THE FUTURE OF IRRIGATION ON THE U.S. GREAT PLAINS

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ABSTRACT

The future of irrigation on the United States Great Plains was examined through the lens of past changes in water supply and innovations in irrigation technology, management and agronomy. The innovations have greatly increased the efficiency of water application and use, and the agricultural productivity of the Great Plains. We analyze the history of irrigation agriculture through the 1900s to the present day. We also examine the changes in water stored in the High Plains Aquifer, which is the region's principle supply for irrigation water. The aquifer has been impacted minimally in Nebraska, despite large increases in irrigated area. Greatly increased irrigation efficiency has played a role in this, but so also has the recharge to the aquifer from the Nebraska Sand Hills and from rivers crossing the state. The outlook for irrigation is less positive in western Kansas, eastern Colorado and the Panhandles of Oklahoma and Texas. The aquifer in these regions is recharged at rates much less than current pumping, and the aquifer is declining as a result. Improvements in irrigation technology and management plus changes in crops grown have made irrigation ever more efficient. There is good reason to expect that future research and development on the part of federal and state researchers and industry, often in concert, will continue to improve the efficiency of irrigated agriculture. Public policy changes will also play a role in regulating consumption and motivating on-farm efficiency improvements. Water supplies, while finite, will be stretched much further than projected by some who look only at past rates of consumption. Thus, irrigation will continue to be important economically for an extended period. Sustaining irrigation is crucial to sustained productivity of the Great Plains "bread basket" because irrigation doubles the efficiency with which water is turned into crop yields compared with what can be attained with precipitation alone.

INTRODUCTION

Past performance is often a good predictor of future performance. While it is difficult to find persons with good records of predicting the future, this dictum can be applied to the people of the Great Plains and their social and political systems, including their interaction with the land through agricultural innovations influenced by a pioneering spirit. To have a chance at glimpsing the future, we must understand the past and the historical journey that has led to the present day. This journey involves initial recognition of natural resources and attempts to exploit them in agriculture, through innovations to better use soil and water resources while minimizing resource loss, to recognition of the political necessity of some limited regulation of resource use in order to provide for sustainable rural communities.

IRRIGATION on THE GREAT PLAINS – HISTORICAL OVERVIEW

Geographical Background

The Great Plains extend from the northern part of the state of Coahuila, Mexico through west Texas and northward through the United States to the provinces of Alberta, Manitoba and Saskatchewan in Canada (Fig. 1). The western edge is delineated by the foothills of the Rocky Mountains, but the eastern edge is less clearly defined, occurring roughly along the eastern borders of North and South Dakota, Nebraska, Kansas, Oklahoma and central Texas.

In the Central Great Plains, there are two primary water sources for irrigation: Rivers and reservoirs fed by snow melt from the Rocky Mountains and delivered as surface water through canal systems, and the High Plains (Ogallala) aquifer (Fig. 1). Important rivers include the North and South Platte rivers, which join in Nebraska to form the Platte, the Republican, which flows from Colorado and Kansas into southern Nebraska and back into Kansas, and the Arkansas, which flows from Colorado into Kansas. In addition to surface water diversions, pumping from shallow alluvial aquifers along river systems is important, as are the irrigation return flows to these systems.

All these river systems are over allocated, Colorado front-range municipalities are diverting an increasing amount of flow by purchasing agricultural water rights, and interstate agreements and disagreements are key factors in water availability for irrigated agriculture. River systems play important roles in parts of Nebraska, Colorado, Wyoming and Kansas, but not in the Panhandles of Texas and Oklahoma where the High Plains aquifer is practically the only water source for irrigation. In much of western Kansas, eastern Colorado and Nebraska, the High Plains aquifer is the major source of irrigation water. Irrigation withdrawals greatly exceed aquifer recharge in the Panhandles, Kansas, eastern Colorado and western Nebraska.

Most soils in the region formed from silt-textured loess deposited by winds in the Quaternary period, but in some places greatly modified by weathering to clay, formation of clay and carbonate rich (caliche) layers, and erosion and deposition along stream and river valleys (Aandahl, 1982). Wind-blown sand deposits formed along some river valleys and areas downwind of erosional sources, resulting, for example, in the sand hills of Nebraska and sandy soils in some parts of eastern Colorado, southwestern Kansas and the western Panhandles. But in general, the soils are nearly level and deep with moderate to slow permeability and superactive clay content that holds nutrients well. The soils are often well suited for irrigation and quite productive when water is available.

Annual precipitation varies from approximately 20 inches (500 mm) along the 100^{th} meridian to 14 inches (355 mm) in the western Great Plains (Fig. 2), with little variation from north to south, making the western half of the Great Plains a semi-arid region. Inter-annual precipitation variability is large, and the region is rendered even more risky for dryland agriculture by the large evaporative demand, which varies from approximately 63 inches (1600 mm) of pan evaporation in the eastern part to more than 95 inches (2400 mm) in the most western parts of the Southern High Plains (Farnsworth et al., 1982). Evaporative demand increases from north to south as well, being considerably less in Nebraska (approx. 50 inches) than in southwestern Kansas and the Panhandles (68+ inches) (Fig. 2). Overall, evaporative demand is greater than precipitation by 200-500%, explaining the pre-historical and current development of irrigation in the region and the emphasis on soil water management.

IRRIGATION ON THE GREAT PLAINS – PAST TO PRESENT DAY

Ancient Times to Settler Days

Irrigation has been practiced in the region since pre-historical times, then as now in response to the high evaporative demand and uncertain rainfall. Prehistoric irrigation occurred as diversions of surface waters in Kansas (Erhart, 1969) and in the Oklahoma and Texas Panhandles (Thoburn, 1926, 1931). Hispanic farmers and sheep herders initiated irrigated agriculture along the Canadian River in Texas near Tascosa in the 1870s (Nostrand, 1996, Green, 1973), which was approximately the time that historical agriculture began in the southern Great Plains. In Colorado, irrigation began along the Platte River in the early 1860s to feed the growing population of miners; and most good Poudre River water rights were claimed before 1870. One of the first recorded instances of irrigation in Nebraska dates back to 1870 near Fort Sidney, where a ditch from Lodgepole Creek brought water to gardens, lawns and trees. However, it wasn't until the 1930's that a significant investment was made to bring surface water to areas along the North Platte River in the panhandle and west central portions of Nebraska. In Colorado and Kansas, irrigation from diversion of the Arkansas River began in the 1880s (Erhart, 1969).

In the 1880s, irrigation from wells began in semi-arid western Texas, with steam or gasoline powered pumps irrigating areas of from 5 to 1,000 acres, and windmills irrigating areas of up to 7 acres (Hutson, 1898). Some pumping plants delivered 2,500 gallons per minute, enough for hundreds of irrigated acres (Huston, 1898). Huston (1898) described well water availability as follows: Water "is reached by wells of from 40 to 200 feet in depth. Many of these wells are capable of furnishing a supply almost inexhaustible to ordinary means of pumping", a far cry from the depths of up to 1000 feet and well capacities of <250 gpm common today.

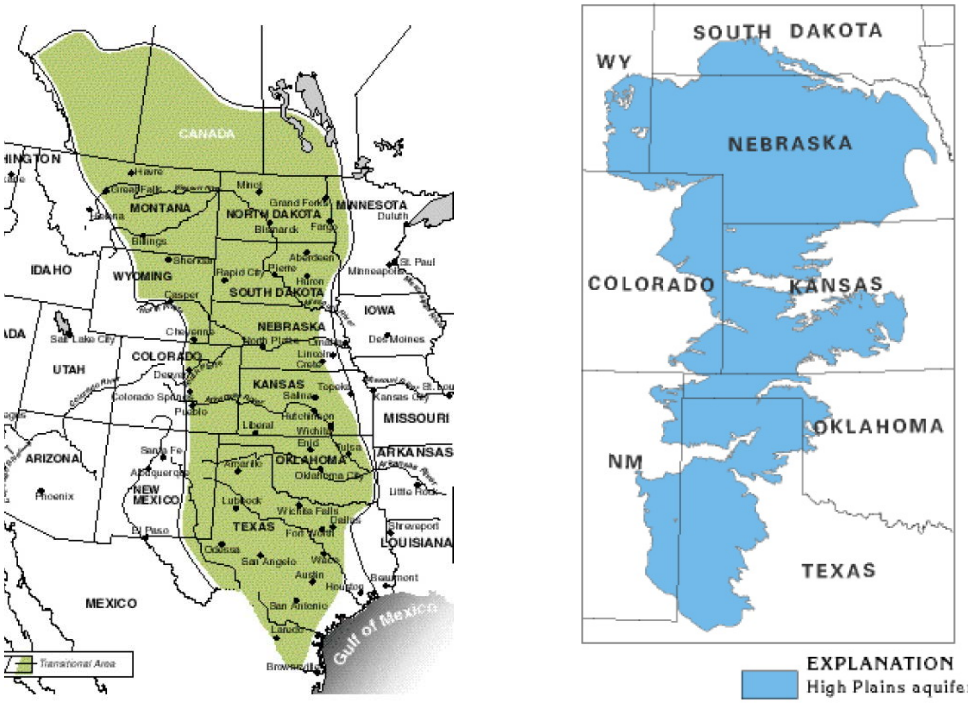

Figure 1. Spatial coverage of the Great Plains shown in green (left) (Miksinski, 1998), and areas underlain by the High Plains aquifer (right) (USGS, 2008).

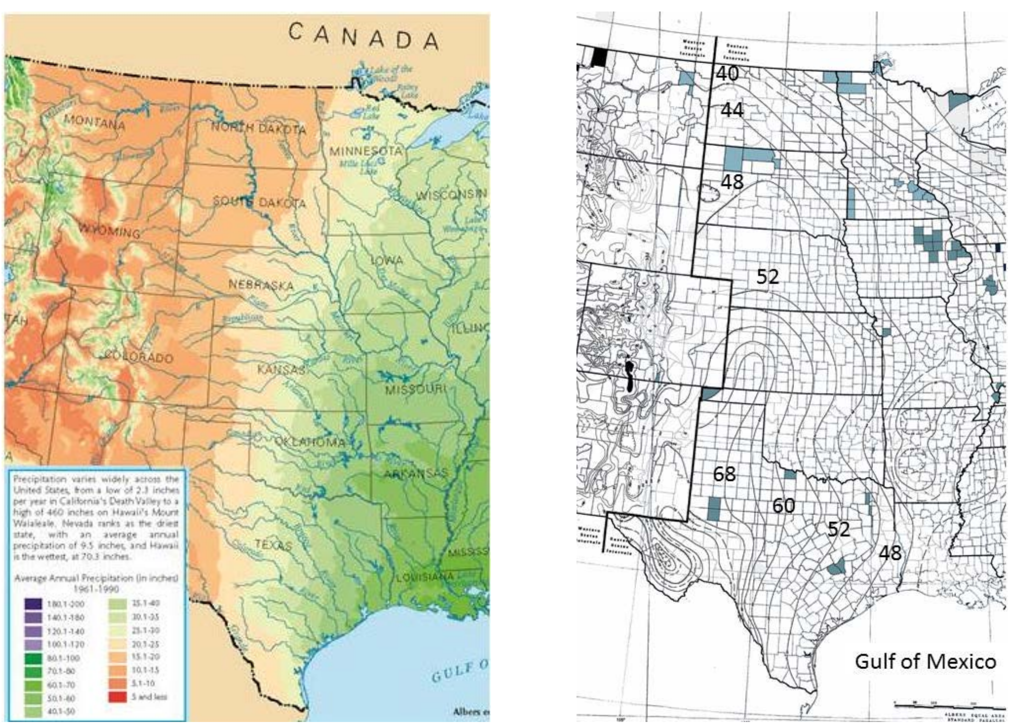

Figure 2. (Left) Mean annual precipitation (USDI/USGS. www.nationalatlas.gov/). (Right) Mean pan evaporation (inches) (Farnsworth et al., 1982).

The future of irrigation in the Texas Panhandle was described from the perspective of the 1890s by Huston (1898), "Of the future of irrigation here in general, it may be said that there is opportunity for but the little indicated, at these widely scattered spots, but that this little will prove to be just that small amount needed for rendering practicable the utilization of the high plains for stock raising, under conditions that will be bearable for those who have to live upon these great pasture lands for the conduct of the stock industry." Huston would have been surprised by the rapid expansion of irrigation after 1940; but he may have been prescient about the future of irrigation in the Texas Panhandle and elsewhere on the Great Plains.

Rapid Expansion after 1940

Large interannual variations in flow and upstream diversions if the Arkansas River slowed irrigation expansion in Kansas until the 1940s when rapid expansion became possible due to adaption of well drilling technologies from the oil industry and the availability of deep well pumps, internal combustion engines and rapid expansion of the electrical grid (Green, 1973). In Nebraska, public power and irrigation districts obtained water rights to divert water from the Platte, Republican, Loup, Dismal, and Niobrara Rivers. Eventually nearly 1 million acres of land were irrigated using surface irrigation methods. Eight of these irrigation districts received surface water rights to deliver water to over 450,000 acres of Nebraska farmland. Expansion of irrigation in the Great Plains was greatly motivated by the drought of the 1950s and aided by the GIs returning from WWII, reaching a high point in Kansas of 3,500,000 acres in 1980 before declining to approximately 3,000,000 acres by 2000 (Rogers and Wilson, 2000). The pattern of expansion in Kansas was mirrored in the Texas Panhandle, reaching 5.98 million acres (2.42 million ha) in 1974, before declining to 3.93 million acres (1.59 million ha) by 1989 and then increasing to 4.62 million acres (1.87 million ha) by 2000 (Colaizzi et al., 2009). In the plains of Colorado and in Nebraska, surface water diversions began in the later 1800s. A lack of knowledge about crop water consumptive use and river hydrology were factors in diverting more water than some rivers could supply reliably, which circumstance led to law suits and negotiations between the states that continue to the present in some cases and that have consequences for irrigation water availability. But, as in Kansas, Oklahoma and Texas, from the 1940s forward, irrigation expanded rapidly elsewhere in the central Great Plains wherever the aquifer was available and the soils and terrain were suitable for irrigation (Ganzel, 2009).

In Nebraska, interest in irrigation was shared by those too far away from the Platte River to receive water via the extensive system of canals and reservoirs. Beginning in the 1930's, irrigation wells were drilled to pump groundwater, which was used to irrigate thousands of acres. By 1969 nearly 3 million acres were irrigated and 33,000 registered wells had been drilled in Nebraska alone. Since that time there has been a steady increase in registered irrigation wells which now total over 95,000 wells (NDNR, 2014).

As the number of irrigation wells increased, so did the number of irrigated acres. According to the 1930 Census of Agriculture just over 400,000 acres of land were irrigated in Nebraska. By 1964 the number had risen to 2.1 million. The 2007 Census of Agriculture listed 8.6 million acres of irrigated land in Nebraska. Based on the continued develop of new irrigation wells it is estimated that the number of irrigated acres now totals over 9 million acres, making the irrigated area of Nebraska equivalent to that of California or the Mid South.

In 1940, irrigation was by surface application using flood, furrow or borders. Water loss due to run off or percolation below the plant root zone, led to reduced water for crops to use, and relatively small yields per unit of water applied (small water use efficiencies, WUE). Seepage losses in unlined canals and ditches were also important, as was water logging of plants near canals. Uneven furrow flows resulted from the manual distribution into furrows via V-notches cut into the earthen canal or distribution ditch walls. This problem was addressed by the advent of the irrigation siphon tube, which quickly became popular due to the more uniform distribution and dependable flow into each furrow that it offered and the fact that it could be used with concrete lined canals, which were being encouraged to reduce seepage losses and water logging of crops. In 1945, plastic siphon tube manufacturing began in Nebraska (Ganzel, 2009).

Siphon tubes did, however, require a lot of labor and could only be used with open ditches. Concrete lining of canals was expensive and did not stop all seepage losses. Canals also were not suitable for some farm layouts and reduced the irrigated land area to that which was downhill from the water source, resulting in a switch to install underground piping to eliminate seepage losses and more easily route water to irrigable land. Although pressures in these pipe systems were small, this began the advent of pressurized water delivery. With pressurized water, gated pipe became popular as an alternative to siphon tubes and remains popular to this day in some locales. In later years, many attempts were made to mechanize surface irrigation to reduce labor requirements. For example, cablegation was invented to move a plug down a gated pipe using a clocking mechanism, resulting in a continuously moving irrigation set across the field (Kemper et al., 1981); but it was never widely adopted in the USA with only about 100 systems having been installed by 1990 (Trout and Kincaid, 1994). After WWII, the pressurization of irrigation systems began to increase. Today, pressurized systems supply water to >52% of the irrigated area in the United States, eliminating most conveyance losses to the field and essentially removing surface transport phenomenon from the infiltration and soil water redistribution processes.

In 1948, Frank Zybach in Nebraska invented the center pivot sprinkler irrigation system, taking advantage of pressurized water delivery. At that time, irrigation through sprinklers mounted on pressurized riser pipes in the field was available, though not widely used in the Great Plains. During and after WWII, labor became more difficult to find due to wartime manpower needs and post war urbanization. As a self-moving system, the center pivot sprinkler solved this problem, as well as the problem of seepage and deep percolation losses in gravity flow irrigation systems. And, it could be used on land with complex topography without land leveling, making more lands irrigable. In Nebraska, the total number of pivots was less than 2700 in 1972 but had increased to nearly 12,000 by 1976 based on remote sensing studies conducted by the UNL Remote Sensing Center (1977). The 2002 Farm and Ranch Irrigation report showed just over 72% of the irrigated area in Nebraska was irrigated by sprinklers (NASS, 2002). That number increased by 5% in just 5 years to 78% (NASS, 2008). The estimate for 2013 is that 82% of the irrigated acres in Nebraska are irrigated with sprinkler systems and almost exclusively center pivots, which now number more than 55,000. Today >70% of the irrigated area in the Southern High Plains is served by such systems (Colaizzi et al., 2009; Rogers and Wilson, 2000). The land area percentage in Kansas for center pivot sprinkler irrigation increased from approximately 50% in 1990 to nearly 92% today (Rogers and Lamm, 2012).

Irrigation Research Advances Efficiencies

Irrigation research programs were established at several Great Plains research stations (e.g., the Water Management Research Unit at Fort Collins and the Soil and Water Management Research Unit at Bushland, Texas) after WWII to seek ways to improve irrigations efficiencies and to improve crop water use efficiencies during this period of rapid irrigation expansion. Crop water use was measured by soil water balance in most dryland and irrigated experiments, at first by taking soil cores, but later using the neutron probe (NP). USDA-ARS at Bushland, Texas, was involved in the early NP trials and development of these meters as early as 1959 (Hauser, 1959), an involvement in soil water sensor development that continues to this day. By the 1970s, farmers were adopting methods from research reports for tailwater retention and utilization for furrow irrigation (Schneider, 1976), retention of surface crop residues to reduce evaporative losses (Unger, 1976; Unger and Wiese, 1979), and stubble mulch tillage of irrigated wheat (Allen et al., 1976). These methods of water conservation increased the yields produced per unit of water pumped, largely by reusing runoff water and reduction of unproductive evaporation losses.

As water table depths and well yields declined, limited irrigation of sorghum and sunflower was shown to improve the overall water use efficiency due to both reduction of evaporative losses and more effective use of rainfall (Stewart et al., 1983; Unger, 1983). However, too much reduction of irrigation was shown to be harmful for corn and soybean (Eck, 1986; Eck et al., 1987; Musick and Dusek, 1980). Alternate furrow irrigation was shown to reduce water needs but not yields of corn and sorghum and to increase WUE (Musick and Dusek, 1982), mostly through reduction of wetted surface soil and thus of evaporative losses. Still, inefficiency in furrow irrigation led to furrow compaction research that demonstrated reduced losses to deep percolation, although this effect was soil specific (Musick et al., 1985; Musick and Pringle, 1986). In the ten years from 1974 to 1984, average irrigation applications were reduced from 15.9 to 13.8 inches (404 to 347 mm) by adoption of these methods plus reduced pre-plant irrigations and in some cases shifting to crops more compatible with limited irrigation (Musick and Walker, 1987). Pre-plant irrigation is sometimes practiced in the Great Plains region as a means of extending marginal well capacities through droughty conditions by increased soil water storage within the profile. However, although it may have merit under these conditions, it often has low overall application and storage efficiencies (Lamm and Rogers, 1985; Musick and Lamm 1990; Stone et al., 2008).

Although irrigation application efficiency had been studied since the early sprinkler irrigation research in the 1950s, rapid progress was delayed due to excessive application rates and runoff. The mid 1980s saw progress with the introduction of furrow diking and low-energy-precision-application (LEPA) technology for moving irrigation systems (Howell, 1997). Moving systems replaced solid set (stationary) systems so that, by 1984, 37% of the total irrigated area was irrigated by moving systems (Musick and Walker, 1984). LEPA technology became more important by the end of the 1980s as gravity irrigated area continued to decline, particularly on more permeable soils (Musick et al., 1988). By 1990, the percentage of sprinkler irrigated land rose to 44% in the northern Texas Panhandle (Musick et al., 1990). Irrigation application efficiencies increased from the less than 60% achieved with gravity irrigation to >80% with impact sprinklers in the Texas Panhandle and elsewhere on the Great Plains (Musick et al., 1988). Lyle and Bordovsky (1983) demonstrated consistent application efficiencies of >95% with LEPA systems in furrow-diked fields. Adoption of the complete LEPA management system varied across the Great Plains and variants that included in-canopy and near-canopy spray applications are more prevalent in the central Great

Plains due to greater land slope and well capacities (Howell et al., 2006; Lamm et al., 2006,2007). Overall farm WUE increased with these improvements in application efficiency, but did not directly translate to reductions in water pumping. New (1986) remarked that "center pivots improve water application efficiency enough to irrigate 20% to 25% more area than can be covered with furrow irrigation with the same water". By 1990, the predevelopment water storage in the High Plains aquifer was estimated to have declined by 30% (Musick et al., 1990), motivating a continued search for ever more efficient irrigation methods and improved water use efficiency in cultivars and irrigation management.

Irrigation itself improves overall WUE as was demonstrated by Musick et al. (1994) who summarized 178 crop seasons of irrigated and dryland wheat data from Bushland, Texas in terms of water use, grain yield and WUE. Maximum yields required 25.6 to 31.5 inches (650 to 800 mm) of water, a quantiy that was only available through irrigation. Importantly, the WUE for irrigated production was about double that for dryland production; and the relationship for WUE versus yield showed that high yields were necessary for efficient water use (Fig. 3, left). The curved line indicated that the rate of increase in WUE became less strong at the largest yields. Except for a few seasons, the WUE of irrigated production was greater than that of dryland production.

Further improvements in yield and WUE in irrigated winter wheat-dryland sorghum rotations were demonstrated for no-tillage as opposed to other tillage methods such as disk and sweep tillage (Unger and Wiese, 1979; Unger, 1984). Although a combination of pricing and yield has led to corn supplanting sorghum on much land in the Great Plains, there has been continual advancement of sorghum yields. Unger and Baumhardt (1999) attributed 46% of sorghum yield increases from 1939 to 1998 to improved hybrids and the rest to improved soil water content at planting time that was due to adoption of limited and no tillage practices that were made possible by improved herbicides. In Colorado, reduced tillage was shown to increase snow capture and thus soil water at planting time, resulting in improved yields (Nielsen, 1998).

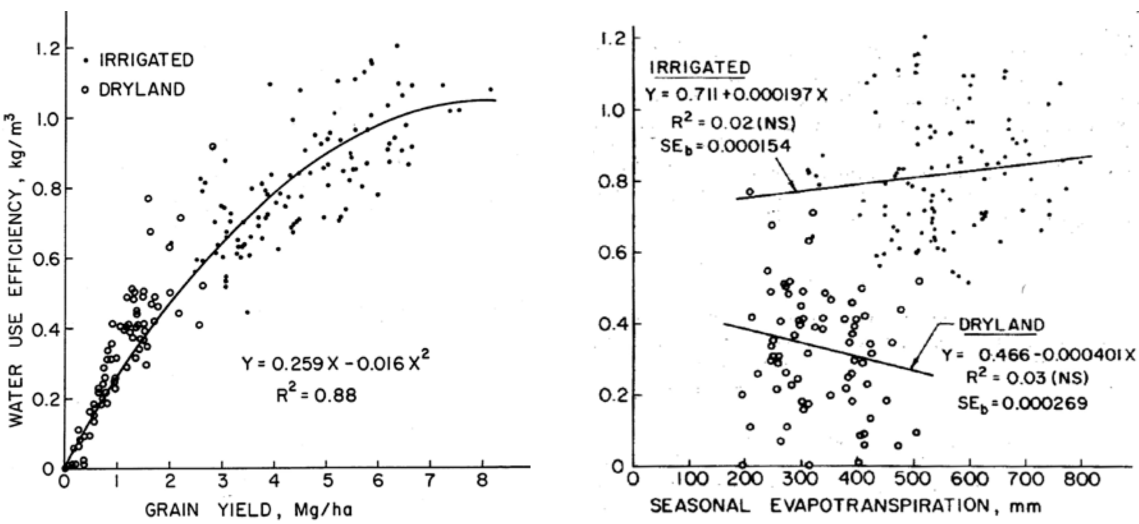

Figure 3. Winter wheat water use efficiency is about doubled by irrigating compared to dryland production, and mean yield is more than doubled (left). In the 15.7 to 19.7 inch (400 to 500 mm) range of water use, water use under dryland conditions was equal to that under irrigated conditions, but water use efficiency and yields were doubled with irrigation (right). Data are from 178 cropping seasons at Bushland, Texas (Musick et al., 1994).

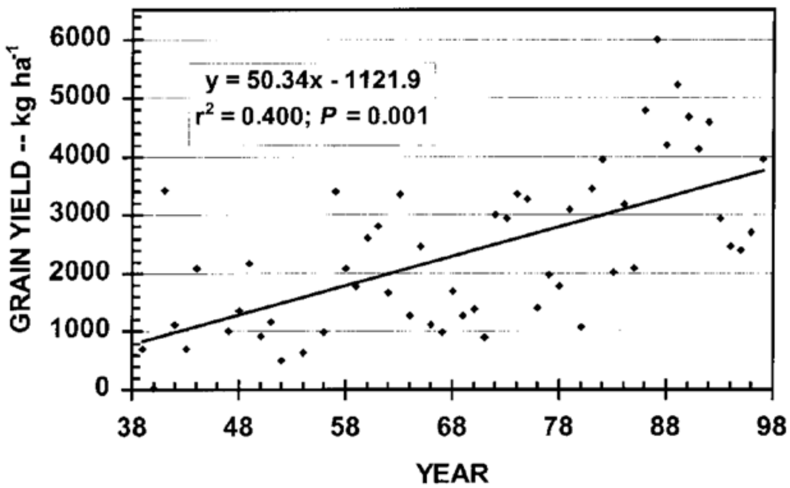

Figure 4. Dryland sorghum yields have increased steadily by and average of 44.6 lbs/acre (50 kg/ha) annually since 1939 (Unger and Baumhardt, 1999).

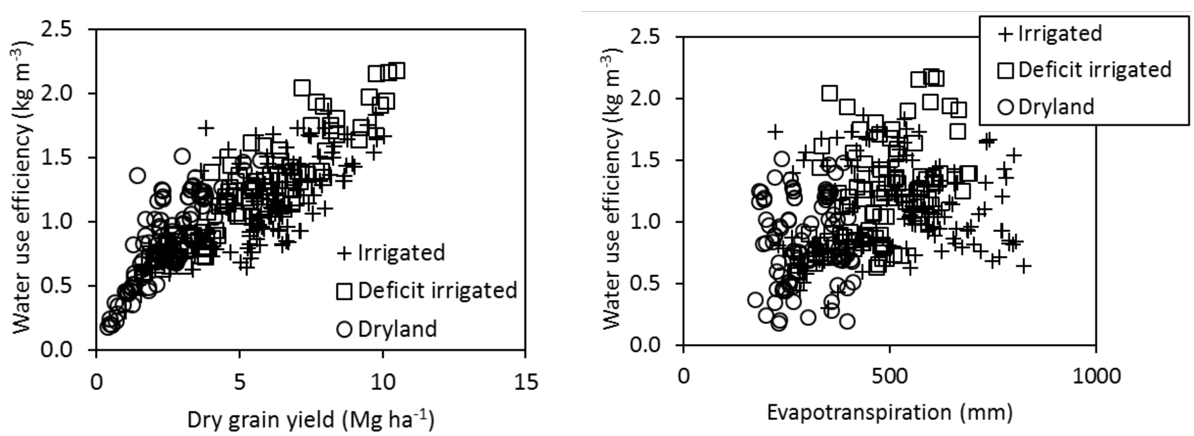

Figure 5. Sorghum water use efficiency and yield are increased when irrigation is used to supplement precipitation and soil water storage at planting (left). The greatest water use efficiencies were obtained with deficit irrigation practices (right), which also tended to have the greatest yields (left). Data are for 352 treatment years between 1960 and 2010 (Evett et al., 2013).

As with winter wheat, irrigation of sorghum increases not only yield but overall water use efficiency (Evett et al., 2013). The greatest water use efficiencies are obtained with deficit irrigation practices (Fig. 5). Somewhat surprisingly, the greatest yields also were obtained with deficit irrigation, indicating that full irrigation to meet crop water demand results in excessive vegetative growth and smaller harvest index.

With the advent of advanced sprinkler irrigation methods, research turned to more accurate irrigation scheduling as a means to improve overall water use efficiency by reducing deep percolation and evaporation losses, and by avoiding “luxury” consumption of water over that needed for optimal yields. Water use for well irrigated crops was determined by soil water balance using the neutron probe or soil coring to determine deep profile water contents at several research locations in the Central Plains. At the USDA-ARS-CPRL these methods were supplemented with four large weighing lysimeters for direct crop water use measurements (Marek et al., 1988) under dryland, irrigated and deficit irrigated regimes. Throughout the 1990s and 2000s, the crop water use and WUE of fully and deficit irrigated alfalfa, corn, cotton, sorghum, soybean, sunflower and winter wheat were determined; and for some of these the dryland water use was determined as well.

In partnership with Texas A&M AgriLife Research and Extension, a network of weather stations covering the Panhandle was established to provide the data needed to estimate daily crop water use for all producers and all major crops in the region. What became the Texas High Plains Evapotranspiration Network stretched from Pecos at the southwest edge of the Plains, to Munday and Chillicothe in the Rolling Plains on the east, and to Dalhart and Perryton in the north. Daily crop water use estimates were provided for the major crops currently growing in the region, with separate values of ET for three to four planting dates (for annual crops) and with growth stage estimates. Data were delivered by e-mail message and facsimile transmission directly to producers and were available on the Internet. Estimates of crop ET were based on the crop coefficients determined at the USDA-ARS-CPRL and daily reference ET values calculated from the weather data using the Penman Monteith equation (ASCE, 2005) (Evett et al., 2000b; Howell et al., 1997b, 1998, 2004). The crop coefficients were determined by the ARS team, which also made important contributions to the ASCE Penman Monteith standardized reference ET equations. Similar efforts have been established in Colorado. Kansas has been providing ET estimates for irrigation scheduling by radio since the late 1970s (probably 1978) and through radio and internet since 2000.

There are currently nearly 430 evapotranspiration weather stations in the Great Plains producing daily estimates of reference evapotranspiration for irrigation scheduling. These weather station networks include the North Dakota Agricultural Weather Network (NDAWN) with 82 stations, the High Plains Automated Weather Data Network (AWDN) covering South Dakota (31 stations), Nebraska (64 stations), and Kansas (11 stations), the Colorado Meteorological Network (CoAgMet) with 36 stations on the Great Plains (plus 12 stations in the Northern Water network), the West Texas Mesonet with 77 stations, and the Oklahoma Mesonet with 110 stations. Weather data and reference ET are available on a daily, and in some cases hourly, basis from the web sites of the various networks. Many networks also include estimates of crop coefficients and daily crop water use for crops commonly grown in the region. Several states also include water balance-based irrigation scheduling software that growers can use to estimate water use and irrigation requirements for each of their fields. In several states, the ET data are now accessible through “smart” phone irrigation scheduling applications.

IRRIGATION ON THE GREAT PLAINS – FUTURE PERSPECTIVES

Irrigation research in the 1990s and beyond reflected the search for ever more efficient application and management methods, and the use of these to reduce evaporative losses and increase the ratio of transpiration (*T*, which is tied to yield) to total water use (Schneider and Howell, 1993, 1994, 1995b, 1998, 1999). Earlier work focused on LEPA systems (Schneider and Howell, 1995a; Schneider, 2000; Schneider et al., 2000), but later spray, LEPA and subsurface drip irrigation (SDI) methods were compared (Colaizzi et al., 2004; Schneider et al., 2001), and SDI was shown to have advantages where well capacities did not allow full irrigation. Subsurface drip irrigation, a type of microirrigation, first began to be adopted to an important extent in the cotton industry near Lubbock, Texas. But, SDI was also shown to be feasible and profitable for corn in the Kansas and Texas High Plains (Howell et al., 1997a; Lamm et al., 1995; Lamm and Trooien, 2003). Evett et al. (1995) showed that drip irrigation was more efficient and improved WUE due to the smaller wetted soil surface area (Evett et al., 1995).

More recently, Howell (2006) has summarized the challenges of increasing WUE to sustain profitable irrigated agriculture. Perhaps as important as the choice of application technology, scheduling irrigation to meet the needs of the crop without water loss to over irrigation is key, and further gains can be made by precision deficit irrigation that mildly stresses a crop without large yield reductions. Although information provided by ET weather station networks allows farmers to make appropriate irrigation application decisions, it cannot guarantee success. In an effort to make precision deficit irrigation a feasible reality for producers, automatic irrigation scheduling and control systems that use real-time soil water and crop sensing have been the subject of research at both Bushland and Lubbock, Texas since the early 1990s (Evett et al., 1996; Wanjura et al., 1992).

Automatic irrigation systems based on plant temperature sensing have been implemented for both SDI (Evett et al., 2000a) and center pivot irrigation (Evett et al.,2006; Peters and Evett, 2008; O'Shaughnessy and Evett, 2010a). These systems were shown to improve yields and WUE compared with scheduling based on the neutron probe and the soil water balance, which itself is superior to scheduling based only on reference ET estimates from weather station network data and estimated crop coefficients. Evett et al. (2013) looked at results from 83 treatment years of automatic deficit irrigation of sorghum based on plant temperatures compared with dryland and full irrigation based on neutron probe readings (Fig. 6). Automated deficit treatments in the range of 50 to 80% of full, produced the greatest water use efficiencies, and yields were comparable to or exceeded those of full irrigation. Similar results were obtained with corn under automated SDI (Evett et al., 2000a). Because corn is sensitive to mistakes with deficit irrigation during silking, the automated system maintained corn yields when irrigation based on soil water sensing was not responsive enough to prevent yield loss due to hot, dry winds during silking.

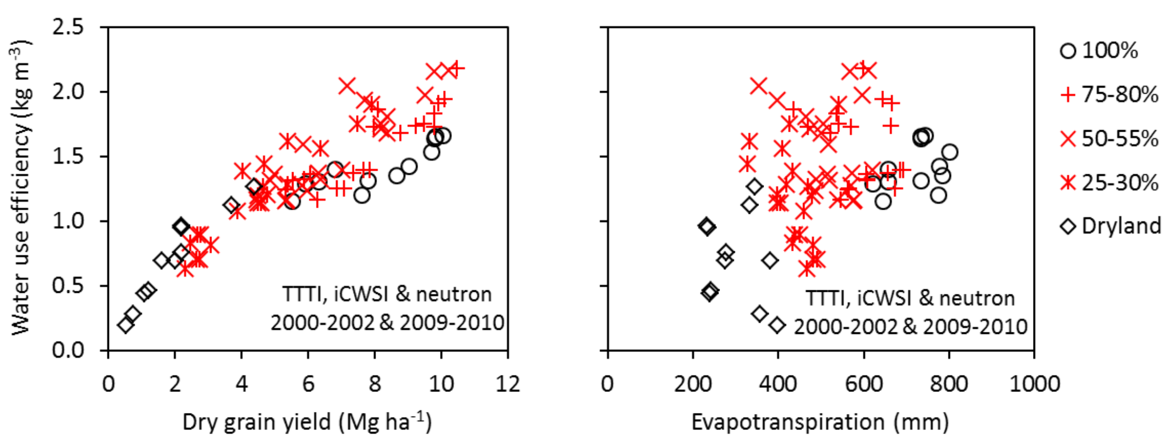

Figure 6. Comparison of water use efficiencies, grain yields and water used (evapotranspiration) for sorghum obtained using automated deficit irrigation with those obtained for dryland and full irrigation (100%) based on neutron probe readings (Evett et al., 2013).

Today, there is considerable interest in the use of variable rate irrigation (VRI) for improving irrigation managment. Variable watering rates can be applied using mechanical move irrigation systems outfitted with computerized control panels for speed control or more extensive hardware for zone control (Kranz et al., 2012). Computerized control panels have been available for some time. Now VRI packages for zone control, capable of precision delivery (Dukes and Perry, 2006, Han et al., 2009; Chavez et al., 2010; O'Shaughnessy et al., 2013a), are commercially available. The paradigm for VRI is to optimize irrigation scheduling dependent on within-field spatio-temporal variability of crop water needs. Such variability can be driven by differences in soil properties, field topography, crop management practices, biotic stresses, and other drivers. Strides in precision irrigation management using VRI systems have included the integration of wireless sensor network systems for plant canopy sensing (temperature and reflectance) (O'Shaughnessy et al., 2010b) and soil water sensing (Vellidis et al., 2008), and algorithms using data from sensor networks for irrigation control (Kim et al., 2008; Hedley and Yule, 2009; O'Shaughnessy et al., 2013b).

Sensor network systems deployed on moving irrigation systems or established as static sensors in the field will enable the development of dynamic prescription maps (O'Shaughnessy et al., 2012), which is essential for responding to changing patterns of variability throughout the growing season. Advances in the reliability of wireless data transmission, above the plant canopy and underground (Dong et al., 2013), will facilitate precision irrigation management. Fully implemented systems are still in commercial development through public-private partnerships, although some system components are now available commercially. Scheduling irrigation in direct response to plant and soil sensing may well be part of the next wave of improvements in overall water use efficiency in the Great Plains.

Changes in Irrigated Area, Aquifer Storage and Policy

In the eight states underlain by the High Plains aquifer, the overall aquifer depletion between 1980 and 2007 was 8.2% (Table 1), but depletion rates varied greatly between the states. The smallest depletion rates (1%) were in Nebraska, which overlies 36.6% of the aquifer area – the most of any state, and South Dakota, which overlies only 2.7% of the aquifer area. The largest depletion rates were in Kansas (19.7%), New Mexico (20.6%) and the Texas High Plains (35.9%). Texas overlies the second largest area of the aquifer, at 20.4%, and its High Plains have only the aquifer for irrigation water supplies. In the more southern Great Plains states, the irrigation water supply has decreased somewhat in step with water table and well yield declines since circa 1950. The Southern High Plains stands to lose 35% of its irrigated land surface in the next 20 to 30 years at current rates of depletion (Scanlon et al., 2012). Between 1980 and 2007, depletion was concentrated in certain areas, with mean depletion being 33 ft (7 m) in Kansas and 36.1 ft (11 m) in Texas (Scanlon et al., 2012), but in some areas being much greater. Chloride mass balance studies have shown recharge to be greatest (1 to 8.3 inch/y or 25 to 210 mm/y) in Nebraska and NE Colorado, and least (<0.08 to 0.98 inch/yr or 2 to 25 mm/y) in SW Kansas, SE Colorado and the Oklahoma and Texas Panhandles (Scanlon et al., 2012).

Rogers and Lamm (2012) summarized irrigation trends in Kansas where the sprinkler and furrow-irrigated land areas were approximately equal in 1990. Beginning in about 1993 there was a rapid conversion period lasting until about 2000 during which approximately 988,000 acres (400,000 ha) of furrow-irrigated land was converted to center pivot sprinkler irrigation. This conversion of furrow irrigation to center pivot sprinklers or SDI continues. The remaining furrow-irrigated area is estimated to only be 173,000 acres (70,000 ha). Subsurface drip irrigation is practiced on less than 1% of the total irrigated land area in Kansas, but continues to grow at a pace of approximately 4900 acres/year (2000 ha/year). As more producers gain experience with SDI, it is anticipated that this method will see increased usage particularly in areas of greatest decreases in groundwater well capacity. With declining water resources, water diversions in Kansas are gradually decreasing at a rate of approximately 45,400 acre-feet/year (56 million m^3/year) and are currently at a total of 30 million acre-feet (3.7 billion m^3/year). Average irrigation applications are decreasing approximately 0.20 inch/year (5 mm/year). Recent changes in Kansas water laws are designed to allow more flexibility in managing water at the local and also at the producer level. A group of producers can voluntarily develop a Local Enhanced Management Area (LEMA) to help restrict water diversions with the goal of conserving water and improving equitable sharing of the limited water resources. Multiple year flexible water use allocations allow individual producers to balance their water use across inter-annually variable climatic conditions.

Changing economics and genetics are influencing the kings of crops grown on irrigated lands. Corn is currently produced on approximately 50% of the irrigated land areas in Kansas; and the land in corn has been relatively stable since 2000 at approximately 1.48 million acres (600,000 ha). Corn yield advances and economics have reduced irrigated wheat and grain sorghum land area to approximately 680,000 to 185,000 acres (275,000 and 75,000 ha), respectively, from the roughly equal division of irrigated land area between corn and these two crops in the mid 1980s.

In Nebraska there has been a fairly steady increase in irrigated area to approximately 9 million acres presently, even though the number of active wells has not increased greatly. This is likely due to improvements in irrigation efficiency as pressurized systems have been placed on former gravity irrigated land. The area irrigated by center pivot systems has also increased (now >80%) as has the number of such systems powered by electricity (~55% presently). Aquifer levels in Nebraska have fallen less than a foot on average over the last 60 years (Scanlon et al., 2012); the small water table decline being accounted for by recharge nearly keeping up overall with withdrawals. The greater recharge is due to both sandier soils and less evaporative demand. The number of Natural Resource Districts (NRDs) that have implemented Integrated Water Management Plans (IWMPs) has nevertheless steadily increased (Fig. 4). These plans usually include rules pertaining to water meters, yearly water allocation and limitations on new irrigated areas. Even NRDs in which available water is not fully allocated are trending towards voluntary implementation of IWMPs. In the far west, pumping restrictions mean no additional area can be irrigated and a water allocation limits water withdrawal over a period of 3 to 5 years. These restrictions are gradually moving further east in response to the development of irrigation wells in areas that traditionally have supported only rainfed agricultural systems. In 2012, the Lower Elkhorn NRD in northeast Nebraska placed a moratorium on new irrigated acres; and in 2013 the district implemented a water allocation plan that required the installation of water meters on over 200 irrigation wells.

Another trend is the dwindling supply of water available for delivery by surface water projects in Nebraska and parts of Colorado and Kansas. In 2014, Nebraska irrigators along the Republican River can expect to receive between 0 and 2.5 inches of water. In the Mirage Flats Irrigation District in the Nebraska panhandle, 2014 delivery has been set at 2.5 inches. These two examples are indicative of the increased level of competition for available water supplies and the diminishing supply of surface water available for irrigation.

Table 1. Summary of the overall water supply in the High Plains Aquifer and how much was depleted prior to 2007.

State	Percent of total aquifer area, %	Average area-weighted saturated thickness in 1980, ft	Volume of drainable water in storage in 1980, million ac-ft	Portion of H.P. Aquifer Drainable Water in State (1980), %	Change in Storage from ~ 1950 to 2007, million ac-ft	2007 Aquifer Depletion as Percent of 1980 Storage
CO	**8.6**	**79**	**120**	**3.7%**	**-17.4**	**14.5%**
KS	**17.5**	**101**	**320**	**9.8%**	**-63**	**19.7%**
NE	**36.6**	**342**	**2,130**	**65.5%**	**-21.4**	**1.0%**
NM	**5.4**	**51**	**50**	**1.5%**	**-10.3**	**20.6%**
OK	**4.2**	**130**	**110**	**3.4%**	**-12.2**	**11.1%**
SD	**2.7**	**207**	**60**	**1.8%**	**-0.6**	**1.0%**
TX	**20.4**	**110**	**390**	**12.0%**	**-140.1**	**35.9%**
WY	**4.6**	**182**	**70**	**2.2%**	**-2.3**	**3.3%**
Total	**100**	**190**	**3,250**		**-267.5**	**8.2%**

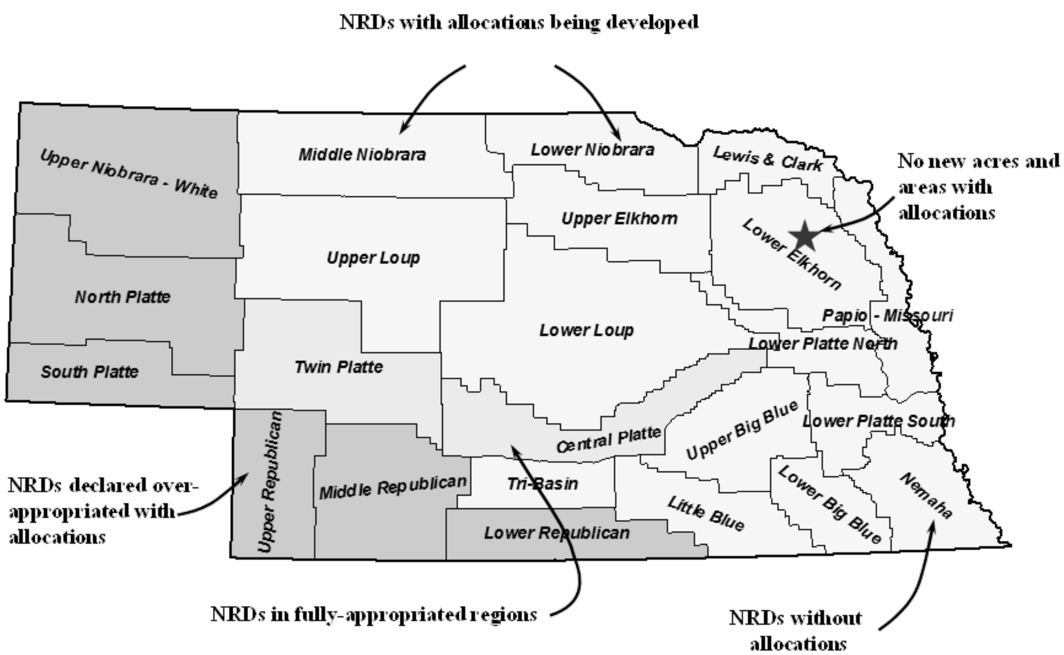

Figure 7. Nebraska map showing natural resources districts that have been declared over-appropriated, fully-appropriated, or not fully-appropriated.

In Colorado, over-allocation of water supplies, growing urban populations and water needs, and the desire to improve riparian areas will result in a decrease in water available for irrigation. The 2010 Statewide Water Supply Initiative report estimates that water availability on the eastern plains will result in a reduction in irrigated area of between 130,000 and 180,000 ha by 2050, over 20% of currently irrigated area (CWCB, 2010). Under Colorado water law, groundwater, including the high plains aquifer, is considered hydraulically connected to surface water, and thus is regulated under the same prior appropriation rules. Under this ruling, over 1000 groundwater wells have been shut down in response to declining river flows. Growers who wish to continue pumping groundwater often must compensate for any impacts their pumping might have on river flows through an "augmentation" plan in which they recharge the groundwater from unclaimed surface water or otherwise replace projected river flow depletions. Current research studies and policy debates are focused on ways to use the groundwater conjunctively with surface waters to maximize flexibility and benefits. Water rights in Colorado are also based on consumptive use (evapotranspiration), rather than diversions or pumped amounts. Thus, non-consumptive water is assumed to return to river and groundwater supplies. For this reason, improvements in irrigation efficiency will not necessarily result in more water available for irrigation production in Colorado. This greatly reduces the technical options available to sustain current production levels. Current research on regulated deficit irrigation is seeking ways to sustain productivity with reduced consumptive use, but results in Colorado have not been as encouraging as elsewhere.

In the Texas High Plains, irrigated area was 4.5 million acres in 1958, reaching a peak of nearly 6 million acres in 1974, declining to 3.9 million acres by 1989, but increasing to 4.7 million acres by 2008, slightly greater than the 1958 area when detailed surveys were first conducted (Fig. 8) (TWDB, 2001; TWDB, 2011; TWDB, 2012; NASS, 2008). Most land was irrigated by gravity (graded furrow) until around 1994, when sprinkler irrigated area exceeded that irrigated by gravity flows. Sprinklers were mainly the center pivot type. The total gravity irrigated area increased until 1974 but decreased continuously thereafter due to both reduction in total irrigated area and conversion to sprinkler. By 2008, less than 900,000 acres (<19%) were irrigated by gravity. Sprinkler irrigated area grew from about 10% in 1958 to 78% by 2008. Sprinkler adoption was most rapid after 1989, when total irrigated area began to increase again after the lull due to greater energy prices earlier in the 1980s. Microirrigation (mainly SDI) has been used in the Trans Pecos and Southern High Plains areas since circa 1984 mainly for cotton production (Henggeler, 1995), but adoption began to increase more rapidly after 2000. By 2008, microirrigation was used on 173,272 acres (~3%) in Texas (NASS, 2008).

The volume of water pumped for irrigation in the Texas High Plains followed a somewhat similar trend as irrigated area (Fig. 9) (TWDB, 2001; TWDB, 2011; TWDB, 2012). After 1958, when 5.2 million acre feet were pumped, withdrawals increased to a peak of 8.2 million acre feet in 1974, declined to 4.7 million acre feet by 1989, and increased again to 5.62 million acre feet by 2008. Because well yields have declined since irrigation development began, the number of wells has more than doubled from 48,160 in 1958 to 101,299 by 2000 in order to maintain the volume of water pumped (TWDB, 2001). The average amount pumped per unit irrigated area (i.e., before application losses) will depend on numerous factors such as rainfall and climate, energy costs, crops grown, and irrigation technology and management. However, it should be noted that the irrigation volume pumped and the amount per unit area both decreased from 2000 to 2008. This is despite an increase in irrigated area and decreasing rainfall. As discussed previously, this was likely possible due to several factors, such as adoption of pressurized irrigation systems, improved irrigation management based on ET and sensors, reduced well capacities, adoption of reduced tillage to conserve soil and water, and improved drought tolerance and better water use efficiency of crop varieties.

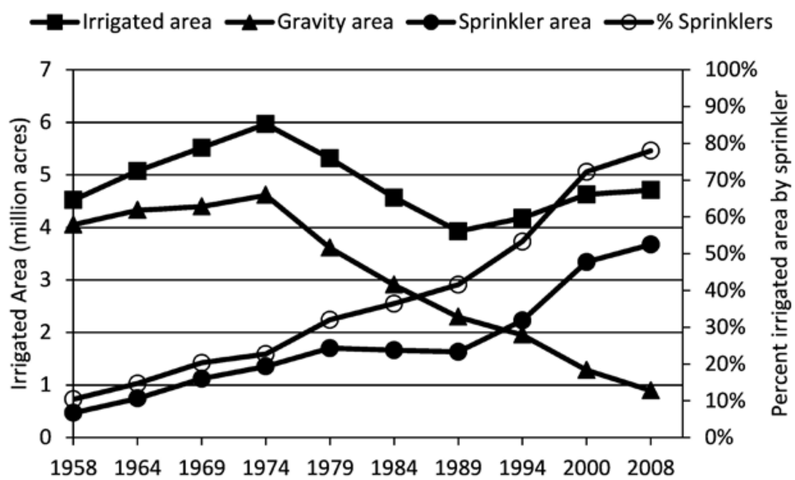

Figure 8. Irrigated area in the Texas High Plains (TWDB, 2001; TWDB, 2011; TWDB, 2012; NASS, 2008).

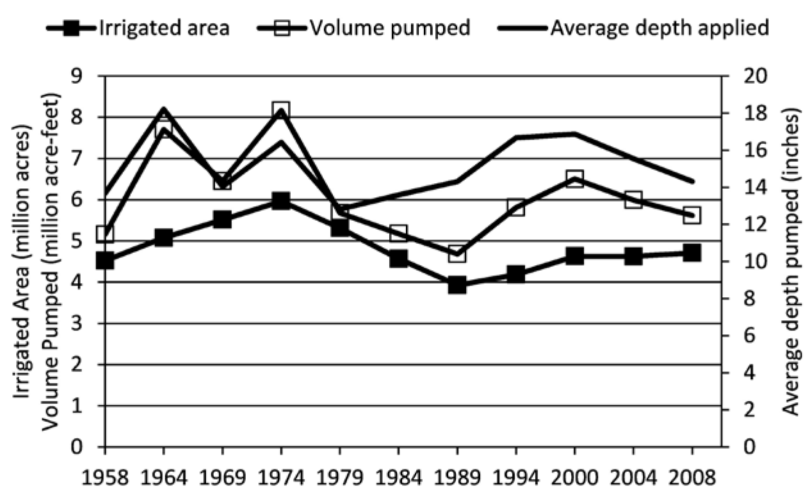

Figure 9. Irrigated area, volume pumped, and average depth pumped in the Texas High Plains (TWDB, 2001; TWDB, 2011; TWDB, 2012).

Although the volume of water pumped for irrigation in the Texas High Plains was slightly greater in 2008 compared with 1958, this will no doubt decrease during this century due to declines in available groundwater, increased lift requirements, and regulations that will limit pumping. The State of Texas recently required that all groundwater conservation districts establish desired future conditions (DFCs) of groundwater availability (Mace et al., 2006). In order to meet this mandate, districts in the Texas High Plains and elsewhere have mandated metering of irrigation wells and have become more aggressive in promoting or requiring water conservation practices (TWDB, 2012). Even if DFCs are achieved, regional groundwater planning groups project that the Ogallala Aquifer will yield only 50 to 60% of its 2010 capacity by 2060 (TWDB, 2012). Hence the loss of irrigated area will be inevitable (Scanlon et al., 2012), but increases in crop water productivity will play an important role in mitigating this.

Changing price structures and demands for particular crops will also influence the extent of irrigated lands and the crops grown on them. In Texas as in Kansas, land area devoted to irrigated corn production is currently greater that for any other crop. However, Almas et al. (2006) conducted an economic optimization balancing water availability and extraction costs against crop revenues and projected a steady decline in corn area, an even steeper decline in irrigated wheat area, and further declines in irrigated sorghum area. Cotton was projected to lose the least percentage of area and to still be irrigated in 2061, while alfalfa was projected to gain irrigated area and become the most irrigated crop by 2061. Simplifying assumptions make exact predictions impossible with such economic models, however, and changes in irrigation technology, crop genetics and farmer decisions to spread risk were not included in their report.

IRRIGATION ON THE GREAT PLAINS – SUMMARY

In the Great Plains, soil and water conservation is being achieved in both dryland and irrigated agricultural systems, and increasingly in combinations of these systems. Reduced tillage has increased the retention of crop residues on the surface and reduced the evaporative loss of water, making more water available for plant growth and yield formation in both dryland and irrigated systems. Irrigation application efficiencies have steadily improved due to the move from gravity to pressurized systems and the ongoing improvements in reduction of evaporative losses in pressurized systems. Efficiency increases also resulted from the introduction of piped delivery systems, alternate furrow irrigation, and LEPA and drip irrigation technologies. Improved irrigation scheduling methods and technologies, including automation, have reduced losses of water to runoff and deep percolation, and have also reduced yield loss due to under irrigation, leading to overall improvement in water use efficiency.

The future of the Great Plains often has been viewed as tied to only one moving target: the steady decline of the aquifer. Recently, the moving target of climate change has been added to the perspective, reducing expectations for precipitation and increasing the expectations for evaporative demand due to warming, particularly in the southern half of the Great Plains. Two other moving targets have been largely ignored in predictions of the future, however, and they are key to understanding what is to come. One is the moving target of improving irrigation technologies coupled with improving cultivars to steadily improve crop water use efficiency, making irrigated agriculture more economically sustainable with decreasing water supply. However, improvements in irrigation management, methods and technologies can only improve the efficiency with which water is used for crop production; they alone cannot reduce pumping of the mostly non-renewable water resource in the southern part of the High Plains aquifer. Thus, the fourth key moving target is water policy. In the end, either the aquifer will be pumped until supplies economically obtainable for irrigation are exhausted, or the people of the Plains will decide at some point in time to institute policies and regulations that limit pumping to sustainable levels. Fortunately, the sustainability of irrigated agriculture with reduced water supplies has been greatly increased due to advances in irrigation application and management methods resulting from combined state, federal and private research and development efforts. This should allow for a longer and smoother transition to a less irrigated agriculture in the U.S. Great Plains. A partial victory to be sure, given the need for overall agricultural production increases to feed the future world.

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