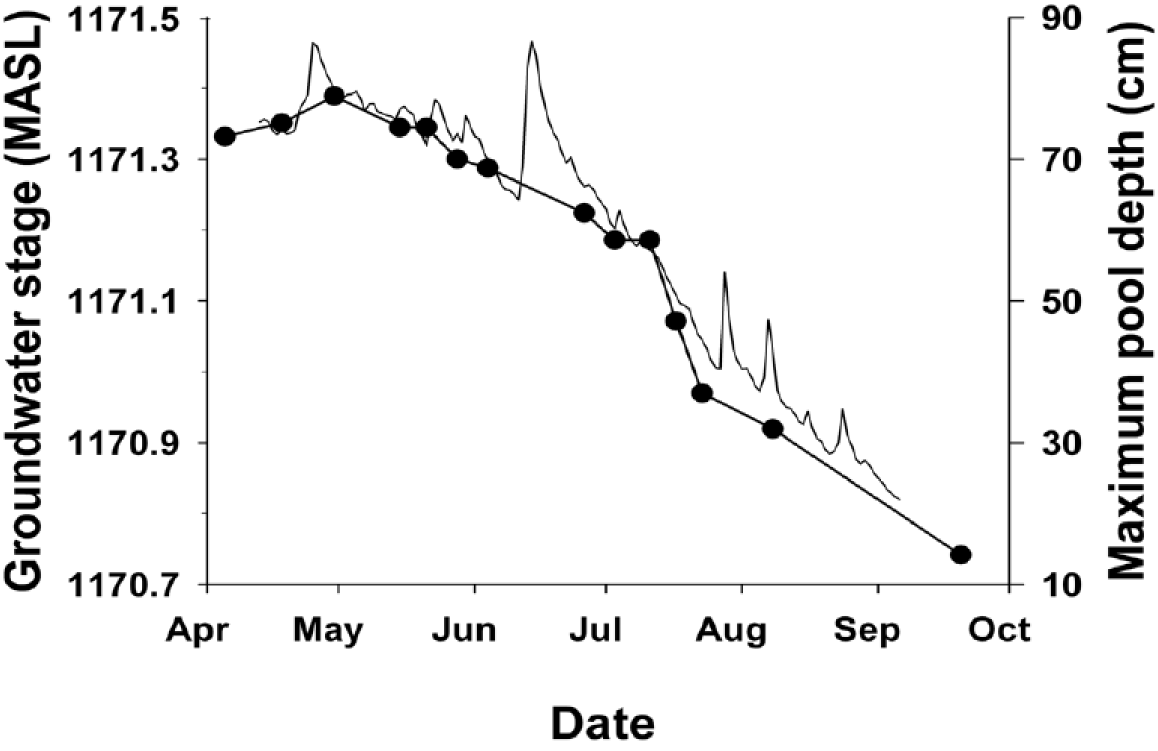


Figure 5.15: Arikaree River Pool Depth and Groundwater Stage Correlation in 2006 (Falke 2009)

5.1.1.2 Assumptions for Results

The analysis rests on coupling a modern groundwater model with a multi-scale analysis of fish habitat dynamics. The analysis performed using equations 4.1 through 4.4 and shown in Figures 4.15 through 5.24 are dependent on these underlying assumptions. The predictions made in this paper are only valid for this set of assumptions. Altering these assumptions will result in different water table decline slopes and times to pool drying. The assumptions used in this analysis are as follows:

- The pre-development water balance has negligible storage change over time ($\Delta S = 0$). That is, the groundwater table recovers after each growing season, and there is no long-term change in storage volume (Squires 2007).
- The second assumption was that current irrigation pumping rates within the Arikaree River basin would continue during the period of the forecast (2010-2050). Since large-scale agricultural irrigation began in Yuma County during the 1960s, the volume of groundwater used for irrigation has been relatively constant since 1975. In the 2007 Census of Agriculture (2009), the irrigated land in Yuma County decreased by 0.7% from 2002 to 2007. This decrease in irrigated land is very small and supports the assumption no or minimal irrigation pumping. Also, note that as the water table declines, the cost of pumping will increase, new costs of redrilling the irrigation wells deeper, and decreasing flow rate from the well will force farmers to evaluate their water usage. The additional costs noted will economically induce farmers to reduce water use, use water more wisely, and participate in water conservation practices.

- Information from the 1958 head contours and bedrock elevations are accurate to calculate the groundwater inflow and outflow from the High Plains aquifer and the alluvial aquifer.
- Information from 1983 hydraulic conductivity is accurate to calculate the groundwater inflow and outflow from the High Plains aquifer and the alluvial aquifer.
- Groundwater inflow and outflow from the High Plains aquifer are constant throughout time.
- Groundwater inflow from the western boundary alluvial aquifer is constant throughout time.
- Groundwater outflow from the alluvial aquifer changed depending on the saturated thickness.
- Stream outflow taken from 2010 to 2050 showed declines at approximately 12,007 m^3/year.
- Stream inflow assumed to be 10% of stream outflow basing this value on conclusions established in previous research by Squires (2007).
- 7% of precipitation was assumed to uniformly recharge the High Plains aquifer determined by research completed by Reddell (1967) and Sophocleous (1992).
- 15% of precipitation was assumed to uniformly recharge the alluvial aquifer (1933 to 1960) based on research completed by Willard Owens Consultants (1988) and from calibration of regional water balances (Squires 2007).
- 20% of precipitation was assumed to uniformly recharge the alluvial aquifer (1975 to 2010). This value calibration was to align the water balance model and the measured water elevation well data.

- Precipitation falls at a long-term average of 44 cm/year.
- The assumed Sya was 0.17 in the High Plains aquifer. The apparent specific yield was calculated by Squires (2007) and (R. Magelky, personal communication, April 2009) using well response water level data.
- The assumed Sya was 0.125 in the alluvium. The apparent specific yield calculation is based on the research of Squires (2007) using well response water level data.
- The assumed cottonwood ET was 89.2 cm/yr over 908.5 ha as calculated by in previous research by Riley (2009).
- Grass ET was assumed to be 10 cm/yr over remainder of alluvium (27,621.5 ha). Hanks et al. (1968) found that in Akron Colorado that native grasses used 9 cm, 10.6 cm, and 19 cm respectively in 1966, 1966, and 1967.
- The area of the High Plains aquifer was assumed to be 121,450 ha at calculated by Squires (2007).
- The assumed area of the alluvium was 28,530 ha as calculated by Wachob (2006).
- The assumed length of the transitional area was 6,470 m.
- The assumed slope of the water table was small to satisfy the Dupuit-Forcheimer assumptions that are all flows are horizontal and hydraulic gradient causing discharge is proportional to slope of water table (McWhorter and Sunada 1977).
- Water table declines assumed to occur uniformly across the aquifer resulting in average water table declines.

5.1.1.3 Status Quo Water Balance Model Results

The first scenario examines the impacts of no changes to the current water usage and pumping rates throughout the High Plains aquifer and the alluvium. The High Plains aquifer will continue to decline at a linear rate of approximately 0.183 m/year (future Projections). This rate is a lower decline rate than the modeled rate of 0.24 m/year from 1968 to 2009 (Figure 5.16). The reason for this reduced decline is that the High Plains aquifer saturated thickness is decreasing and therefore the flow out of the High Plains aquifer is decreasing. The calculated changes in water table elevations in the alluvium are approximately linear. The decline starts out small in the 1960's and 1970's and increases with time (1985 to 2009) because the alluvial aquifer is sensitive to changes in the groundwater flux. When less water feeds the alluvium, more water is taken from storage causing the water table elevation to decline. The modeled alluvial water table is decreasing approximately linearly at a rate of 0.193 m/year as shown in Figure 5.17. Figure 5.17 shows the water balance modeling for post-development and then extending the model until 2050. The modeling data matches very well with water level data from well #10741. The change in groundwater flux from the regional aquifer to the alluvium is non-linear as shown in Figure 5.18. The time-to-drying for the deepest pool in the upper segment varies from approximately 8 to 12 years depending on interactions along the river, hydraulic parameters around the pool, and the High Plains aquifer flux into the pools.

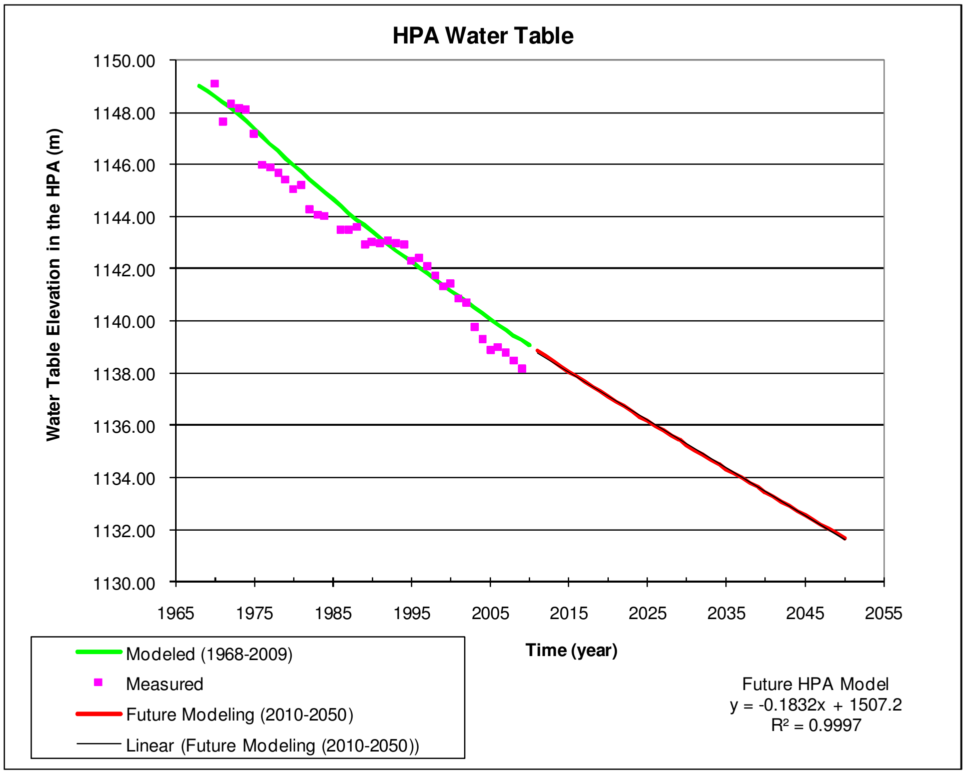


Figure 5.16: High Plains Aquifer Water Balance Model with No Changes

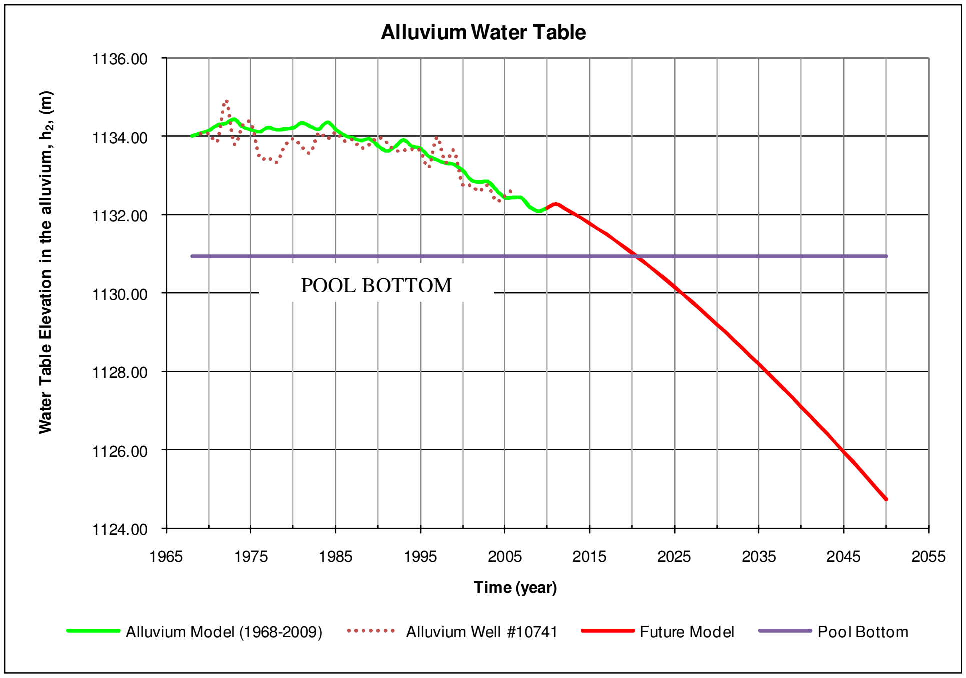


Figure 5.17: Alluvial Aquifer Water Balance Model with No Changes

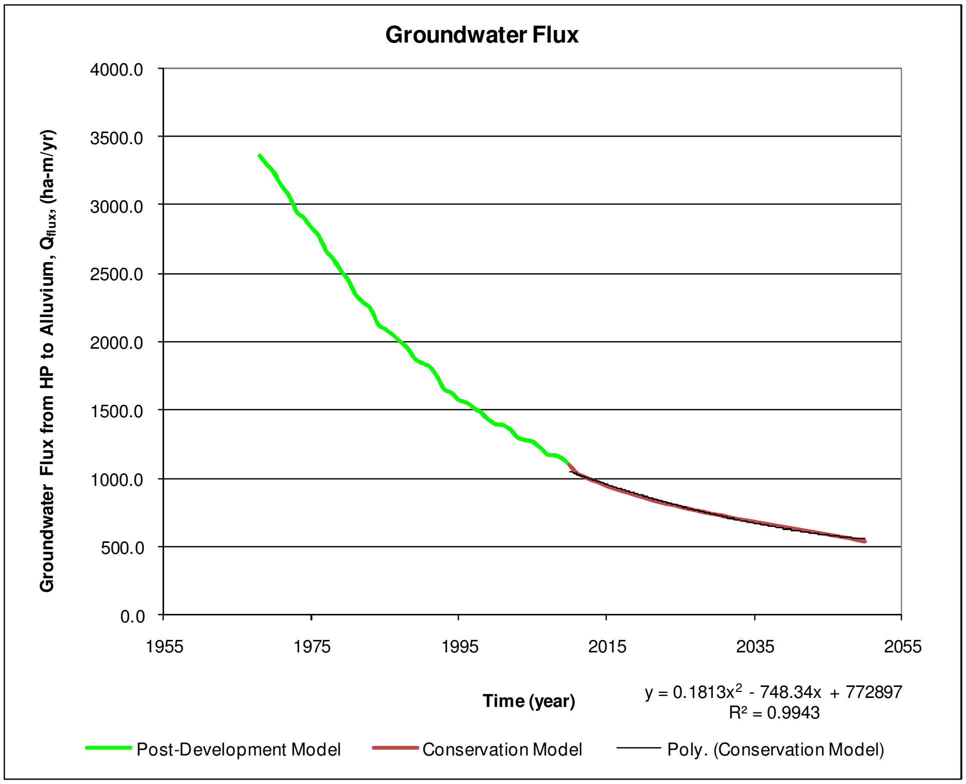


Figure 5.18: Qflux from the High Plains Aquifer to Arikaree River Alluvial Aquifer

5.1.1.4 Removal of Alluvial Wells Results

This model scenario could have immediate impact on the alluvial aquifer and would have no impact on the High Plains aquifer. The model created with 18 pumps in operation within the alluvial aquifer based on aerial photographs. The immediate impact to the Arikaree River is due to the close proximity and the direct impact that these wells have on the river. Based on the predominant hydraulic conductivities in the project area of 30 to 45 m/day, water conservation return flows to the river near the outer boundaries (17,840 m) could be between 390 to 585 days. On the other hand, nearer boundaries (5,700 m) could have return flows between 125 to 186 days. The alluvium wells that are only approximately 1390 m (#10741) from the river could have flows returned to the Arikaree River within 30 to 45 days.

This scenario will have very little to no impact on High Plains aquifer since only the wells in the alluvium are removed. The only impact on the High Plains aquifer is the change in gradients between the aquifer due to the reduced decline of the alluvial aquifer as shown in Figure 5.19. This scenario creates a temporary rise in the alluvial aquifer because of the sudden increase in flows to the alluvium. The interaction of the High Plains aquifer and alluvial systems in post-development has equilibrium declining at 0.0791 m/year with constant pumping. When the pumping is stops, it creates a temporary increase and then could create another equilibrium decline at a rate of 0.0941 m/year according to the water balance model. This scenario could potentially extend the projected pool dry up time to approximately 30 years as shown in Figure 5.20.

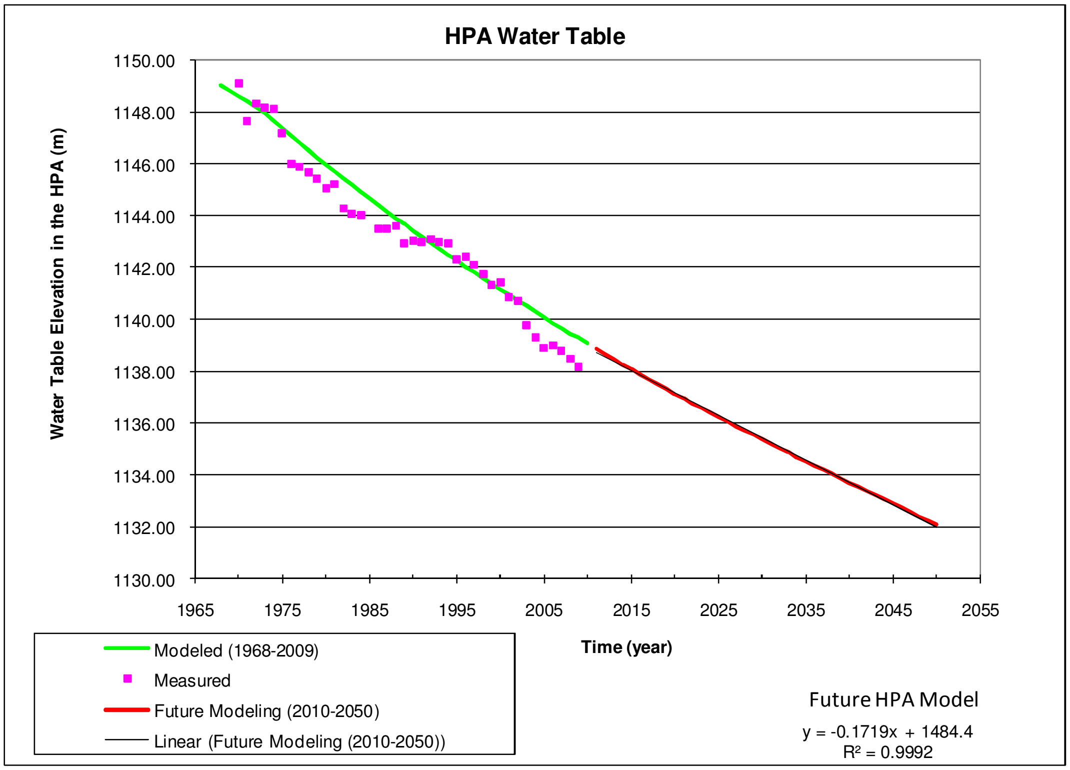


Figure 5.19: High Plains Aquifer Water Balance Model with Removal of Alluvial Wells

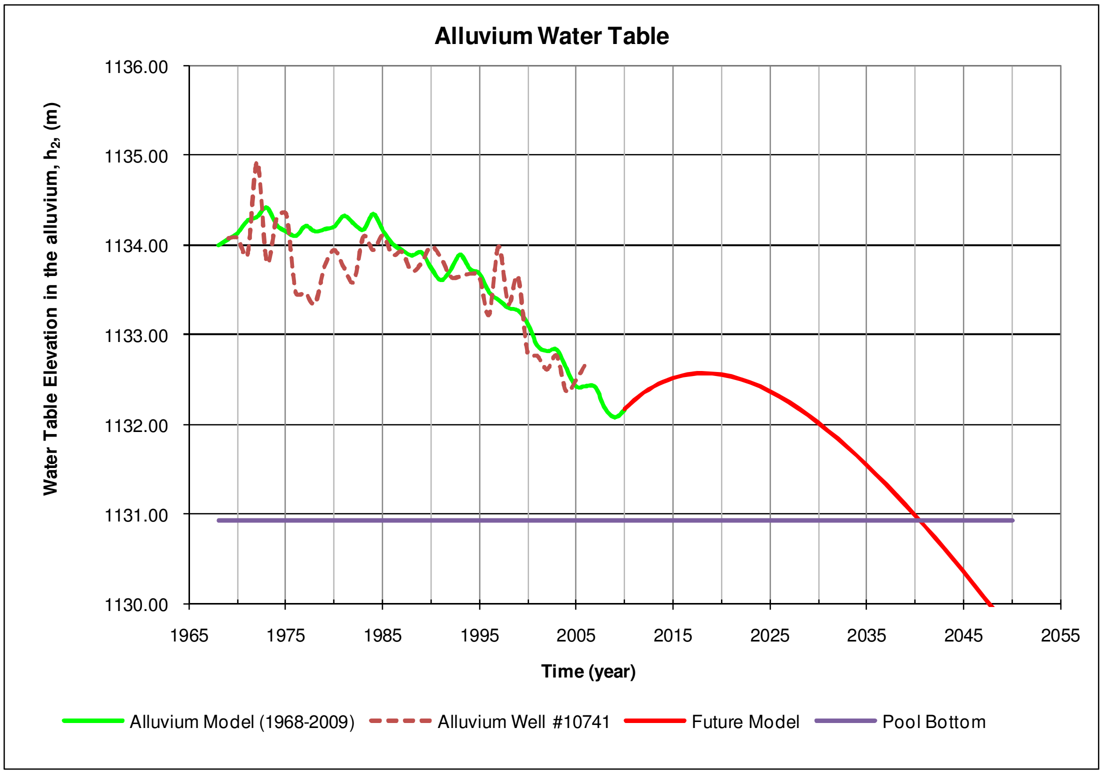


Figure 5.20: Alluvial Aquifer Water Balance Model with Removal of Alluvial Wells

5.1.1.5 No Decline in High Plains Aquifer Water Balance Results

The next model scenario evaluates what level of participation in the identified water conservation practices would be required to stop the decline in the High Plains aquifer. The model developed included the top conservation alternatives from each of the five survey sections. The impacts to the High Plains aquifer and alluvial aquifer were modeled because of reducing the quantity of water pumped by the sum of 44.8 million cubic meters due to the conservation measures. It was determined that, in order to stop the decline of the High Plains aquifer water tables it would require 77% participation of local farmers in the project area as shown in Figure 5.21. Participation would require all participants to practice all five top identified conservation practices. At 77% participation, there would need to be approximately 9,446 ha implemented with the most feasible conservation alternatives (no-till, low-pressure sprinkler package, drought tolerant crops, water use limits, and conversion to dry beans). Based on the water balance model results, stopping the decline of the High Plains aquifer would also stop the decline of the alluvial aquifer as shown in Figure 5.22. The elimination of the High Plains aquifer decline will allow a constant groundwater flux out of the High Plains aquifer into the alluvial aquifer. This constant flux into the alluvial aquifer will potentially put the system back into equilibrium. This equilibrium rate will be at a significantly lower level than the pre-development equilibrium prior to irrigation pumping.

The future water balance modeling utilized average or constant values for all parameters projected into the future. For example, the stream flow out was linearly decrease at a rate of 0.0033 m/m that was the best-fit line for stream flow for the last 10 years. An average parameter used in the future water balance modeling was precipitation data that was an average from 1932 to 2009 of 0.44 meters. The actual future water levels in the High Plains aquifer would fluctuate due to varying climatic conditions such as droughts and wet years. The water levels of the High Plains aquifer and alluvial aquifer have significant impacts from recharge that is directly proportional to precipitation.

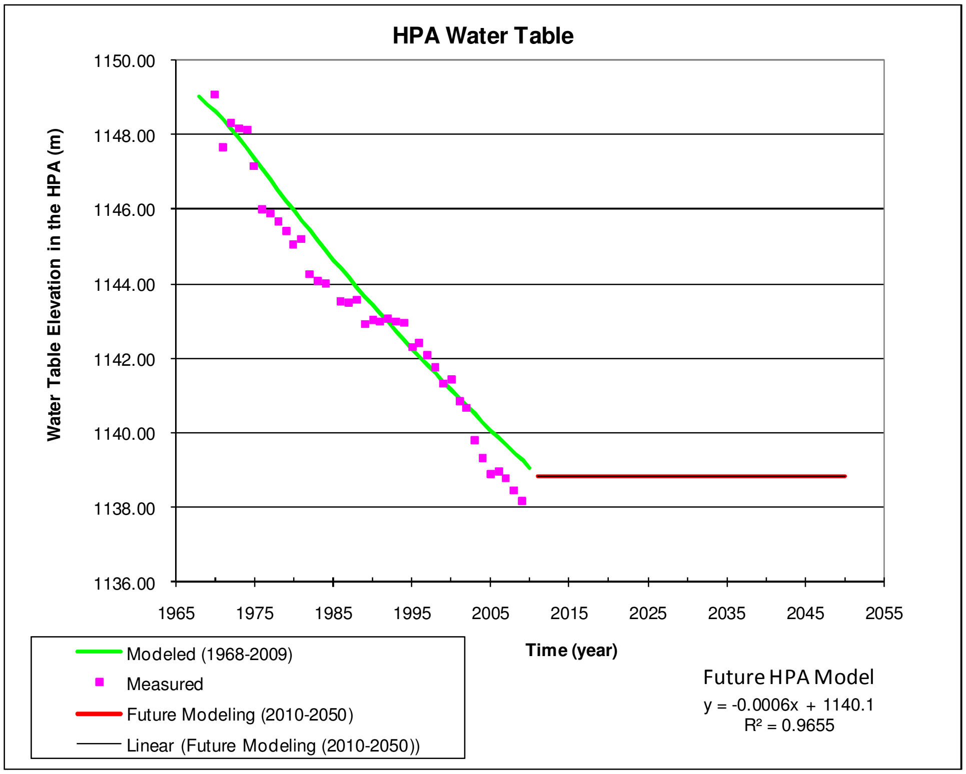


Figure 5.21: High Plains Aquifer Water Table Model with 77% Future Participation

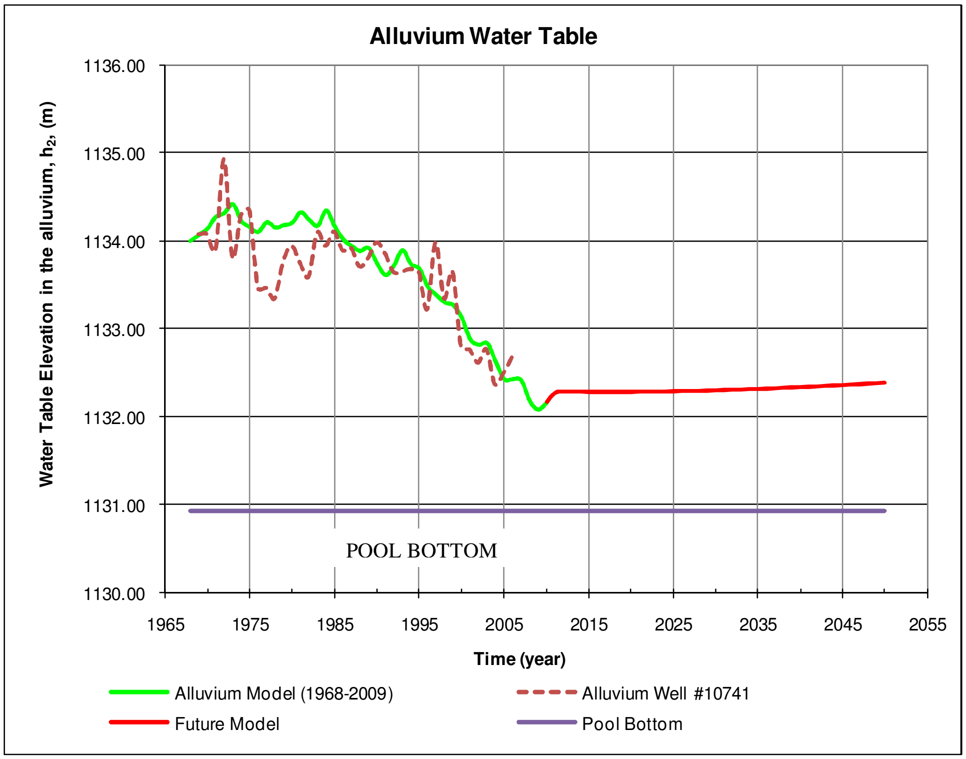


Figure 5.22: Alluvium Water Table Model with 77% Future Participation

Table 5.1 demonstrates the conservation alternative's water savings and economic impact to the local economy with 77% future participation. This level of participation would be difficult to achieve without mandatory implementation throughout the basin. The water balance model demonstrated that pumping would need reduced by at least 44.8 million cubic meters or 62.9% to maintain the current High Plains aquifer water levels and alluvial aquifer.

Table 5.1: Water Savings and Economic Impacts of 77% Participations

77% Future Participation		
Conservation Alternative	**Water Savings (m^3/year)**	**Economic Impact ($/Year)**
No-Tillage	3.72E+06	-$193,058
Low Pressure Sprinkler Package	5.46E+06	-$17,812
Drought Tolerant Crops	6.35E+06	-$358,005
Water Use Limits	2.07E+07	-$406,587
Converting to Dry Beans	1.05E+07	$481,179

5.1.1.6 Delayed Pool Dry Participation Levels

This scenario examined what level of future participation would be required to delay the habitat pool drying from the estimated current drying in approximately 10 years to 20, 30, and 40 years as shown in Figure 5.22 to 5.28. The required conservation participation to extend the pools another 20 years will require future participation of approximately 43%. Mandatory water conservation over the extended time period of 30 years would need 57% participation. The next extended time period would be 40 years with compulsory water conservation at approximately 62% participation. The water savings and economic impacts for extending the habit pool drying by 20, 30, and 40 years as shown in Table 5.2.

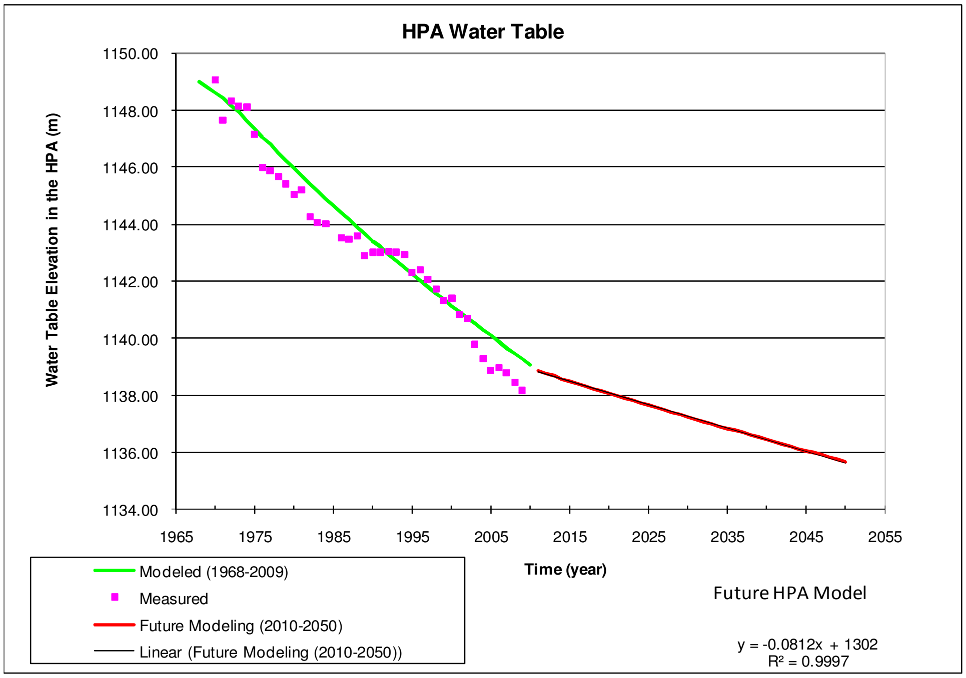


Figure 5.23: High Plains Aquifer Declines for 43% Future Participation

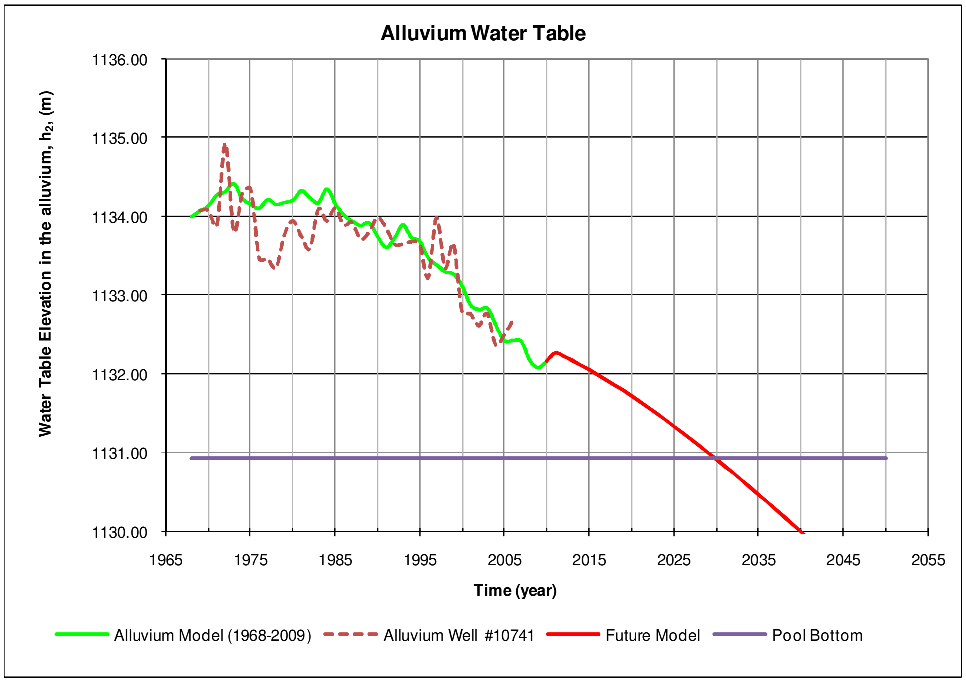


Figure 5.24: Alluvial Aquifer Declines for 43% Future Participation

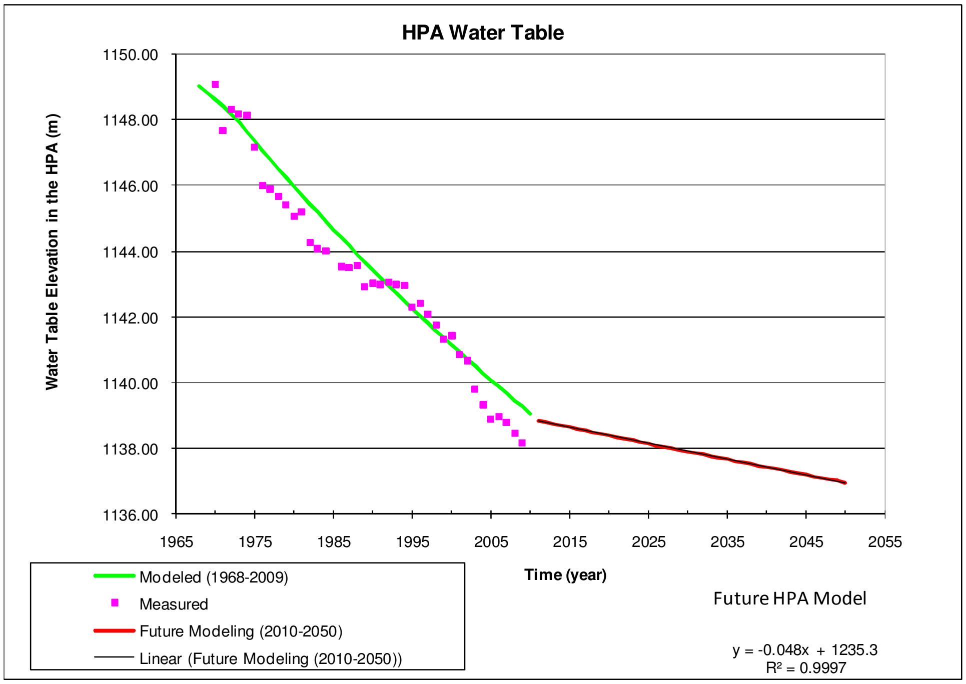


Figure 5.25: High Plains Aquifer Declines for 57% Future Participation

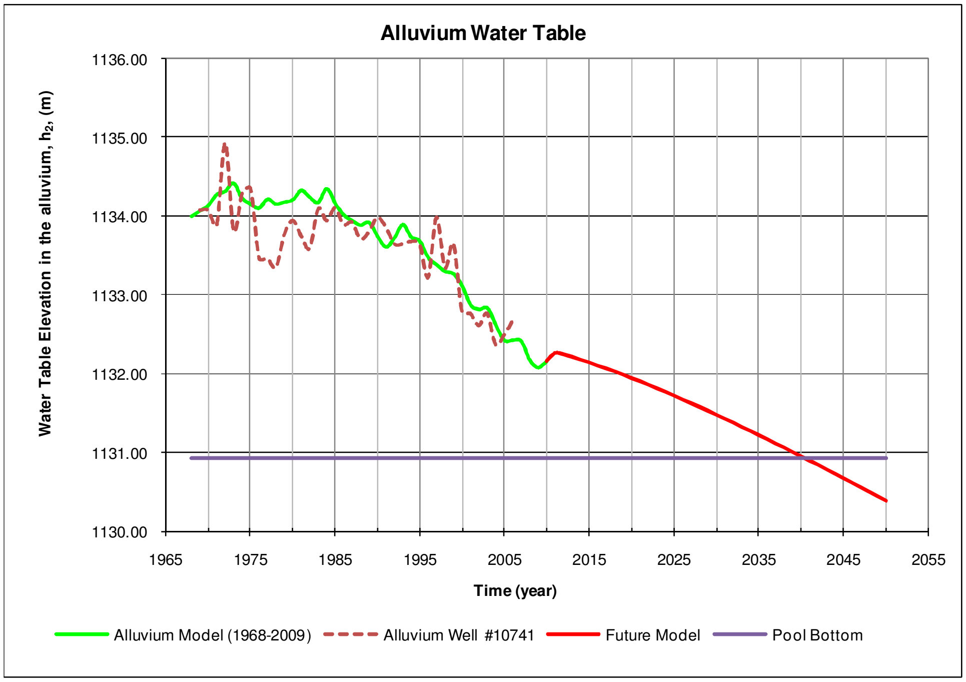


Figure 5.26: Alluvial Aquifer Declines for 57% Future Participation

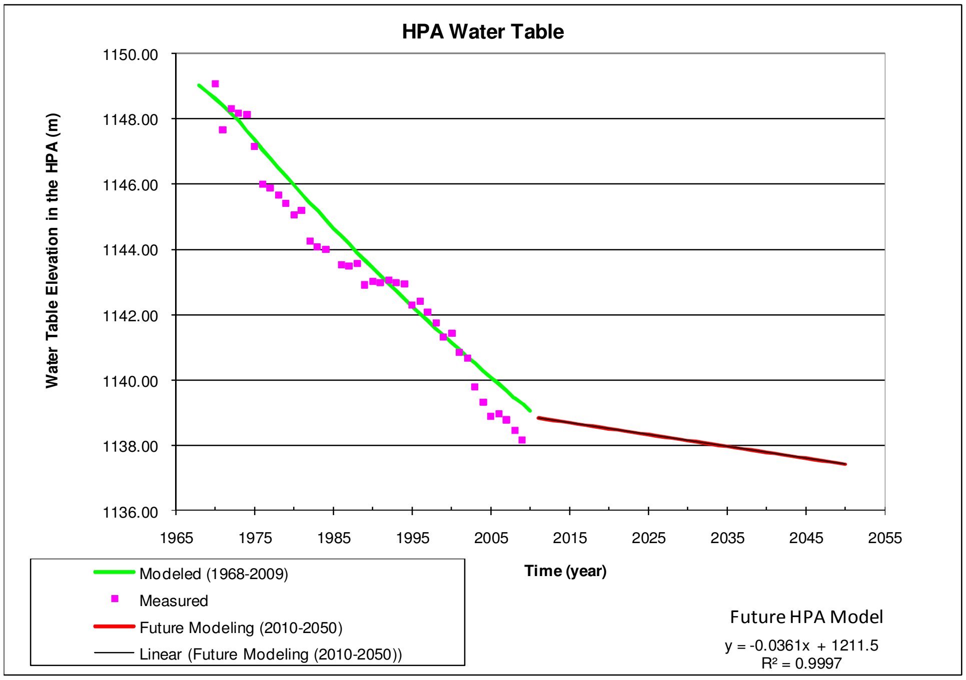


Figure 5.27: High Plains Aquifer and Alluvial Aquifer Declines for 62% Future Participation

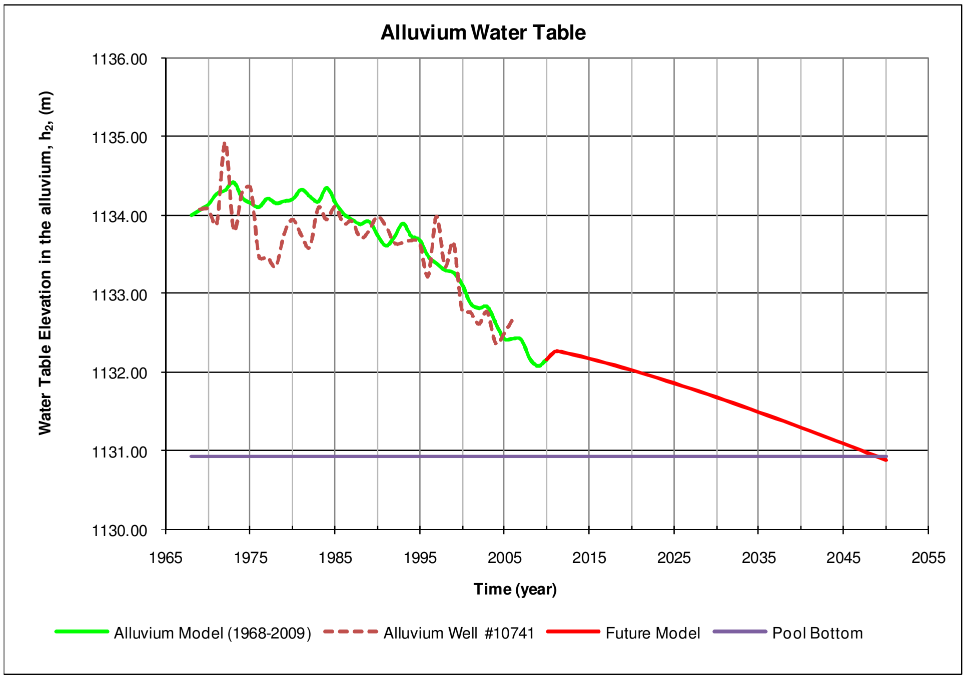


Figure 5.28: High Plains Aquifer and Alluvial Aquifer Declines for 62% Future Participation

Table 5.2: Water Savings and Economic Impacts of Varying Participation

43% Future Participation		
Conservation Alternative	**Water Savings (m^3/year)**	**Economic Impact ($/Year)**
No-Tillage	2.08E+06	-$107,812
Low Pressure Sprinkler Package	3.05E+06	-$9,947
Drought Tolerant Crops	3.54E+06	-$199,925
Water Use Limits	1.16E+07	-$227,055
Converting to Dry Beans	5.84E+06	$268,711

57% Future Participation		
Conservation Alternative	**Water Savings (m^3/year)**	**Economic Impact ($/Year)**
No-Tillage	2.75E+06	-$142,913
Low Pressure Sprinkler Package	4.05E+06	-$13,186
Drought Tolerant Crops	4.70E+06	-$265,017
Water Use Limits	1.53E+07	-$300,980
Converting to Dry Beans	7.74E+06	$356,198

62% Future Participation		
Conservation Alternative	**Water Savings (m^3/year)**	**Economic Impact ($/Year)**
No-Tillage	2.99E+06	-$155,450
Low Pressure Sprinkler Package	4.40E+06	-$14,342
Drought Tolerant Crops	5.11E+06	-$288,264
Water Use Limits	1.67E+07	-$327,382
Converting to Dry Beans	8.42E+06	$387,443

5.1.1.7 Alluvial Aquifer Decline Impacts

Declining alluvial groundwater levels due to irrigation pumping will have negative effects that extend beyond the aquatic ecosystem in these Great Plains basins. Riparian habitat areas along the Arikaree River are a critical component of stream-riparian ecosystems in the Great Plains, providing stable stream banks, cooler stream temperatures from shading, and habitat for many terrestrial species (Rood et al. 2003). One suggestion is to reduce flows from the river by removing phreatophytes (e.g., riparian trees and grasses) that depend on shallow alluvial groundwater. The removal or lack of persistence of the riparian canopy can lead to increased stream temperatures and stream bank erosion causing negative effects on fish, and other aquatic organisms. The valuable economic and cultural human activities that depend on the riparian habitats would be destroyed if there was a collapse of the riparian area forests. Overall, declining alluvial groundwater levels will have far-reaching, negative effects across both terrestrial and aquatic ecosystems in the Arikaree River basin.

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

The Arikaree River located on the eastern High Plains of Colorado is one of the last strongholds for the state's threatened Brassy Minnow (*Hybognathus hankinsoni*) in Colorado. The Arikaree River and its alluvial aquifer connect hydraulically to the High Plains aquifer. River drying occurs during the growing season due to riparian ET and irrigation pumping to reduce aquatic habitat.

The objective of this research was to identify feasible implementation of water conservation alternatives in the future within eastern Colorado. This research also identified the impact of implementing the water conservation measures on the High Plains aquifer, Arikaree River, and alluvial aquifer. The links between the groundwater aquifers are dynamic to fish habitat in the Arikaree River. This objective was accomplished with the development and calibration of a numerical water balance model, an economic model, and a conservation water savings model. Combining these tools resulted in a model that predicts river drying and the impact of irrigation pumping to local farmers and the community.

6.1 SUMMARY

The basis for the research was gathering information about feasible water conservation alternatives for future implementation in eastern Colorado. A water conservation survey was distributed to farmers in eastern Colorado (predominantly in Yuma County) to identify the top three conservation alternatives in each section. The discussed water conservation methods were in the following sections: field practices, irrigation practices, management practices, water conservation programs, and conversion to less water consumptive crops.

A first attempt to create an economic model examined the impact to farmers of costs of water savings, reducing pumping, and yield reductions. It was determined that conservation alternatives could have savings or costs that will affect the implementation of conservation alternatives. Use this information carefully because the model did not incorporate all factors, but it is valid for comparison in evaluating the water conservation measures.

The water conservation savings model developed from a comprehensive literature review of agricultural water conservation alternatives. Incorporating these water savings and yield impacts data into a model facilitated understanding of the impact to the project area. Using these conservation alternatives and water saving methods, the future impact to the High Plains aquifer and Arikaree River was projected.

A numerical water balance model of the alluvial aquifer-stream system was developed to link groundwater to pool depths in the Arikaree River for two conditions: before the installation of high-capacity wells and after the installation of high-capacity wells to determine the relationship between the regional High Plains aquifer and the alluvial aquifer. The relationships between yearly regional water table declines, the yearly alluvial water table declines, and the groundwater flux from the regional aquifer to the alluvium required estimation. These relationships used in conjunction with Darcy's Law to predict the groundwater flux, regional water table elevation, and alluvial water table elevation into the future.

Coupling the water balances with Darcy's Law demonstrated that pumping in the regional High Plains aquifer causes a decline in the water table elevation which is linearly approximated at 0.25 m/year. The change in groundwater flux from the regional aquifer to the alluvium is non-linear due to the continued water level decline in the High Plains aquifer. The calculated changes in water table elevations in the alluvium are also non-linear from the beginning of irrigation pumps and linearly declining from 1985 to 2010. The decline is small initially and increases with time because the alluvial aquifer is sensitive to changes in the groundwater flux. When less water feeds the alluvium, more water comes from storage. As a result, the water table elevation declines.

Long-term modeling used the equations determined from the water balance and Darcy's Law. The calculations show that the river is at a critical point for preservation and could go dry in the next 8 to 12 years with no changes to the current pumping. The river may not have another thirty to fifty years as other research has suggested (Squires 2007; Falke 2009). Removing the 18 alluvial wells will have immediate impact on the alluvial water table and pool depth. The removed alluvial wells will also extend the time to pool dry by approximately 30 years. This research showed that to maintain the current High Plains aquifer water levels and alluvial aquifer, it would require 77% participation in the water conservation programs or reduction of at least 44.8 million cubic meters of irrigation pumping. The results could be a significantly higher or lower water level elevation because of changing climatic conditions and therefore should be evaluated in future research.

The upstream river segment provides more fish habitat throughout the season than the middle river segment. During the summer months, the riparian evapotranspiration mainly influence the upstream river segment because it is outside of the radius of the influence of the alluvial and regional wells. Pumping from alluvial wells influences the middle river segment. The upper portion of the middle segment is also influenced by riparian evapotranspiration and pumping. Declining alluvial groundwater levels due to irrigation pumping will have negative effects that extend beyond the aquatic ecosystem in the Arikaree River. Riparian habitat areas along the Arikaree River is a critical component of stream-riparian ecosystems in the Great Plains, providing stable stream banks, cooler stream temperatures from shading, and habitat for many terrestrial species (Rood et al. 2003). The breakdown of riparian area forests ruins any activities that depend on riparian habitats. Overall, declining alluvial groundwater levels will have far-reaching, negative effects across both terrestrial and aquatic ecosystems in the Arikaree River basin.

The analysis in this thesis indicates that the impacts of pumping in the regional High Plains aquifer are likely to be more important on river stage and aquatic habitat over years due to the alluvial aquifer sensitivity to reducing flux from the High Plains aquifer. The intraseasonal fluctuations caused by alluvial stresses such as riparian ET and precipitation do not appear to cause long term declines in the alluvial water table. This is because the alluvium is very sensitive to the changes in groundwater flux from the regional aquifer. This research examined many different alternatives to implement in order to reduce the decline to the High Plains aquifer and the Arikaree River.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

- The extensive and inclusive analysis of economic impact of the top water conservation methods from all five sections from the survey would be the first recommendation for research. This analysis will provide a more accurate assessment of the potential impact of the water conservation economics to local farmers and to the local communities. This research will provide a guide to local farmers as to the feasible water conservation methods and their economic impact.
- Another research needed is the further survey analysis to determine the feasibility of top water conservation methods from all five segments of the survey. This survey data could also collect more information on potential participation of local farmers in the region and expand the survey area to include more responses throughout eastern Colorado.
- On-site farm study with local farmers to implement water conservation methods identified from one of the five segments of the survey. The on-site farm research with local farmers in eastern Colorado would identify the potential water savings and benefits of identified water conservation methods. The research will meter water usage on selected fields with and without water conservation methods over a two-year period. The two-year study period is a minimum amount of time required to establish trends. Although, having longer periods of research can reduce the possible impacts on trends due to variable weather. Results from the research will allow water users to evaluate current and future conservation techniques, their effect on groundwater levels, and on flows into surrounding rivers and streams.

- Monitor test wells to determine the interaction of the High Plains aquifer to determine how it supplies water to the Arikaree River alluvial aquifer. The test wells or existing irrigation wells would be located at specified distances from river. Then use this interaction of the two systems to update the flow model to the Arikaree River in order to gain a better understanding of the interaction.
- On-site farm study of dry land farming and/or alternatives for low water use crops. Identify the water savings from low water use crops, yields, and the economic impact to individual farmers and local community.
- Study of the current and future participation of water conservation programs in Yuma County. On-site farm study of the actual water saving of a specific water conservation program implemented in Yuma County
- Another recommendation for research is to make future predictions of the High Plains aquifer and the Arikaree River alluvial aquifer impacts from historical and extrapolated climatic data as well as incorporating the climate change. The research will also look at impacts from potential climate change on future water supplies and agricultural production.
- Evaluate different management scenarios to determine how to reestablish dynamic equilibrium in the Arikaree River basin. The model will also be useful to evaluate the impacts of water management decisions in the river.

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CHAPTER 8 APPENDICES

8.1 WATER CONSERVATION SURVEY

Agricultural Water in Colorado

A Survey of Potential Water Conservation in Eastern Colorado

Colorado State University
College of Civil and Environmental Engineering
By Dr. Ramchand Oad and Adam Prior

Questions about the survey and about water conservation research may be directed to Adam Prior at (970) 420-7607.
Please complete the survey to the best of your ability with current knowledge of agricultural water conservation practices. Survey can also be completed online at http://www.engr.colostate.edu/~aprior/survey.htm*.*
Thank you for your participation.

SECTION 1. General Farm Information

In order to better understand how water resources are used in your farming operation, we would like to learn a little of the farm's characteristics. Please answer the following questions to the best of your ability.

1. In what county is the majority of your farm located?
2. How many *total cropland* acres do you farm, both irrigated and dryland, including land that you own and rent from others?
3. How many of these acres are **irrigated**?

County
Acres

4. What are your sources of irrigation water? (*This column should add up to 100 %)*

Source	% of Supply in "Normal" Year
Individual Diversion	%
Irrigation District	%
Ditch Company	%
Groundwater	%
Total	**100 %**

5. Colorado farmers may have reduced irrigation supplies as part of compact compliance, drought conditions, and where well capacity cannot meet crop water requirements. How many inches of water could you voluntarily reduce pumping from your well(s) (Inches)?

Inches

6. Please indicate your expected cropping plans for 2009 by completing the table below. If unsure of your plans, please make your best estimate.

Crop	Irrigated Acres	Dry-Land Acres	Crop	Irrigated Acres	Dry-Land Acres
Alfalfa Hay	Acres	Acres	Sugar Beets	Acres	Acres
Corn Silage	Acres	Acres	Potatoes	Acres	Acres
Corn Grain	Acres	Acres	Onions	Acres	Acres
Dry Beans	Acres	Acres	Wheat	Acres	Acres

Grass Hay/Pasture	Acres	Acres	Sunflower	Acres	Acres
Perennial Forge Crops	Acres	Acres	Barley/Oats	Acres	Acres
Soybean	Acres	Acres	Proso Millet	Acres	Acres
Sudan for Hay	Acres	Acres	Other (Please List)	Acres	Acres
Sorghum, Grain	Acres	Acres	Other (Please List)	Acres	Acres

SECTION 2. Field Practices

We would like to know more about the conservation practices that you currently use on your farm, the practices you are most likely to add in the future, and the reasons why you would not use these practices. That field method(s) are practiced on your irrigated acres? (please check ☑) If you would not use the practice, please check ☑ the reason(s) why. Rank the top three field practices that are most feasible to implement on your farm that are not already in use (Ranked 1st, 2nd, 3rd-Only 3 responses).

		If NOT Likely to Adopt the Field Practice in the Next 5 Years, Please Check ☑ the Reason(s) Why You Would Not Adopt This Practice.					
Field Practices	**I Use This Field Practice (Please Check if YES)**	**This Practice Reduces Profits per Acre Too Much**	**I Do Not Have the Funds to Implement This Practice**	**I Do Not Know How to Implement This Practice**	**My Farm's Soils are Not Suited for This Practice**	**I Lack the Equipment to Perform This Practice**	**Rank the Top 3 Practices I Am Most Likely to Begin Using in the Next 5 Years. (Ranked 1st, 2nd, 3rd- Only 3 Responses)**
No Tillage	☐	☐	☐	☐	☐	☐	
Minimum Tillage	☐	☐	☐	☐	☐	☐	
Strip Tillage or Zone Tillage	☐	☐	☐	☐	☐	☐	
Mulch Tillage or Other Conservation Tillage	☐	☐	☐	☐	☐	☐	

Land Leveling	☐	☐	☐	☐	☐	☐	
Manage Crop Residue/Tillage to Reduce Evaporation	☐	☐	☐	☐	☐	☐	
Build Conservation Bench Terraces	☐	☐	☐	☐	☐	☐	
Other (Please List)	☐	☐	☐	☐	☐	☐	

SECTION 3. Irrigation System Information

This section will help us learn about typical irrigation systems in the Arikaree River Basin and Eastern Colorado, so that we can better design irrigation research. That irrigation system improvement(s) are currently utilized on your irrigated acres (please check ☑)? If you would not adopt the irrigation system, please check ☑ the reason(s) why. If you plan to adopt a new system, upgrade your current system now or in the future, list the top three irrigation system upgrades that could be implemented that are not already in use (Ranked 1st, 2nd, 3rd-Only 3 responses).

Irrigation Improvements		**If NOT Likely to Adopt the Irrigation System in the Next 5 Years, Please Check ☑ the Reason(s) Why You Would Not Adopt This Practice.**					
Sprinkler Systems	**I Currently Utilize This Irrigation Practice (Please Check if YES)**	**This Practice Reduces Profits per Acre Too Much**	**I Do Not Have the Funds to Implement This Practice**	**I Do Not Know How to Implement This Practice**	**My Farm's Soils are Not Suited for This Practice**	**I Lack the Equipment to Adopt This Practice**	**Rank the 3 Improvements You are Most Likely do in the Next 5 Years. (Ranked 1st, 2nd, 3rd-Only 3 Responses)**
Use Multi-function Irrigation System (Fertigation and Chemigation)	☐	☐	☐	☐	☐	☐	
Install Low Pressure Heads on Drop Tubes	☐	☐	☐	☐	☐	☐	

Retrofit Well with Smaller or More Efficient Pump	☐	☐	☐	☐	☐	☐	
Replace Old or Leaking Underground Pipe	☐	☐	☐	☐	☐	☐	
Low Pressure Sprinkler Packages (MESA, LPIC, LESA, and LEPA)	☐	☐	☐	☐	☐	☐	
Use Drip Irrigation – Higher Efficiency	☐	☐	☐	☐	☐	☐	
Recover Water from Air Injection in Drip Systems-Subsurface Drip System – Shown to Increase Yields and Reduce Crop Stress – Less Water	☐	☐	☐	☐	☐	☐	
Remove End Gun – Can Create Uniformity Problems	☐	☐	☐	☐	☐	☐	
Remote and Automated Control Systems	☐	☐	☐	☐	☐	☐	
Other (Please List)	☐	☐	☐	☐	☐	☐	

SECTION 4. Management Practices

In Colorado, farmers may have reduced irrigation supplies as part of compact compliance, drought conditions, and where well capacity cannot meet crop water requirements. We would like to learn your opinion about the reduced irrigation practices listed below even if you have not been faced with limited water supplies. Please check ☑ whether you currently use the management practices listed in the table below. If you would not adopt the management practices, please check ☑ the reason(s) why. List the top three management practices that could be implemented that are not already in use (Ranked 1st, 2nd, 3rd -Only 3 responses).

		If NOT Likely to Adopt the Practice in the Next 5 Years, Please Check ☑ the Reason(s) Why You Would Not Adopt This Practice.					
Management Practices	**I Use This Management Practice Currently**	**This Practice Reduces Profits per Acre Too Much**	**I Do Not Have the Funds to Implement This Practice**	**I Do Not Know How to Implement This Practice**	**My Farm's Soils are Not Suited for This Practice**	**I Lack the Equipment to Adopt This Practice**	**Rank the 3 Practices You are Most Likely to Adopt in the Next 5 Years (Ranked 1st, 2nd, 3rd- Only 3 Responses)**
Plant Crops That Use Less Water or Drought Tolerant Crops	☐	☐	☐	☐	☐	☐	
Plant Crops with Shorter Growing Season	☐	☐	☐	☐	☐	☐	
Reduce Irrigation (Deficit Irrigate) Throughout the Season	☐	☐	☐	☐	☐	☐	
Reduce Irrigation Early in the Season, but Irrigate Fully Later in the Season	☐	☐	☐	☐	☐	☐	
End the Irrigation Season Earlier than Usual	☐	☐	☐	☐	☐	☐	
Schedule Irrigation Based on Crop Requirement (Monitor Soil Moisture, Rainfall, ET)	☐	☐	☐	☐	☐	☐	
Schedule Irrigation Based on Crop Requirements (Crop Consultant)	☐	☐	☐	☐	☐	☐	
System Performance (Well Water Meter, Routinely Checking Pumping Efficiency)	☐	☐	☐	☐	☐	☐	
Incorporate a Fallow Period into the Crop	☐	☐	☐	☐	☐	☐	

Rotation							
Grow a Dryland Crop as Part of a Crop Rotation that Includes Irrigated Crops	☐	☐	☐	☐	☐	☐	
Fallow a Portion of a Formerly Irrigated Field and Fully Irrigate the Remainder	☐	☐	☐	☐	☐	☐	
Convert to a Non-Irrigated Crop or Pasture	☐	☐	☐	☐	☐	☐	
Switch to Cool Season Crops (e.g. Wheat)	☐	☐	☐	☐	☐	☐	
Splitting Pivots Between Crops that Use Irrigation at Different Times	☐	☐	☐	☐	☐	☐	
Other (Please List)	☐	☐	☐	☐	☐	☐	

SECTION 5. Programs

One alternative for addressing water shortage is for the State, County, or conservation district to provide conservation programs with incentives to reduce the water irrigated. We would like to learn about the programs that you might find most promising with regard to your farm so that we can research them more fully and use them in our extension programming. Please check ☑ whether you currently participate in programs listed in the table below. Please check ☑ whether you would participate in the programs listed in the table below. Rank the top three programs that you would be willing to participate in that you are not already participating (Ranked 1st, 2nd, 3rd - Only 3 responses). Please indicate the minimum payment to participate in this program ($/acre) and the maximum percentage of land included in the program (%).

State, Country, and District Programs	**I Currently Participate in This or a Similar Program**	**I Would be Willing to Participate in This Program, If Compensated Enough (Please Check)**	**Rank the 3 Programs I am Most Likely Participate (Ranked 1st, 2nd, 3rd- Only 3 Responses)**	**Minimum Payment per Acre to Participate ($/acre)**	**Maximum Percent of Irrigated Land Committed to Program (%)**
Permanent Voluntary Retirement of Irrigation Well.	☐	☐ YES ☐ NO			
Temporary Well Retirement Program	☐	☐ YES ☐ NO			
Rotational Fallow Incentive	☐	☐ YES ☐ NO			
Federal Land Retirement Program (e.g., CRP, CREP, GSWC, WRP, and GRP)	☐	☐ YES ☐ NO			

Voluntary Conservation Incentives to Implement Conservation Practices	☐	☐ YES ☐ NO			
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	☐	☐ YES ☐ NO			
Financial Incentives for Conservation Irrigation Equipment Upgrades	☐	☐ YES ☐ NO			
Tax or Payment Incentive for Ceasing to Irrigate Less Productive Land and Convert to Dryland Farming or Environmental Easements	☐	☐ YES ☐ NO			
Incentive for Conversion to Less Water Intensive Crop	☐	☐ YES ☐ NO			
Other (Please List)	☐	☐ YES ☐ NO			

SECTION 6. Crop Selection

In Colorado, farmers may choose or be given incentives to reduce irrigation water use, we would like to learn your opinion about how likely it is that you would include the following lower water use crops listed below in your rotation. Each of these corps would receive some irrigation water, but would not receive more than typical fully irrigated corn. Please check ☑ whether you would adopt the crop listed in the table below. Please check ☑ whether you would participate in the programs listed in the table below. If you would not adopt these lower water use crops, please check ☑ the reason(s) why. Rank the top three low water use crops that could be implemented and are not already in (Ranked 1st, 2nd, 3rd- Only 3 responses).

		If NOT Likely to Plant the Crop, Please Check ☑ the Reason(s) Why You Would Not Plant This Crop.					
Low Water Use or Drought Tolerant Crops	**I Would Plant This Low Water Use Crop (Please Check)**	**This Crop is Not Profitable Enough**	**I Do Not Have the Knowledge to Convert to This Crop**	**My Farm's Soils are Not Suited for This Crop**	**I Lack the Equipment to Grow This Crop**	**Rank the 3 Crops I am Most Likely to Plant (Ranked 1st, 2nd, 3rd- Only 3 Responses)**	**Maximum Percent of Irrigated Land I Would Convert if Compensated (%)**
Barley/Oats	☐ YES ☐ NO	☐	☐	☐	☐		
Beans, Dry	☐ YES ☐ NO	☐	☐	☐	☐		
Hay Millet	☐ YES ☐ NO	☐	☐	☐	☐		
Proso Millet	☐ YES ☐ NO	☐	☐	☐	☐		
Sorghum, Grain	☐ YES ☐ NO	☐	☐	☐	☐		
Soybeans	☐ YES ☐ NO	☐	☐	☐	☐		
Sudan for Hay	☐ YES ☐ NO	☐	☐	☐	☐		
Sunflowers	☐ YES ☐ NO	☐	☐	☐	☐		
Irrigated Wheat, Winter	☐ YES ☐ NO	☐	☐	☐	☐		
Irrigated Wheat/Barley, Spring	☐ YES ☐ NO	☐	☐	☐	☐		
Perennial Forage Crops	☐ YES ☐ NO	☐	☐	☐	☐		
Other (Please List)	☐ YES ☐ NO	☐	☐	☐	☐		
Other (Please List)	☐ YES ☐ NO	☐	☐	☐	☐		

SECTION 7. Demographic Information

Demographic information will help us to target our outreach information and technical assistance. The information is completely confidential and will only be reported as averages.

1. On the irrigated farming operation , I am the: (check all that apply)
   ☐ Owner/Operator ☐ Manager ☐ Other_______________
   ☐ Absentee owner ☐ Employee

2. Please check the range of year when you were born:
   ☐ Before – 1938 ☐ 1939 – 1948 ☐ 1949 – 1958
   ☐ 1959 – 1968 ☐ 1969 – 1978 ☐ 1979 – 1988
   ☐ 1989 – 1998 ☐ 1999 – After

3. Please check the last year of education that you completed:
   ☐ Elementary School ☐ Technical/Vocational ☐ Bachelors Degree
   ☐ High School ☐ Some College ☐ Some Post-Graduate Education
   ☐ Post-Graduate Degree

4. Please check your estimated annual **gross** farm and ranch sales.
   ☐ Less Than $25,000 ☐ $101,001 - $250,000 ☐ Between $1 and $5 million
   ☐ $25,001 - $50,000 ☐ $250.001 - $500,000 ☐ Over $5 million
   ☐ $50,001 - $100,000 ☐ $500,001 - $1,000,000

5. What percent of your annual **gross** farm and ranch sales come from irrigated farming? _______%

6. Do you have another job off the farm?
   ☐ Yes ☐ No
   If you answered ***yes***, what percent of your household income comes from farming/ranching? _______%

THANK YOU *very much for taking the time to answer this questionnaire. Your responses will be kept confidential. Please return the completed survey in the enclosed postage-paid envelope. Please feel free to use the space below to give us any additional comments you may have.*

8.2 WATER BALANCE MODELS

Pre-Development Water Balance:

Table 8.1: Regional Water Balance (High Plains Aquifer and Alluvial Aquifer)

Regional	**Value**	**Units**
RechargeHPA	3.73E+07	m^3
RechargeAlluv	1.88E+07	m^3
GWHPAin	3.77E+06	m^3
GWAlluvin	4.45E+06	m^3
Sfin	2.30E+06	m^3
Sfout	2.30E+07	m^3
Riparian ET	8.10E+06	m^3
Grass ET	2.77E+07	m^3
GWHPAout	6.77E+06	m^3
GWAlluvout	1.03E+06	m^3
Balance	**0.00**	$\mathbf{m^3}$

Table 8.2: High Plain Aquifer and Alluvial Aquifer Water Balances

HPA	**Value**	**Units**	**Alluvial**	**Value**	**Units**
RechargeHPA	3.73E+07	m^3			
			RechargeAlluv	1.88E+07	m^3
GWHPAin	3.77E+06	m^3			
			GWAlluvin	4.45E+06	m^3
			Sfin	2.30E+06	m^3
			Sfout	2.30E+07	m^3
			Riparian ET	8.10E+06	m^3
			Grass ET	2.77E+07	
GWHPAout	6.77E+06	m^3			
			GWAlluvout	1.03E+06	m^3
Qflux	3.43E+07	m^3	Qflux	3.43E+07	m^3
Balance	**0.00**	$\mathbf{m^3}$	**Balance**	**0.00**	$\mathbf{m^3}$

Post-Development Water Balance:

Table 8.3: Regional Water Balance (High Plains Aquifer and Alluvial Aquifer)

Regional	**Value**	**Units**
RechargeHPA	3.73E+07	m^3
RechargeAlluv	1.88E+07	m^3
GWHPAin	3.77E+06	m^3
GWAlluvin	4.45E+06	m^3
Sfin	2.30E+06	m^3
Sfout	2.30E+07	m^3
Riparian ET	8.10E+06	m^3
Grass ET	2.77E+07	m^3
GWHPAout	6.77E+06	m^3
GWAlluvout	1.03E+06	m^3
Pumping-AlluvOut	6.68E+06	m^3
Pumping-HPAOut	6.45E+07	m^3
Balance	**-7.12E+07**	**m^3**

Table 8.4: High Plains Aquifer and Alluvial Aquifer Water Balances

HPA	**Value**	**Units**	**Alluvium**	**Value**	**Units**
RechargeHPA	3.73E+07	m^3			
			RechargeAlluv	1.88E+07	m^3
GWHPAin	3.77E+06	m^3			
			GWAlluvin	4.45E+06	m^3
			Sfin	2.30E+06	m^3
			Sfout	2.30E+07	m^3
			Riparian ET	8.10E+06	m^3
			Grass ET	2.77E+07	
GWHPAout	6.77E+06	m^3			
			GWAlluvout	1.03E+06	m^3
Qflux	3.43E+07	m^3	Qflux	3.43E+07	m^3
			Pumping-AlluvOut	6.68E+06	m^3
Pumping-HPAOut	6.45E+07	m^3			
Balance	-6.45E+07	m^3	**Balance**	-6.68E+06	m^3

Table 8.5: Post-Development Calculations

Qflux	**Time**	**h1**	**h2**	**Δy_{HPA}**	**Δy_{alluv}**	**Qwell alluv**	**Qwell HPA**
m^3/m/d	**year**	**m**	**m**	**m**	**m**	**m^3/yr**	**m^3/yr**
Eqn 4.2		**Eqn 4.4a**	**Eqn 4.4b**	**Eqn 4.3**	**Eqn 4.4**		
0.543	1968	1149.00	1134.00				
0.532	1969	1148.81	1134.07	0.190	-0.070	4.14E+06	4.00E+07
0.522	1970	1148.62	1134.14	0.212	-0.135	4.67E+06	4.52E+07
0.507	1971	1148.41	1134.27	0.234	-0.044	5.21E+06	5.03E+07
0.495	1972	1148.17	1134.32	0.255	-0.102	5.74E+06	5.55E+07
0.477	1973	1147.92	1134.42	0.270	0.191	6.14E+06	5.94E+07
0.470	1974	1147.65	1134.23	0.289	0.074	6.68E+06	6.45E+07
0.458	1975	1147.36	1134.15	0.287	0.049	6.68E+06	6.45E+07
0.448	1976	1147.07	1134.10	0.284	-0.109	6.68E+06	6.45E+07
0.431	1977	1146.79	1134.21	0.281	0.060	6.68E+06	6.45E+07
0.420	1978	1146.51	1134.15	0.276	-0.026	6.68E+06	6.45E+07
0.408	1979	1146.23	1134.18	0.272	-0.029	6.68E+06	6.45E+07
0.396	1980	1145.96	1134.21	0.269	-0.120	6.68E+06	6.45E+07
0.379	1981	1145.69	1134.33	0.265	0.088	6.68E+06	6.45E+07
0.370	1982	1145.43	1134.24	0.260	0.067	6.68E+06	6.45E+07
0.363	1983	1145.17	1134.17	0.257	-0.176	6.68E+06	6.45E+07
0.345	1984	1144.91	1134.35	0.255	0.183	6.68E+06	6.45E+07
0.338	1985	1144.65	1134.17	0.250	0.149	6.68E+06	6.45E+07
0.332	1986	1144.40	1134.02	0.248	0.073	6.68E+06	6.45E+07
0.324	1987	1144.15	1133.95	0.246	0.059	6.68E+06	6.45E+07
0.316	1988	1143.91	1133.89	0.244	-0.036	6.68E+06	6.45E+07
0.304	1989	1143.67	1133.92	0.241	0.175	6.68E+06	6.45E+07
0.298	1990	1143.42	1133.75	0.238	0.135	6.68E+06	6.45E+07
0.294	1991	1143.19	1133.61	0.236	-0.110	6.68E+06	6.45E+07
0.283	1992	1142.95	1133.72	0.235	-0.173	6.68E+06	6.45E+07
0.268	1993	1142.72	1133.90	0.231	0.159	6.68E+06	6.45E+07
0.263	1994	1142.48	1133.74	0.227	0.053	6.68E+06	6.45E+07
0.255	1995	1142.26	1133.68	0.225	0.206	6.68E+06	6.45E+07
0.252	1996	1142.03	1133.48	0.223	0.091	6.68E+06	6.45E+07
0.246	1997	1141.81	1133.39	0.222	0.085	6.68E+06	6.45E+07
0.240	1998	1141.59	1133.30	0.220	0.031	6.68E+06	6.45E+07
0.232	1999	1141.37	1133.27	0.218	0.148	6.68E+06	6.45E+07
0.226	2000	1141.15	1133.12	0.216	0.242	6.68E+06	6.45E+07
0.225	2001	1140.93	1132.88	0.214	0.061	6.68E+06	6.45E+07
0.220	2002	1140.72	1132.82	0.214	-0.016	6.68E+06	6.45E+07
0.210	2003	1140.51	1132.84	0.212	0.214	6.68E+06	6.45E+07
0.208	2004	1140.29	1132.62	0.209	0.194	6.68E+06	6.45E+07
0.206	2005	1140.08	1132.43	0.209	-0.002	6.68E+06	6.45E+07
0.199	2006	1139.87	1132.43	0.208	0.013	6.68E+06	6.45E+07
0.191	2007	1139.67	1132.42	0.206	0.237	6.68E+06	6.45E+07
0.189	2008	1139.46	1132.18	0.204	0.097	6.68E+06	6.45E+07
0.186	2009	1139.26	1132.08	0.203	-0.080	6.68E+06	6.45E+07

Post Development Calculations cont.

Time	Qflux	HpA elev	Alluv elev	Sfout	Qalluvout	Precip	Ralluv
year	m^3/yr	m	m	m^3/yr	m^3/yr	m	m^3/yr
1968	3.36E+07	32.00	9.00	1.01E+07	1.03E+06	0.34	1.45E+07
1969	3.29E+07	31.81	9.07	1.51E+07	1.03E+06	0.53	2.25E+07
1970	3.23E+07	31.60	9.20	8.34E+06	1.03E+06	0.34	1.44E+07
1971	3.14E+07	31.36	9.25	8.61E+06	1.03E+06	0.42	1.81E+07
1972	3.06E+07	31.11	9.35	2.02E+07	1.03E+06	0.45	1.92E+07
1973	2.95E+07	30.84	9.16	2.08E+07	1.03E+06	0.60	2.56E+07
1974	2.91E+07	30.55	9.08	1.20E+07	1.03E+06	0.33	1.90E+07
1975	2.84E+07	30.26	9.04	1.04E+07	1.03E+06	0.42	2.39E+07
1976	2.77E+07	29.98	9.14	5.38E+06	1.03E+06	0.25	1.40E+07
1977	2.66E+07	29.70	9.08	1.03E+07	1.03E+06	0.40	2.26E+07
1978	2.60E+07	29.42	9.11	4.21E+06	1.03E+06	0.31	1.78E+07
1979	2.52E+07	29.15	9.14	7.88E+06	1.03E+06	0.44	2.52E+07
1980	2.45E+07	28.88	9.26	1.41E+07	1.03E+06	0.42	2.41E+07
1981	2.35E+07	28.62	9.17	1.63E+07	1.03E+06	0.49	2.78E+07
1982	2.29E+07	28.36	9.10	1.22E+07	1.03E+06	0.59	3.34E+07
1983	2.24E+07	28.10	9.28	9.38E+06	1.03E+06	0.32	1.85E+07
1984	2.13E+07	27.84	9.10	1.03E+07	1.03E+06	0.38	2.17E+07
1985	2.09E+07	27.59	8.95	9.20E+06	1.03E+06	0.42	2.38E+07
1986	2.06E+07	27.35	8.88	7.91E+06	1.03E+06	0.41	2.35E+07
1987	2.00E+07	27.10	8.82	7.12E+06	1.03E+06	0.47	2.67E+07
1988	1.96E+07	26.86	8.85	7.13E+06	1.03E+06	0.34	1.97E+07
1989	1.88E+07	26.61	8.68	5.06E+06	1.03E+06	0.35	2.00E+07
1990	1.85E+07	26.38	8.54	5.54E+06	1.03E+06	0.52	2.95E+07
1991	1.82E+07	26.14	8.65	8.55E+06	1.03E+06	0.61	3.47E+07
1992	1.75E+07	25.91	8.83	1.23E+07	1.03E+06	0.47	2.70E+07
1993	1.65E+07	25.68	8.67	9.29E+06	1.03E+06	0.51	2.90E+07
1994	1.63E+07	25.45	8.61	9.73E+06	1.03E+06	0.42	2.42E+07
1995	1.58E+07	25.22	8.41	7.95E+06	1.03E+06	0.48	2.72E+07
1996	1.56E+07	25.00	8.32	6.97E+06	1.03E+06	0.47	2.67E+07
1997	1.52E+07	24.78	8.23	3.63E+06	1.03E+06	0.46	2.60E+07
1998	1.48E+07	24.56	8.20	3.33E+06	1.03E+06	0.38	2.19E+07
1999	1.43E+07	24.34	8.05	8.39E+06	1.03E+06	0.41	2.36E+07
2000	1.40E+07	24.12	7.81	4.47E+06	1.03E+06	0.47	2.69E+07
2001	1.39E+07	23.91	7.75	6.81E+05	1.03E+06	0.46	2.63E+07
2002	1.36E+07	23.70	7.77	2.85E+05	1.03E+06	0.32	1.81E+07
2003	1.30E+07	23.48	7.55	1.30E+06	1.03E+06	0.36	2.03E+07
2004	1.28E+07	23.27	7.36	4.17E+05	1.03E+06	0.47	2.66E+07
2005	1.27E+07	23.07	7.36	1.43E+06	1.03E+06	0.48	2.71E+07
2006	1.23E+07	22.86	7.35	4.99E+05	1.03E+06	0.33	1.88E+07
2007	1.18E+07	22.65	7.11	1.98E+06	1.03E+06	0.45	2.56E+07
2008	1.17E+07	22.45	7.01	1.92E+06	1.03E+06	0.56	3.19E+07
2009	1.15E+07	22.24	7.09	8.05E+05	1.03E+06	0.44	2.50E+07

8.3 WATER BALANCE CALCULATIONS

Table 8.6: Water Balance Future Projections (77% Participation)

Qflux	Time	h1	h2	Δy_{HPA}	Δy_{alluv}	Qwell alluv	Qwell HPA
m^3/m/d	year	m	m	m	m	ha-m/yr	ha-m/yr
Eqn 4.2		Eqn 4.4a	Eqn 4.4b	Eqn 4.3	Eqn 4.4		
0.18	2010	1139.05	1132.16	0.202	-0.102	667.5	6452.5
0.17	2011	1138.85	1132.27	0.003	-0.013	247.8	2395.6
0.17	2012	1138.85	1132.28	0.001	0.001	247.8	2395.6
0.17	2013	1138.85	1132.28	0.001	0.001	247.8	2395.6
0.17	2014	1138.85	1132.28	0.001	0.001	247.8	2395.6
0.17	2015	1138.85	1132.28	0.001	0.001	247.8	2395.6
0.17	2016	1138.84	1132.28	0.001	0.000	247.8	2395.6
0.17	2017	1138.84	1132.28	0.001	0.000	247.8	2395.6
0.17	2018	1138.84	1132.28	0.001	0.000	247.8	2395.6
0.17	2019	1138.84	1132.28	0.001	0.000	247.8	2395.6
0.17	2020	1138.84	1132.28	0.001	-0.001	247.8	2395.6
0.17	2021	1138.84	1132.28	0.001	-0.001	247.8	2395.6
0.17	2022	1138.84	1132.28	0.001	-0.001	247.8	2395.6
0.17	2023	1138.84	1132.28	0.001	-0.001	247.8	2395.6
0.17	2024	1138.84	1132.28	0.001	-0.002	247.8	2395.6
0.17	2025	1138.84	1132.28	0.001	-0.002	247.8	2395.6
0.17	2026	1138.84	1132.28	0.001	-0.002	247.8	2395.6
0.17	2027	1138.84	1132.29	0.001	-0.002	247.8	2395.6
0.17	2028	1138.84	1132.29	0.001	-0.002	247.8	2395.6
0.17	2029	1138.83	1132.29	0.001	-0.003	247.8	2395.6
0.17	2030	1138.83	1132.29	0.001	-0.003	247.8	2395.6
0.17	2031	1138.83	1132.30	0.001	-0.003	247.8	2395.6
0.17	2032	1138.83	1132.30	0.001	-0.003	247.8	2395.6
0.17	2033	1138.83	1132.30	0.001	-0.003	247.8	2395.6
0.17	2034	1138.83	1132.31	0.001	-0.003	247.8	2395.6
0.17	2035	1138.83	1132.31	0.001	-0.004	247.8	2395.6
0.17	2036	1138.83	1132.31	0.001	-0.004	247.8	2395.6
0.17	2037	1138.83	1132.32	0.000	-0.004	247.8	2395.6
0.17	2038	1138.83	1132.32	0.000	-0.004	247.8	2395.6
0.17	2039	1138.83	1132.32	0.000	-0.004	247.8	2395.6
0.17	2040	1138.83	1132.33	0.000	-0.004	247.8	2395.6
0.17	2041	1138.83	1132.33	0.000	-0.005	247.8	2395.6
0.17	2042	1138.83	1132.34	0.000	-0.005	247.8	2395.6
0.17	2043	1138.83	1132.34	0.000	-0.005	247.8	2395.6
0.17	2044	1138.83	1132.35	0.000	-0.005	247.8	2395.6
0.17	2045	1138.83	1132.35	0.000	-0.005	247.8	2395.6
0.17	2046	1138.83	1132.36	0.000	-0.005	247.8	2395.6
0.17	2047	1138.83	1132.36	0.000	-0.005	247.8	2395.6
0.17	2048	1138.83	1132.37	0.000	-0.005	247.8	2395.6
0.17	2049	1138.83	1132.37	0.000	-0.006	247.8	2395.6
0.17	2050	1138.83	1132.38	0.000	-0.006	247.8	2395.6

Water Balance Future Projections (77% Paricipation) cont.

Time year	Qflux ha-m/yr	HpA elev m	Alluv elev m	Sfout ha-m/yr	Qalluvout ha-m/yr	Precip m	Ralluv ha-m/yr
2010	1100.6	22.04	7.20	80.5	103.0	0.44	2501.1
2011	1052.3	22.04	7.21	79.41	103.0	0.44	2501.1
2012	1049.7	22.04	7.21	78.27	103.0	0.44	2501.1
2013	1049.6	22.04	7.21	77.13	103.0	0.44	2501.1
2014	1049.6	22.04	7.21	75.98	103.0	0.44	2501.1
2015	1049.5	22.04	7.21	74.83	103.0	0.44	2501.1
2016	1049.4	22.03	7.21	73.68	103.0	0.44	2501.1
2017	1049.3	22.03	7.21	72.53	103.0	0.44	2501.1
2018	1049.2	22.03	7.21	71.37	103.0	0.44	2501.1
2019	1049.0	22.03	7.21	70.20	103.0	0.44	2501.1
2020	1048.8	22.03	7.21	69.04	103.0	0.44	2501.1
2021	1048.5	22.03	7.21	67.87	103.0	0.44	2501.1
2022	1048.2	22.03	7.21	66.70	103.0	0.44	2501.1
2023	1047.9	22.03	7.21	65.52	103.0	0.44	2501.1
2024	1047.6	22.03	7.21	64.34	103.0	0.44	2501.1
2025	1047.3	22.03	7.21	63.16	103.0	0.44	2501.1
2026	1046.9	22.03	7.22	61.97	103.0	0.44	2501.1
2027	1046.5	22.03	7.22	60.78	103.0	0.44	2501.1
2028	1046.1	22.02	7.22	59.59	103.0	0.44	2501.1
2029	1045.7	22.02	7.22	58.39	103.0	0.44	2501.1
2030	1045.2	22.02	7.23	57.20	103.0	0.44	2501.1
2031	1044.8	22.02	7.23	55.99	103.0	0.44	2501.1
2032	1044.3	22.02	7.23	54.79	103.0	0.44	2501.1
2033	1043.8	22.02	7.24	53.58	103.0	0.44	2501.1
2034	1043.2	22.02	7.24	52.37	103.0	0.44	2501.1
2035	1042.7	22.02	7.24	51.15	103.0	0.44	2501.1
2036	1042.2	22.02	7.25	49.93	103.0	0.44	2501.1
2037	1041.6	22.02	7.25	48.71	103.0	0.44	2501.1
2038	1041.0	22.02	7.25	47.48	103.0	0.44	2501.1
2039	1040.4	22.02	7.26	46.26	103.0	0.44	2501.1
2040	1039.8	22.02	7.26	45.02	103.0	0.44	2501.1
2041	1039.2	22.02	7.27	43.79	103.0	0.44	2501.1
2042	1038.6	22.02	7.27	42.55	103.0	0.44	2501.1
2043	1037.9	22.02	7.28	41.31	103.0	0.44	2501.1
2044	1037.3	22.02	7.28	40.06	103.0	0.44	2501.1
2045	1036.6	22.02	7.29	38.81	103.0	0.44	2501.1
2046	1035.9	22.02	7.29	37.56	103.0	0.44	2501.1
2047	1035.2	22.02	7.30	36.31	103.0	0.44	2501.1
2048	1034.5	22.02	7.30	35.05	103.0	0.44	2501.1
2049	1033.8	22.02	7.31	33.79	103.0	0.44	2501.1
2050	1033.1	22.02	7.31	32.52	103.0	0.44	2501.1

8.4 WATER CONSERVATION TABLES

Table 8.7: Field Practices (77% Participation)

Field Top Practices	Water Saved (cm)	Practice In Use (%)	Total Water Savings (m^3)
No Tillage / Minimum Tillage	7.87	50%	3.72E+06
Strip Tillage or Zone Tillage	6.99	54%	3.03E+06

Table 8.8: Management Practices (77% Participation)

Top Management Practices	Potential Savings (%)	Survey Practice In Use (%)	Dominate Crop Water Use (cm)	Percent of Land in Corn (%)	Total Water Savings (m^3)
Plant Crops That Use Less Water or Drought Tolerant Crops	10%	75%	67.2	52%	6.35E+06
Plant Crops with Shorter Growing Season	9%	69%	67.2	52%	5.87E+06
Reduce Irrigation Early in the Season, but Irrigate Fully Later in the Season	23%	58%	67.2	52%	1.44E+07

Table 8.9: Irrigation System (77% Participation)

Top Irrigation Practices	Water Saved (%)	Practice In Use (%)	Traditional Center Pivot Irrigation Efficiency (%)	New Irrigation Efficiency (%)	Dominate Crop Water Use (cm)	Total Water Applied for Corn (cm)	Total Water Savings (m^3)
Use Multi-function Irrigation System	23%	71%	75%	85%	67.2	89.6	2.15E+06
Retrofit Well with Pump or Motor	5%	53%	75%	80%	67.2	89.6	1.50E+06
Low Pressure Sprinkler Packages	19%	61%	75%	90%	67.2	89.6	3.52E+06
Use Drip Irrigation	26%	3%	75%	89%	67.2	89.6	9.05E+06

Table 8.10: Programs (77% Participation)

Top Programs	Dominant Crop Water Use (cm)	Water Use Limit (cm/yr)	Less Water Intensive Crop (Average of Top Crops)	Land Fallow Percentage Per Farmer (Percent)	Water Savings (cm)	Total Water Savings (m^3)
Rotational Fallow Incentive	67.2	-	-	25%	67.2	1.59E+07
Water Use Limits Over Certain Period Incentive	67.2	45.3	-	-	21.9	2.07E+07
Incentive for Conversion to Less Water Intensive Crop	67.2	-	56.0	-	11.2	1.06E+07

Table 8.11: Crop Conversion (77% Participation)

Top Crops	**Crop Water Use (cm)**	**Dominate Crop Water Use (cm)**	**Survey Participation (%)**	**Yuma Crop Use (%)**	**Water Savings (cm)**	**Total Water Savings (m^3)**
Wheat, Winter	47.7	67.2	24%	33%	19.5	1.24E+07
Beans, Dry	55.8	67.2	12%	3%	11.4	1.05E+07
Soybeans	64.4	67.2	11.2%	0%	2.8	2.62E+06

8.5 WATER ECONOMIC TABLES

Table 8.12: Field Practices (77% Participation)

Field Top Practices	Average Equipment Capital Cost Spread Over 20 years ($/m^3)	Production Return ($/m^3)	Savings Water Return ($/m^3)	Savings of Pumping Return ($/m^3)	Sum of Costs/ Returns ($/m^3)	Calculated Water Savings (m^3)	Total Economic Impact ($/yr)
No Tillage / Minimum Tillage	$0.001	-$0.012	-$0.036	-$0.006	-$0.0519	3.7E+06	-$193,058
Strip Tillage or Zone Tillage	$0.001	-$0.012	-$0.036	-$0.006	-$0.0526	3.0E+06	-$159,566

Table 8.13: Irrigation System (77% Participation)

Top Irrigation Practices	Average Capital Costs Spread of 20 years ($/m^3)	Average Annual Costs ($/m^3)	Savings Water Return ($/m^3)	Savings of Pumping Return ($/m^3)	Sum of Costs/Returns ($/m^3)	Calculated Water Savings (m^3)	Total Economic Impact ($/yr)
Use Multi-function Irrigation System	$0.009	$0.027	-$0.036	-$0.006	-$0.005	2.2E+06	-$10,910
Retrofit Well Pump or Motor	$0.003	$0.013	-$0.036	-$0.006	-$0.026	1.5E+06	-$39,235
Low Pressure Sprinkler Packages	$0.009	$0.027	-$0.036	-$0.006	-$0.005	3.5E+06	-$17,812
Use Drip Irrigation	$0.021	$0.051	-$0.036	-$0.006	$0.031	9.1E+06	$279,280

Table 8.14: Management Practices (77% Participation)

Top Management Practices	Average Seed Capital Cost (\$/m^3)	Yield Cost (\$/m^3)	Yield Return (\$/m^3)	Savings Water Return (\$/m^3)	Savings of Pumping Return (\$/m^3)	Sum of Costs/Returns (\$/m^3)	Calculated Water Savings (m^3)	Total Economic Impact (\$/yr)
Plant Crops That Use Less Water or Drought Tolerant Crops	\$0.009	\$0.00	-\$0.023	-\$0.036	-\$0.006	-\$0.056	6.3E+06	-\$358,005
Plant Crops with Shorter Growing Season	\$0.009	\$0.00	-\$0.023	-\$0.036	-\$0.006	-\$0.056	5.9E+06	-\$331,155
Reduce Irrigation Early in the Season, but Irrigate Fully Later in the Season	\$0.00	\$0.022	\$0.00	-\$0.036	-\$0.006	-\$0.020	1.4E+07	-\$282,405

Table 8.15: Programs (77% Participation)

Top Programs	Costs of Reduced Irrigation Area (\$/m^3)	Cost of Crop Change (\$/m^3)	Yield Cost (\$/m^3)	Savings Water Return (\$/m^3)	Savings of Pumping Return (\$/m^3)	Sum of Costs/Returns (\$/m^3)	Calculated Water Savings (m^3)	Total Economic Impact (\$/yr)
Rotational Fallow Incentive	\$0.34	\$0.00	\$0.00	-\$0.036	-\$0.006	0.302	1.6E+07	\$4,796,819
Water Use Limits Over Certain Period Incentive (2, 3, or 5 years)	\$0.00	\$0.00	\$0.022	-\$0.036	-\$0.006	-0.020	2.1E+07	-\$406,587
Incentive for Conversion to Less Water Intensive Crop	\$0.00	\$0.12	\$0.00	-\$0.036	-\$0.006	0.078	1.1E+07	\$831,138

Table 8.16: Crop Conversion (77% Participation)

Top Crop Selection	Dominant Crop Corn Price ($/m^3)	Lower Water Use Crop Price ($/m^3)	Cost of Crop Change ($/m^3)	Savings Water Return ($/m^3)	Savings of Pumping Return ($/m^3)	Sum of Costs/ Returns ($/m^3)	Calculated Water Savings (m^3)	Total Economic Impact ($/yr)
Wheat, Winter	$0.30	$0.08	$0.21	-$0.036	-$0.006	$0.172	1.2E+07	$2,130,756
Beans, Dry	$0.30	$0.21	$0.09	-$0.036	-$0.006	$0.046	1.0E+07	$481,179
Soybeans	$0.30	$0.24	$0.06	-$0.036	-$0.006	$0.017	2.6E+06	$45,836

8.6 PROJECT MAPS

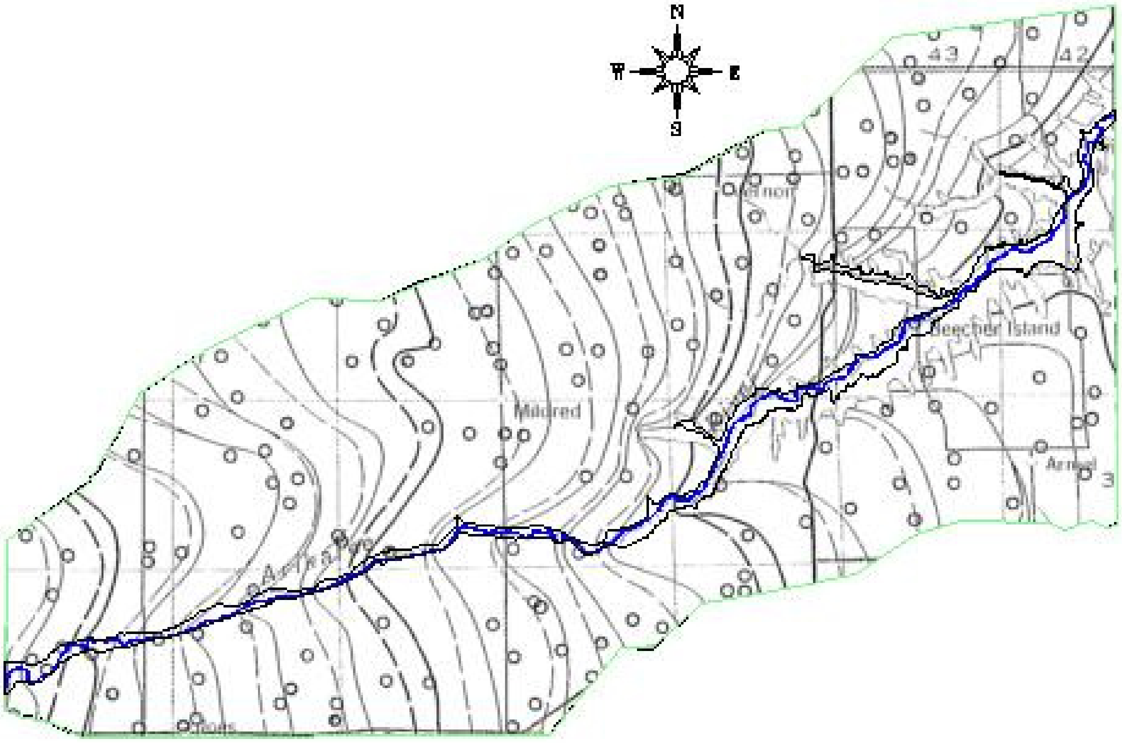

Figure 8.1: Project Area Water Contour Map (Borman et al. 1983)

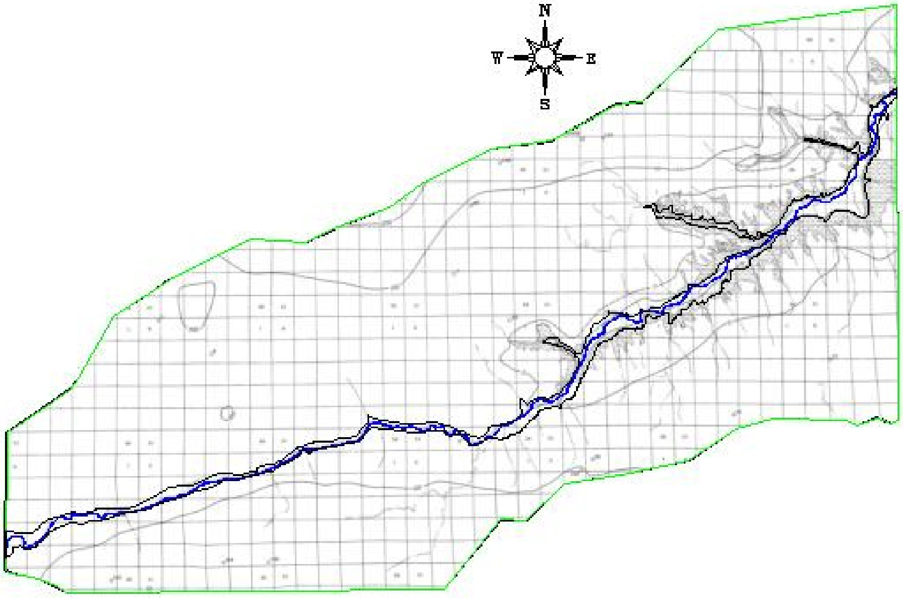

Figure 8.2: Project Area Saturated Thickness Map (Weist, 1964)

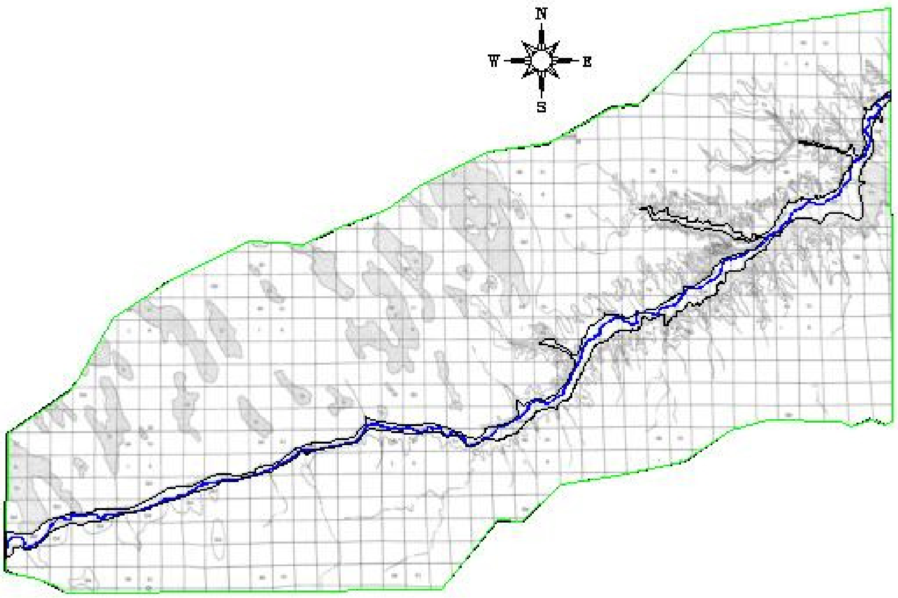

Figure 8.3: Project Area Alluvial Geology Map (Weist, 1964)

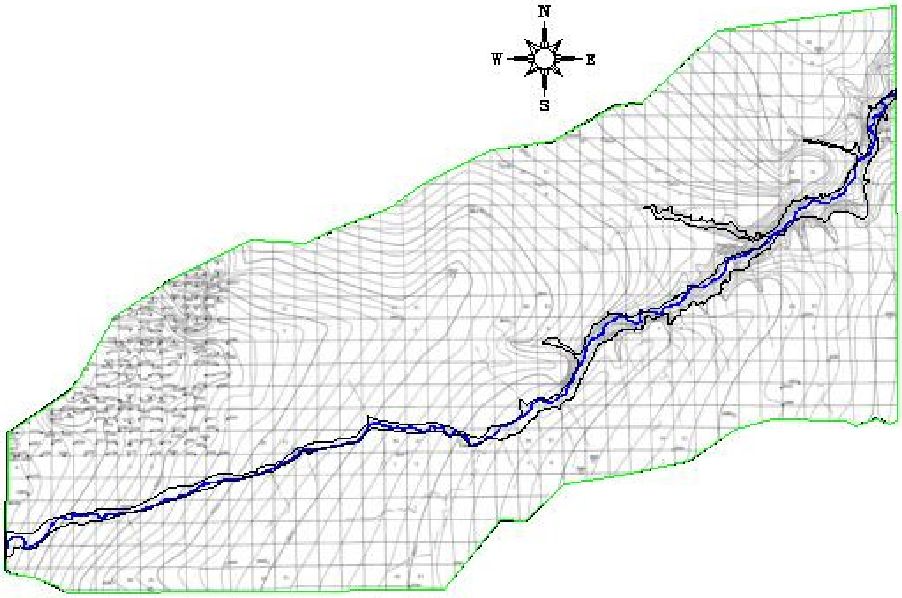

Figure 8.4: Project Area Bedrock Contour Map (Weist, 1964)

8.7 HIGH PLAINS AQUIFER AND ALLUVIAL WELL DATA

Table 8.17: High Plains Aquifer Well #9380

Location #	Site ID	Township	Range	Section	Q160
SC00404404DCC	9380	4S	44W	4	SE
Q40	Q10	Well Elevation	Well Depth	Data Source	
SW	SW	3985	343	DWR	1965-2006
UTM X	UTM Y	Lat	Long		
731277.3	4401509.8	39.732129	-102.301257		
Date	**Depth to WL (ft)**	**Elev of WL (ft)**	**Change (ft)**	**Year**	**Elev of WL (m)**
1965-04-30	215.00	3770.00	0.00	1965	1149.10
1970-02-20	215.10	3769.90	-0.10	1970	1149.07
1971-01-24	219.70	3765.30	-4.60	1971	1147.66
1972-01-19	217.60	3767.40	2.10	1972	1148.30
1973-01-19	218.03	3766.97	-0.43	1973	1148.17
1974-02-19	218.23	3766.77	-0.20	1974	1148.11
1975-01-22	221.32	3763.68	-3.09	1975	1147.17
1976-01-08	225.15	3759.85	-3.83	1976	1146.00
1977-01-11	225.50	3759.50	-0.35	1977	1145.90
1978-01-05	226.30	3758.70	-0.80	1978	1145.65
1979-01-08	227.12	3757.88	-0.82	1979	1145.40
1980-02-13	228.31	3756.69	-1.19	1980	1145.04
1981-01-13	227.75	3757.25	0.56	1981	1145.21
1982-01-11	230.85	3754.15	-3.10	1982	1144.26
1983-01-10	231.52	3753.48	-0.67	1983	1144.06
1984-01-22	231.72	3753.28	-0.20	1984	1144.00
1986-01-14	233.30	3751.70	-1.58	1986	1143.52
1986-12-07	233.43	3751.57	-0.13	1987	1143.48
1988-02-17	233.10	3751.90	0.33	1988	1143.58
1989-01-13	235.30	3749.70	-2.20	1989	1142.91
1990-01-10	234.90	3750.10	0.40	1990	1143.03
1991-01-14	235.00	3750.00	-0.10	1991	1143.00
1992-01-17	234.80	3750.20	0.20	1992	1143.06
1993-01-15	235.00	3750.00	-0.20	1993	1143.00
1994-01-14	235.20	3749.80	-0.20	1994	1142.94
1994-12-23	237.30	3747.70	-2.10	1995	1142.30
1995-12-21	237.00	3748.00	0.30	1996	1142.39
1996-12-29	238.00	3747.00	-1.00	1997	1142.09
1998-01-09	239.10	3745.90	-1.10	1998	1141.75
1999-01-15	240.50	3744.50	-1.40	1999	1141.32
2000-01-15	240.20	3744.80	0.30	2000	1141.42

2000-12-30	242.10	3742.90	-1.90	2001	1140.84
2002-01-01	242.60	3742.40	-0.50	2002	1140.68
2002-12-25	245.50	3739.50	-2.90	2003	1139.80
2004-01-07	247.10	3737.90	-1.60	2004	1139.31
2004-12-18	248.50	3736.50	-1.40	2005	1138.89
2006-01-18	248.20	3736.80	0.30	2006	1138.98
2006-12-18	248.80	3736.20	-0.60	2007	1138.79
2008-01-15	249.90	3735.10	-1.10	2008	1138.46
2008-12-30	250.80	3734.20	-0.90	2009	1138.18

Table 8.18: Alluvial Well #11755

Location #	Site ID	Township	Range	Section	Q160
SC00104227BC	11755	1S	42W	27	NW
Q40	Q10	Well Elevation	Well Depth	Data Source	
SW		3450	83	DWR	1967-2009
UTM X	UTM Y				
750215.4	4425588.5				
Date	**Depth to WL (ft)**	**Elev of WL (ft)**	**Change (ft)**	**Year**	**Elev of WL (m)**
1967-04-20	8.20	3441.80	0.00	1967	1049.06
1987-02-23	7.10	3442.90	1.10	1987	1049.40
1988-02-17	7.00	3443.00	0.10	1988	1049.43
1989-01-16	7.10	3442.90	-0.10	1989	1049.40
1990-01-02	8.40	3441.60	-1.30	1990	1049.00
1991-01-15	10.90	3439.10	-2.50	1991	1048.24
1992-01-18	10.60	3439.40	0.30	1992	1048.33
1993-01-14	11.50	3438.50	-0.90	1993	1048.05
1994-01-10	10.50	3439.50	1.00	1994	1048.36
1994-12-24	12.80	3437.20	-2.30	1995	1047.66
1995-12-22	7.20	3442.80	5.60	1996	1049.37
1996-12-25	6.20	3443.80	1.00	1997	1049.67
1998-01-10	10.30	3439.70	-4.10	1998	1048.42
1999-01-14	12.10	3437.90	-1.80	1999	1047.87
2000-01-16	6.80	3443.20	5.30	2000	1049.49
2000-12-31	13.00	3437.00	-6.20	2001	1047.60
2002-01-02	13.20	3436.80	-0.20	2002	1047.54
2002-12-27	15.00	3435.00	-1.80	2003	1046.99
2004-01-05	16.80	3433.20	-1.80	2004	1046.44
2004-12-18	17.50	3432.50	-0.70	2005	1046.23
2006-01-23	16.60	3433.40	0.90	2006	1046.50
2006-12-17	17.30	3432.70	-0.70	2007	1046.29
2008-01-12	15.70	3434.30	1.60	2008	1046.77
2008-12-08	17.20	3432.80	-1.50	2009	1046.32

Table 8.19: Alluvial Well #10741

Location #	Site ID	Township	Range	Section	Q160
SC00404718AAB	10741	4S	47W	18	NE
Q40	Q10	Well Elevation	Well Depth	Data Source	
NE	NW	4161	85	DWR	1966-2008
UTM X	UTM Y	Lat	Long		
699458.9	4398527.1	39.713313	-102.673134		
Date	**Depth to WL (ft)**	**Elev of WL (ft)**	**Change (ft)**	**Year**	**Elev of WL (m)**
1966-07-01	6.00	4155.00	0.00	1966	1266.44
1969-01-15	8.80	4152.20	-2.80	1969	1265.59
1970-02-15	8.80	4152.20	0.00	1970	1265.59
1971-01-20	9.40	4151.60	-0.60	1971	1265.41
1972-01-21	5.99	4155.01	3.41	1972	1266.45
1973-02-01	9.67	4151.33	-3.68	1973	1265.33
1974-02-23	8.09	4152.91	1.58	1974	1265.81
1976-01-08	7.91	4153.09	0.18	1976	1265.86
1977-01-11	10.80	4150.20	-2.89	1977	1264.98
1978-01-06	10.80	4150.20	0.00	1978	1264.98
1979-01-10	11.19	4149.81	-0.39	1979	1264.86
1980-02-01	9.80	4151.20	1.39	1980	1265.29
1981-01-14	9.23	4151.77	0.57	1981	1265.46
1982-01-06	9.88	4151.12	-0.65	1982	1265.26
1983-01-24	10.38	4150.62	-0.50	1983	1265.11
1986-01-14	8.74	4152.26	1.64	1986	1265.61
1987-02-27	9.23	4151.77	-0.49	1987	1265.46
1988-02-21	8.70	4152.30	0.53	1988	1265.62
1989-01-09	9.40	4151.60	-0.70	1989	1265.41
1989-12-26	9.30	4151.70	0.10	1990	1265.44
1991-01-11	10.00	4151.00	-0.70	1991	1265.22
1992-01-16	9.70	4151.30	0.30	1992	1265.32
1993-01-02	9.10	4151.90	0.60	1993	1265.50
1993-12-26	9.50	4151.50	-0.40	1994	1265.38
1995-01-02	10.20	4150.80	-0.70	1995	1265.16
1996-01-14	10.20	4150.80	0.00	1996	1265.16
1996-12-31	10.10	4150.90	0.10	1997	1265.19
1998-02-01	10.20	4150.80	-0.10	1998	1265.16
1999-01-17	11.60	4149.40	-1.40	1999	1264.74
1999-12-18	9.10	4151.90	2.50	2000	1265.50
2001-01-02	11.20	4149.80	-2.10	2001	1264.86
2002-01-09	10.20	4150.80	1.00	2002	1265.16
2003-01-01	13.00	4148.00	-2.80	2003	1264.31
2004-01-10	13.10	4147.90	-0.10	2004	1264.28
2004-12-18	13.60	4147.40	-0.50	2005	1264.13

2006-01-28	13.10	4147.90	0.50	2006	1264.28
2007-02-28	14.40	4146.60	-1.30	2007	1263.88
2008-01-22	14.00	4147.00	0.40	2008	1264.01
2009-01-02	13.40	4147.60	0.60	2009	1264.19

Table 8.20: Alluvial Well #10741

Location #	Site ID	Township	Range	Section	Q160
SC00404934DBA	19371	4S	44W	34	SE
Q40	Q10	Well Elevation	Well Depth	Data Source	
NW	NE	4395	53	DWR	1965-2006
UTM X	UTM Y	Lat	Long		
684782.6	4392415	39.661584	-102.84594		
Date	**Depth to WL (ft)**	**Elev of WL (ft)**	**Change (ft)**	**Year**	**Elev of WL (m)**
1950-04-01	10.00	4385.00	0.00	1950	1336.55
1987-01-24	15.79	4379.21	-5.79	1987	1334.78
1988-02-16	15.80	4379.20	-0.01	1988	1334.78
1990-01-01	16.30	4378.70	5.00	1990	1334.63
1991-01-09	16.50	4378.50	-0.20	1991	1334.57
1992-01-04	16.10	4378.90	0.40	1992	1334.69
1993-01-02	16.20	4378.80	-0.10	1993	1334.66
1994-01-15	16.30	4378.70	-0.10	1994	1334.63
1995-01-01	17.50	4377.50	-1.20	1995	1334.26
1996-01-13	17.30	4377.70	0.20	1996	1334.32
1996-12-30	17.10	4377.90	0.20	1997	1334.38
1998-01-05	19.00	4376.00	-1.90	1998	1333.80
1999-01-16	19.60	4375.40	-0.60	1999	1333.62
2000-01-05	17.20	4377.80	2.40	2000	1334.35
2001-01-02	19.30	4375.70	-2.10	2001	1333.71
2002-01-06	19.40	4375.60	-0.10	2002	1333.68
2003-01-11	20.00	4375.00	-0.60	2003	1333.50
2004-01-09	20.60	4374.40	-0.60	2004	1333.32
2004-12-19	21.40	4373.60	-0.80	2005	1333.07
2006-02-09	20.30	4374.70	1.10	2006	1333.41
2007-02-27	20.70	4374.30	-0.40	2007	1333.29
2008-01-23	20.50	4374.50	0.20	2008	1333.35
2009-01-02	20.80	4374.20	-0.30	2009	1333.26