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Development and Assessment of a Groundwater Sustainability Index in Climatically Diverse Groundwater Irrigated Regions in Nebraska

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DEVELOPMENT AND ASSESSMENT OF A GROUNDWATER SUSTAINABILITY INDEX IN CLIMATICALLY DIVERSE GROUNDWATER IRRIGATED REGIONS IN NEBRASKA

By

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Maria Ana Mulet Jalil, M.S.

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The aim of this research was to evaluate the impact of regional change in ET on groundwater level changes and the assessment and development of a groundwater sustainability index for climatically diverse regions across Nebraska during 2000-2014. Irrigation in the selected regions is predominantly supplied by groundwater. The hypothesis is that groundwater use can become sustainable if the regional evapotranspiration (ET) is managed so that it equals the ET of vegetation that is native to the region. Site locations were Box Butte, Chase, Dundy, Holt LNNRD and York Counties and 3 ecosystems were evaluated: native vegetation, dryland and irrigated cropping systems. Methodology consisted of remote sensing data analysis, GIS modeling, ASCE-Penman Monteith Evapotranspiration equation (Allen et al., 2005) and analysis of historical data. Precipitation, ET, NDVI, Kc and ET weighed to obtain county average ET .Groundwater level declines and groundwater storage data were assessed and compared with ET. Also the same procedures were applied at the township scale for 5 townships in each county. Results showed that precipitation increased from west to east ranging between 406-693 mm.y^{-1}. York County had the overall highest ET values, and Box Butte County had the lowest. Annual native vegetation ET ranged 382-644 mm.y^{-1}

and county annual ET ranged 415-720 $mm.y^{-1}$ from west to east. The highest groundwater level declines were in Box Butte, Dundy and York Counties (0.26 $m.y^{-1}$) and the lowest in Holt LNNRD (0.12 $m.y^{-1}$).Sustainability index (SI) indicated that Holt LNNRD was the most sustainable in water use (SI=0.94) and Chase County the least sustainable (SI=0.88). County average ET exceeded native vegetation ET in all cases due to the higher ET of irrigated crops. The positive correlation between ET increases and reduction in water storage showed a significant correlation (0.62) at p-value < 0.05 level confidence, n=10. Higher SI resulted in lower reduction in groundwater storage. The negative correlation between SI and reduction in groundwater storage (-0.69) proved to be significant at p-value< 0.025, n=10. However, data suggested that reducing county average ET, approaching that of native vegetation, which kept water levels in balance in the past, could be a promising practice.

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Acknowledgements

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Dedication

This work is dedicated to my lovely parents, Alicia Nelly Jalil and Jorge Sebastian Mulet, who always encouraged me and my siblings with love, support and words of wisdom to achieve goals in life.

I deeply admire my mom, an example of an excellent mother and English Professor at Cuyo University who has always been willing to educate and help others. I really had fun in your summertime English lessons while we walked around the park and across the city. Your great conviction that English was the key way to join people and to understand other cultures was completely right, and is a huge treasure for me. I will be always thankful to you for opening me that magic window.

I also admire my dad, a great father, honest and calm like a good Architect, who never doubted in teaching me the secrets of building constructions, car engines, chemistry and physics, common things of life that might be helpful someday ,by saying “Maria, just in case, you should know that…” You created on me a great self-confidence to become an independent woman today.

Their conviction that Ethics and Education were always the right way in life come to my mind when confronting big challenges. My experience in USA has been wonderful and my greatest challenge too, and for sure my parents’ continuous support have been a key factor to accomplish this big dream.

CHAPTER 1: Development and Assessment of a Groundwater Sustainability Index in Climatically Diverse Groundwater Irrigated Regions in Nebraska

1.1 Abstract

The aim of this research was to evaluate the impact of regional change in ET on groundwater level changes and the assessment and development of a groundwater sustainability index for climatically diverse regions across Nebraska during 2000-2014. Irrigation in the selected regions is predominantly supplied by groundwater. The hypothesis is that groundwater use can become sustainable if the regional evapotranspiration (ET) is managed so that it equals the ET of vegetation that is native to the region. Site locations were Box Butte, Chase, Dundy, Holt LNNRD and York Counties and 3 ecosystems were evaluated: native vegetation, dryland and irrigated cropping systems. Methodology consisted of remote sensing data analysis, GIS modeling, ASCE-Penman Monteith Evapotranspiration equation (Allen et al., 2005) and analysis of historical data. Precipitation, ET, NDVI, Kc and ET weighed to obtain county average ET .Groundwater level declines and groundwater storage data were assessed and compared with ET. Also the same procedures were applied at the township scale for 5 townships in each county. Results showed that precipitation increased from west to east ranging between 406-693 $mm.y^{-1}$. York County had the overall highest ET values, and Box Butte County had the lowest. Annual native vegetation ET ranged 382-644 $mm.y^{-1}$ and county annual ET ranged 415-720 $mm.y-^{1}$ from west to east. The highest groundwater level declines were in Box Butte, Dundy and York Counties (0.26 $m.y^{-1}$) and the lowest in Holt LNNRD (0.12 $m.y^{-1}$).Sustainability index (SI) indicated that Holt LNNRD was the most sustainable in water use (SI=0.94) and Chase County the least

sustainable (SI=0.88). County average ET exceeded native vegetation ET in all cases due to the higher ET of irrigated crops. The positive correlation between ET increases and reduction in water storage showed a significant correlation (0.62) at p-value < 0.05 level confidence, n=10. Higher SI resulted in lower reduction in groundwater storage. The negative correlation between SI and reduction in groundwater storage (-0.69) proved to be significant at p-value< 0.025, n=10. However, data suggested that reducing county average ET, approaching that of native vegetation, which kept water levels in balance in the past, could be a promising practice.

1.2. Introduction

1.2.1 World's Water Resource Current and Future Situation.

According to Iceland (2013),Rockstrom (2009), Vorosmarty et al.(2000), as referred by (Bleed & Babbitt, 2015) world population has been increasing at exponential scale throughout the years. A huge production of food and agricultural development are being required to supply the needs and there is strong evidence that demand will grow higher in the future. This will lead to water supplies and energy resource scarcity, putting us beyond the limits of sustaining life.

Service (2004) as referred by Scanlon et al. (2005), defined groundwater as Earth's largest fresh water source in the world. Brozović (2015), stated on the Foreword of the Nebraska's NRD assessment of a large scale locally water governance framework , human beings use it in agriculture to irrigate crops in order to obtain higher yields and profits .This challenges the long term sustainability of the resource.

1.2.2 Water Resource and Agricultural Production Situation in the United States of America

In the US, during 2010, the total water withdrawals for all off stream categories , reported by USGS (2010) was 1.344 billion $m^3.day^{-1}$.About 86% of it (1.158 Billion $m^3.day^{-1}$) correspond to freshwater withdrawals, of which 0.436 Billion m^3/day were irrigation withdrawals, what means near 38% of total freshwater for all uses. From the total irrigated portion in US, 57% corresponds to surface irrigation (0.249 Billion $m^3.day^{-1}$) and 49.5% (0.187 Billon $m^3.day^{-1}$) to groundwater. With this amount about 25,252,384 hectares were irrigated, just 1.5% more than the total hectares irrigated in 2005 (Maupin et al., 2010)

According to Scanlon et al., (2012) the 60% of irrigation in the country relies on groundwater. In some regions, probably the most important ones in terms of food production, like Nebraska and Texas, among others, agriculture depends mainly on groundwater.

Groundwater irrigation in agriculture used the largest groundwater amount during year 2000 (215,389,930 $m^3.d^{-1}$). The water was provided by 66 principal aquifers, from which the 55% of the total withdrawals are provided by High Plains Aquifer, California Central Valley System, The Mississippi River Valley alluvial aquifer and the Basin and Range Basin-fill aquifers, being the High Plains the most intensively used aquifer (Maupin & Barber, 2005).

As a result, Scanlon et al.,(2012) mentioned that groundwater depletion in irrigated High Plains and California Central Valley accounts for approximately 50% of groundwater depletion in US .The major issue occurs over Southern High Plains where continuing with the current depletion rates, almost the 35% of it will be unable to support irrigation within the next 30 years due to lower recharge, while in the Northern part of High Plains the recharge is higher.

It has been reported in some locations of the country, that water table declined for inadequate use, being groundwater withdrawals higher than groundwater recharge. This may have an impact on the water balance and in the sustainability of systems. (Young et al. 2012)

1.2.3 Nebraska Water Resources Situation and Food Production.

Irmak (2010b), by following NASS (2007) statistics, found out that Nebraska has the most irrigated agriculture in USA and has also been ranked first as center pivot irrigated area, irrigated lands and farms, being the total cropland area 8.74 million ha and total irrigated area 3.36 million ha. The three main crops by 2012 were, corn (3.68 million. ha^{-1}), soybeans for beans (2.016 million ha), and sorghum for grain (1.46 million ha) (USDA NASS, 2012).

According to irrigation water withdrawals USGS (2005),groundwater is the primary source of water for irrigation in Nebraska,33.2 million $m^3.day^{-1}$ by 2005(Kenny et al.,2009).Approximately 75% of irrigated lands correspond to center pivot irrigation while the remaining 25% corresponds to surface irrigation Irmak, (2010b). To irrigate the whole surface of the state, more than 105,000 active irrigation wells have been used. (Irmak, 2010b;Young et al. 2012)

Development of groundwater irrigated agriculture depends on a region’s aquifer capability .The supply may be limited. Some aquifers have limited recharge, leading to limit the amount available for future use and declining the water tables that will result in reduced pumping rates and increased required energy. It is the case of Nebraska (Ungel & Howell, 1999).

Almost all Nebraska's groundwater comes from High Plains aquifer, which includes Ogallala aquifer. In some states, the intensive irrigation has caused declines in water tables. Nebraska has lost less than 0.5% of its groundwater historical levels (Bleed and Babbitt,2015).However, Irmak (2010a), based upon a report of Conservation Survey Division of University of Nebraska Lincoln (2008) mentioned that several consecutive years of drought and increasing total water use caused significant declines such as 18 meters decline in some regions of Nebraska.

In their assessment of data ,from predevelopment (1946-1953) to spring 2013 Young, Burbach, and Howard (2013), showed the largest declines in Southwestern Nebraska, in counties such as Dundy, Chase, Perkins, Panhandle region, Box Butte county, among others, ranging from 1.52-27.43 m. South Central Nebraska experienced declines of 3.048 m in some zones to 6.096 m in others. On the contrary, some counties like Phelps, Kearney and Gosper experienced rises. In some regions of Central Nebraska, in places like Sherman, Valley and Howard, areas where surface irrigation and canals exist, groundwater levels rose up from 3.048-18.28 m.

A shorter time period assessment from spring 2008 to spring 2013done by Young et al. (2013) showed significant declines and rises, due to extremely wet years (as 2009 and 2011) and dry years (2012). About 54.5% of the wells measured, recorded declines. Northeast Nebraska, Elkhorn River basin, North Platte and the Loup/South Loup showed declines ranging 0.6-3.048 m. For western Nebraska the declines were between 0.3-6.096

m. In Nebraska Sandhills, some areas of the South Platte River and North Platte River surrounding large reservoirs it was observed rises in some zones of 0.3-3.048.

Furthermore, when comparing 2012 water level changes with 2013 ones, Young,et al.,(2013) observed that just the 2% of the wells measured showed a rise in water table levels while the 93% showed declines greater or equal 0.3m. The greater decline was at Northern Colfax County, exceeding the 6.09m. In North Platte and the Loup/South Loup rivers the declines observed ranged between 0.6-6.09 m. Western Nebraska including, Dundy, Chase and Box Butte experienced declines of 0.3-4.57 m .

To quantify groundwater level changes, the water balance equation is of major importance for agriculture and the management of fields, since it can provide estimates of water consumption (ET) and groundwater recharge/discharge, among others, thus quantifying water incomes and outcomes (Scanlon, Healy, & Cook, 2002).

1.2.4 Water Budget Equation and Groundwater Sustainability.

The term sustainability is defined as the idea of limiting resources use to levels that could be sustained over the long term (Sophocleous, 1998a).

"*The water budget equation is universal and simple, it can be adaptable because it relies on few assumptions on mechanisms of water storage*" (Healy et al.,2007).

$$P + I = ET + RO + Dperc \qquad \text{[Eq.1]}$$

$$P + I = ET + RO + (I + BF) \qquad \text{[Eq. 2]}$$

Where in [Eq1.] & [Eq2] Dperc is Deep percolation (I+BF), P is precipitation, I irrigation, ET evapotranspiration, RO runoff and, BF baseflow)

Equations 1 and 2 only apply to a system that is in balance, with no changes in water storage in the groundwater and in the vadose zone. (Dean E.Eisenhauer, personal communication, February 2015).

If the variables recharge and discharge are in balance, groundwater levels remain steady and the system is sustainable. On the contrary, if the discharge rate is higher for a long period, depletion occurs and water levels declines leading to unsustainable system (Young, Burbach, & Howard, 2014) .

For the previous mentioned reasons, efficient use of water resources becomes fundamental in Nebraska where producing in a sustainable way plays a main role and is an important key for the future generations (Irmak, 2010a)

Thus, the objectives of this research are 1) to assess the impact of regional change in evapotranspiration (ET) on groundwater level change and 2) to develop a groundwater sustainability index for climatically diverse groundwater irrigated regions in Nebraska

1.3. Hypothesis

Groundwater use can become sustainable if the regional ET is managed so that it equals the ET of vegetation that is native vegetation to the region.

1.4. Methods and Materials.

1.4.1 Site Locations Characteristics

The criteria for the selected locations were to assess sites where irrigation is predominantly groundwater irrigation with little surface water development across Nebraska (Figure 1-1).

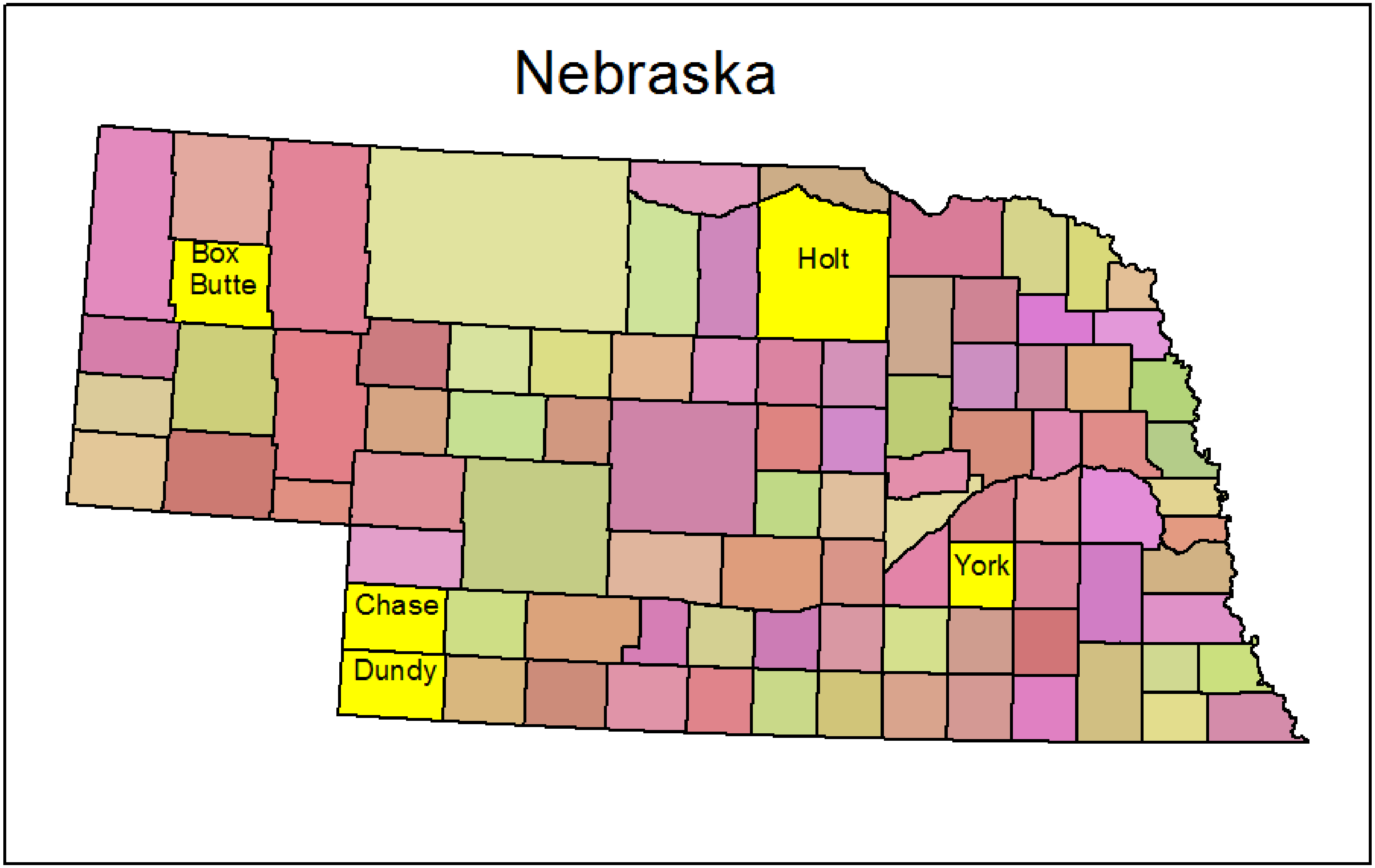

Figure1- 1 Site locations. Box Butte, Chase, Dundy, Upper Elkhorn river part (area between Holt and Lower Niobrara NRD),and York Counties

Box Butte County

Box Butte, located at Panhandle region in North Western Nebraska Latitude:42 º 05'59"N Longitude: 102 º 52'14" W, has an annual precipitation of 397 mm (NOAA). Its total area is 2784 km2.

From the total area, 21% (573 km^2) are irrigated agriculture and 29% (793km^2) dryland croplands. The main crops in the area are winter wheat and corn, 486 km^2 and 276 km^2, respectively. In the case of dryland crops the principal ones are winter wheat and corn, 348 km^2 and 276km^2, respectively. Also there are other crops like dry edible beans (118 km^2) and sugar beets for sugar (87 km^2)(USDA NASS 2012, 2007).

Box Butte's estimated Native Vegetation is 50% (1377 km^2) of its total area. Species consists mainly in mixed grass, short grass prairie species. It can be found patchy areas with bare soil and salt encrusted (Kaul and Rolfsmeier, 1993).

Chase County

Chase County is located at Southwestern Nebraska Latitude: 40 º 31'14" N Longitude: 101 º 38'40" W.

The annual precipitation is 486 m NOAA, (2015). Its total area is 2190 km^2 from which its 30% (646 km^2) pertain to irrigated agriculture while 24% (530km^2) are Dryland crops. The most important crops are corn and winter wheat, 751 km^2 and 203km^2, respectively, followed by dry edible beans (34 km^2). Approximately 152km^2 is dryland corn and 150km^2 dryland winter wheat (USDA NASS, 2012, 2007).

Chase County native vegetation is about 46% of its total territory (530 km^2). The species are mainly sand sage mixed prairies and tall and short grass species. Also, bunchgrasses and forbs are common in the region (Kaul and Rolfsmeier, 1993)

Dundy County

Located at Southwestern Nebraska, Latitude: 40-03'03" N Longitude: 101 º 32'01" W.

Annual precipitation is 480 mm. From its total (2107 km2), about 844km2 pertain to croplands, 18% (384 km^2) irrigated and 22% (460 km^2) dryland. The main crops are corn and winter wheat, 454 km^2 and corn 225 km^2, respectively. From its total 146 km^2 correspond to dryland winter wheat and 134 km^2 to dryland corn. There are also crops such as hay,55 km^2 (used for haylage and silage) and dry edible beans (26 km^2) . (USDA NASS, 2007, 2012)

Native vegetation of Dundy is estimated in 1264 km^2 (60% of its total).The species are similar to Chase County, but also it can be found riparian forest in the surrounding parts of North Platte River margins and lowlands tallgrass species region. (Kaul and Rolfsmeier 1993)

Holt LNNRD

Holt is located at Northeastern Nebraska Latitude: 42 º 27'34" N Longitude: 98 º 38'50" W. Holt annual precipitation is 641 mm.

The main crops in Holt are Hay, corn and soybean, 884 km^2, 814km^2 and 236km^2 respectively. The main dryland crops are hay alfalfa, 79 km^2 and corn 63$km^{2,}$ (USDA NASS,2012,2007)

In this research, only the portion of Holt County that is north of the Elkhorn River is considered. The area is referred as Holt LNNRD since this is the part lying inside the intersection between the Holt County boundaries and the boundaries of the Lower Niobrara NRD. Total area is 2507 km^2, according to non-published data belonging to its manager (Terry Julesgard and Kay Raiser from Lower Niobrara NRD Staff .Personal Interview. June,2016).

From the total Cropland area (1013km^2) the 29% (731km^2) is irrigated agriculture and it is not official but estimated that 11% (282 km^2) is destined dryland crops (USDA NASS, 2012, 2007; Lower Niobrara NRD).

The region under study is 1495 km^2 of native vegetation with species such as Loess Mixed Prairie species and riparian and deciduous forests species. In the moist parts it is common to find tallgrass prairie species (Kaul and Rolfsmeier 1993).

York County

York is located at Southeastern Nebraska Latitude: 40 º 51'59" N Longitude: 97 º 35'32" W. Its annual precipitation is 768 mm (NOAA, 2015).

York County is 1483 km^2. The 74% (1021 km^2) of its area are irrigated crops while the remaining 18% (245 km^2) are dryland crops. Corn and soybean are the main crops either in irrigated crops and dryland. Irrigated area destined to corn was (865 km^2) and (105 km^2) to dryland, and for irrigated soybean (391 km^2) and (72 km^2) to dryland.

The native vegetation of York is mainly tallgrass prairies species Kaul & Rolfsmeier (1993) and its represents less than 8% in the total area of the county

1.4.2 Water Budget Equation

It is shown in [Eq. 1] the water budget equation when in balance:

$$P + I = ET + RO + Dperc \qquad \text{[Eq. 1]}$$

$$P + I = ET + RO + (I + BF) \qquad \text{[Eq. 2]}$$

Where in [Eq 1.] and [Eq2], *Dperc* is deep percolation *(I+BF)*, P is precipitation, *I* irrigation, *ET* evapotranspiration, *RO* runoff and, *BF* baseflow. (Dean E.Eisenhauer, personal communication, February 2015).

Precipitation and Irrigation are considered inputs in the water balance equation, while ET, Runoff and Deep percolation are considered outputs (Healy et al. 2007).

Precipitation (P) is defined as discharge of water in any state (liquid or solid) out of the atmosphere, in places like land or water surfaces (Meinzer, 1923) cited in General Introduction and Hydrologic Definitions (USGS, 2016).

Irrigation (I) is defined as controlled application of water through systems manmade, for supplying water requirements which has not been supplied by rainfall Houk, (1951) referred by Water Science Glossary terms (USGS, 2016).

According to Irmak (2010a), evapotranspiration (ET), it the most important variable in the water budget and in agricultural systems. It represents the plants water consumption and has a crucial role in the hydrologic cycle. ET is a dual component defined as evaporation of the soils and transpiration of plants returned as vapor into the atmosphere. It is driven mainly by climatic conditions such as temperature, radiation, relative humidity, and wind speed. Approximately the 60-70% of the total precipitation is returned to the atmosphere as ET and almost 90% in arids and semi-arids zones. The ET of Nebraska is believed to represent the 90-93% of the total precipitation.

Runoff (surface runoff) (RO), is the flow or rainwater (or snowmelt) over the land surface towards stream channels. So, after it enters a stream, it becomes runoff (Langbein and Iseri 1995) cited in General Introduction and Hydrologic Definitions (USGS, 2016). About less than 10% of the precipitation corresponds to runoff. It is not a direct value to a crop unless is captured for irrigation (Unger & Howell, 1999)

As described by USGS (2016),Deep percolation (Dperc),is the amount of water that passes below the root zone of crops or vegetation (Barret & Milligan, 1953) .Here, evaporation should be minimized as possible in agriculture when plant water use want to be favored van Bavel & Hanks, (1983 cited in Unger & Howell, 1999).Deep percolation is also considered as irrigation plus baseflow, where the irrigation is water added to the fields and baseflow is the sustained runoff (Langbein et al., 1947).

Baseflow (BF) is the sustained flow of a stream in the absence of direct runoff. In the case of natural baseflow it is largely sustained by groundwater discharges (Langbein & Iseri, 1995).

$$P = ET + RO + BF \qquad \text{[Eq. 3]}$$

$$P - ET = RO + BF \qquad \text{[Eq. 4]}$$

$$P - ET = Ds \qquad \text{[Eq. 5]}$$

Where in [Eq. 5],Ds is total stream flow, the water discharge that occurs in a natural channel (Baseflow+Runoff), then:

$$Dsnv = P - ETnv \qquad \text{[Eq.6]}$$

Where in [Eq.6] *Dsnv* is the total streamflow of native vegetation, and *ETnv* is native vegetation ET.

$$Ds = P - ET \qquad \text{[Eq. 7]}$$

Where in [Eq7], Ds is the total county ‘s streamflow and ET is county’s average evapotranspiration.

Following these relations and the hypothesis, the definition of sustainability index for this research was:

$$\text{SI} = \frac{ETnv}{ET} \qquad \text{[Eq. 8]}$$

Where in [Eq. 8] *ETnv* is evapotranspiration of native vegetation, ET is county’s average evapotranspiration and SI is sustainability index .

The Index range values were arbitrary and ranged from 0 to 1, being:

$ET = ETnv$; SI=1 [Eq.8]

ET> Etnv; SI<1 [Eq.9]

ET<Etnv; SI> [Eq.10]

[Eq.8] means that, when *ET* equals *ETnv*, SI equals 1and ET (water consumption) is being sustainable. If ET is higher than *ETnv* [Eq.9] , SI is lower than 1, what means that the water consumption is being not sustainable. If *ETnv* is lower than ET [Eq.10] , SI is higher than 1 and the water consumption is being sustainable.

If *ETnv* and *ET* are not equal, there can be a change in groundwater storage.

$$ETnv - ET = \Delta S \qquad \text{[Eq. 11]}$$

In [Eq.11], the term ΔS is the change in water storage (in soil or the bedrock/groundwater),

Moreover, when SI=1 ΔS=0 and no water depletion might occur.

1.4.3. Growing Season Established Dates

The dates of growing season were established for every type of ecosystem (Table 1-1), for each county using dates suggested (NOAA Climatic Normals, 2016).

Table 1- 1.Growing Season Dates Established for each County and Each Type Of Ecosystem.

		Growing Season Dates		
	Dryland & Irrigated Corn	Dryland Winter Wheat	Dryland Eco-Fallow	Native Vegetation
		(Two periods)		
Box Butte	11May-Sep9	15Apr-Jul15 & Sep15-Oct18		May23-Sep25
Chase ¥	May3-Sep14	Apr11Jul15& Sep15-Oct27	Apr11-Oct27	May10-Oct4
Dundy¥	May5-Sep13	Apr12-Jul15& Sep15-Oct28	Apr11-Oct28	May13-Oct4
Holt LNNRD§	May3-sep12			May12-Oct4
York~	Apr27-Apr14			May5-Oct5

¥Chase and & Dundy Counties Dryland were calculated following continuous period

§Holt County Dryland & Irrigated dates period are the same

~York County Dryland & irrigated dates period are the same

1.4.4. Precipitation

Annual precipitation was calculated through remote sensed data for each year. However, to calculate non-growing season precipitation, daily values were required. The data for those periods were retrieved from NOAA Automated stations as described later in this section.

1.4.4.1. Annual Precipitation

To calculate annual precipitation, a dataset generated by Dr. Christopher Daly and PRISM Climate Group at Oregon State University, with annual precipitation values was retrieved for each year of the 2000-2014 period (Daly et al., 2015)

The use of PRISM datasets have been mentioned by several authors in research (Nelms, Messinger, and MacCoy 2015;Stanton et al., 2011; Szilágyi, Kovács, & Józsa, 2011 ;) as a good approach to estimate precipitation while using remote sensed data. It was mentioned for the first time in 2008 by (Daly et al., 2008).It consists on grids modeled on a monthly basis. Annual grids were produced by averaging (temperatures) or summing (precipitation) the monthly grids. Based upon this method, several datasets as annual, monthly datasets have been generated. The original dataset was 4km resolution (4000 m cell size), 32 bits and .bil format. [http://www.prism.oregonstate.edu/]

For this study, 15 raster images for Annual Precipitation for the entire Nebraska (Figure 1-2) and then, for every single county were generated and converted into 1000m cell size, and projected into Equal Conical Albers Area, Datum D_North American 1983.

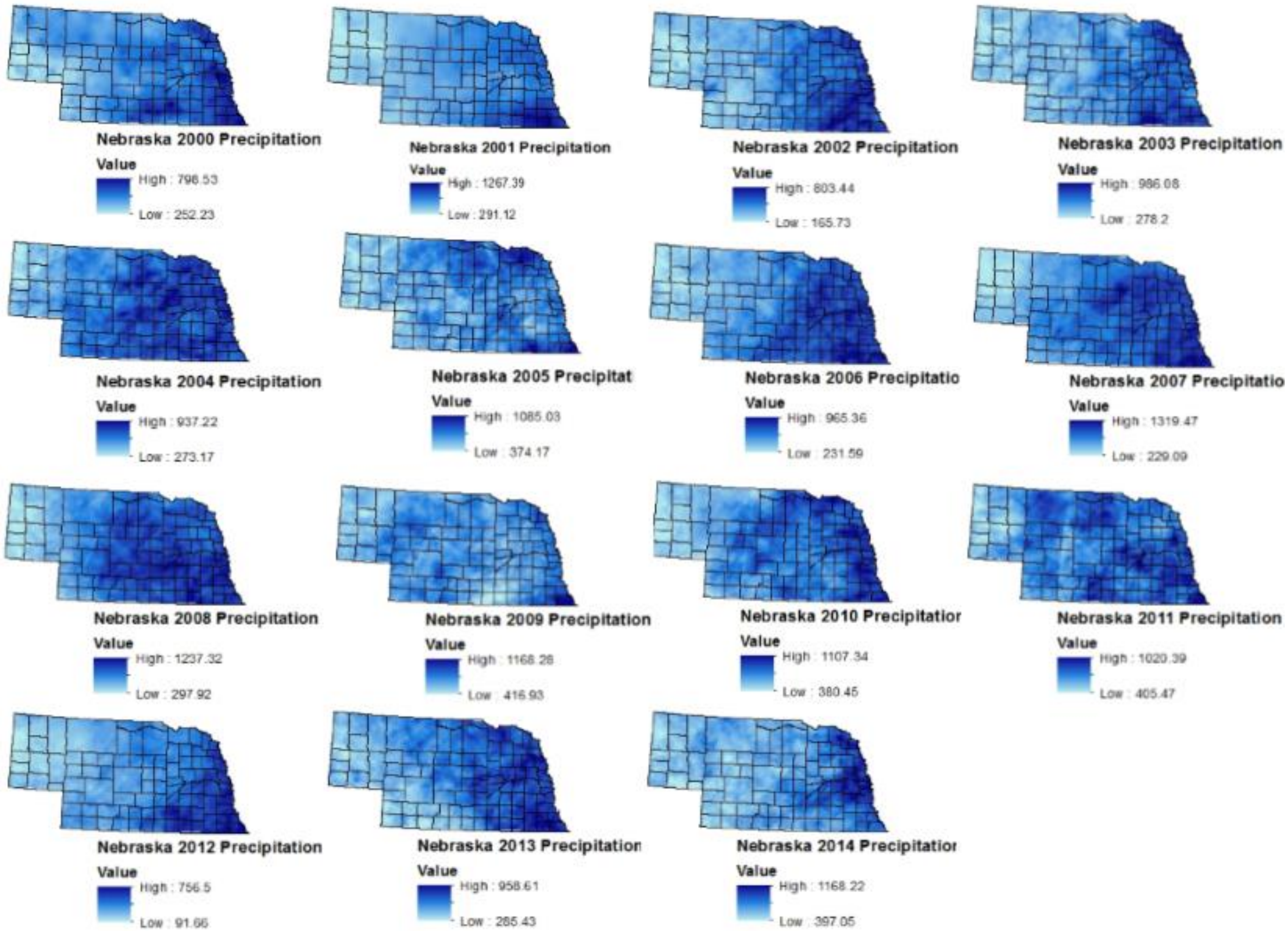

Figure1-2. Annual precipitation averages spatially distributed in Nebraska for the time period 2000-2014

1.4.4.2. Non-Growing Season Precipitation Period Dates

Daily precipitation data for four NOAA stations located in the surrounding areas of the counties were retrieved for the 2000-2014 time period (Table1-2). The dates selected for each county and each type of ecosystems correspond themselves with growing season dates selected for each county in this study (Table 1-3).

Table 1- 2. NOAA stations locations

Station	Latitude(º)	Longitude(º)	Elevation (m)
Alliance Municipal Airport (Box Butte)	40.05722	-102.8	1196
Imperial Municipal Airport (Chase & Dundy)	40.51	-101.62	996.1
O'Neill (Holt LNNRD)	42.46111	-98.6494	606.6
Bradshaw (York)	40.88222	-97.7492	524

Table 1- 3. Estimated Non Growing Season Precipitation dates for each cropping system and Native Vegetation, according to each location.

County	Irrigated crops	Dryland crops	Native Vegetation
Box Butte	10Sep-10May	19Oct-14Apr 16Jul-14Sep	22Sep-22May
Chase	15Sep-2May	28Oct-10Apr	5Oct-9May
Dundy	14Sep-4May	29Oct-10Apr	5Oct-12May
Holt LNNRD	11Sep-2May	11Sep-2May	4Oct-12May
York	15Sep-26Apr	15Sep-26Apr	6Oct-4May

*(NOAA Climatic Normals, 2016)

1.4.5. Evapotranspiration Calculation

The methodology of using remote sensing data, for estimating plant consumption variables and related ones, such as Kc, Actual ET, and vegetation index, have been quite used by researchers(Mutiibwa & Irmak, 2013; Szilágyi et al., 2011; Singh & Irmak, 2009; Allen et al., 2007; Bastiaanssen et al., 1998; Tieszen, Reed, Bliss, Wylie, & DeJong, 1997) in the last decades. They used different algorithms to estimate spatially the energy balance, SEBAL (Bastiaanssen et al. 1998) and METRIC (Allen et al. 2007).Moreover, creation of linear regression equations and models that explain relations between vegetation index and growing season Kc are commonly used too. As referred by (Kamble, Kilic, and Hubbard ,2013) ,Bausch & Neale (1989) proved the application of remote sensing technique to calculate seasonal NDVI-based Kc.

Towards this aim, a variety of sensors with different resolutions are worldwide used, according to the issue to be addressed.

In this study, seasonal actual ET was calculated as ET=Kcr. An NDVI-based Kcr, (Kamble et al. 2013), linear equation for the growing season was applied to get Kcr values.

ETr data from ASCE standardized Penman-Monteith reference ET for alfalfa equation,(Allen et al.,2005) , using HPRCC (High Plains Regional Climate Center) automated ground stations, were estimated, for the time period of 15 years (2000-2014).

Seasonal NDVI (MOD13Q1 250m NDVI product) from NASA (2015), sampling was obtained through ArcMap GIS 10.2 developed models for irrigated crops and native vegetation.

Regarding dryland crops, manual NDVI sampling was applied. The total annual ET for each type of ecosystem, in every county was calculated using different relations based upon precipitation in years 2000-2014.

1.4.5.1. NDVI based Kc simple linear equation.

In this investigation, a simple Linear Regression model

$$Kc_{-NDVI}=1.457*NDVI + 0.1725 \qquad \text{[Eq. 12]}$$

Equation [12] was developed by Kamble, Kilic & Hubbard (2013), was used for obtaining Kc values. It was applied to NDVI Moderate Resolution Imaging Spectroradiometer (MODIS). The 1.457 term represents the slope and -0.1725 the intercept. It can be applied to rangeland, irrigated crops and dryland crops since they showed a strong correlation between NDVI and crop coefficient for all of them, being better explained under no water stress conditions. The correlation coefficient was r^2=0.8259, that means the NDVI variations explain part of changes in Kc. The accuracy via remote sensing was +-9% at 90% confidence level as a consequence of some uncertainties as regards input data, satellite resolution and data accuracy (Kamble et al. 2013).

1.4.5.2. MODIS-NDVI data Normalized Difference Vegetation Index

Vegetation Indices in remote sensing are designed from combinations of spectral values divided, added or multiplied in a manner to yield a single representative value of the vegetation status within a pixel. In NDVI ratio, quotients between Near Infrared band (NIR) and Red band (R) are used: NDVI= NIR-R/NIR+R. NDVI values ranges between 0-1 (Campbell & Wynne, 2011).

MOD13Q1 250m NDVI product from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, managed by National Aeronautics and Space Administration (NASA) is a promissory product to apply for land use/land cover mapping at regional scale. It provides global coverage and has a spatial 250m, spectral, temporal (16-day composites) and 12-bit radiometric resolutions (Wardlow, Egbert & Kastens, 2007).

MOD13Q1 product is cloud corrected, only the higher quality cloud free pixels are selected for the 16-day compositing, resulting representative tiles of the status of the vegetation [http://modis.gsfc.nasa.gov/data/dataprod].

In this research, MOD13Q1 250m spatial resolution product was selected to calculate the NDVI for native vegetation, irrigated crops and dryland crops.

The measures for seasonal NDVI were obtained from MODIS Terra 16-day composites, using gridded NDVI tiles acquired on DOY 97, 113, 129, 145, 161, 177, 193, 209, 225, 241 257, 273, 289, 305, 321, for Nebraska's zone tile h10v04, for the 15 years (2000-2014). Each tile contains the maximum NDVI value during the16 day period. Data values used for each county and type of ecosystem were selected according to the dates of growing season of each one.

All the tiles had been previously projected in the same system Equal Conical Albers, and Geographic Coordinate System GCS_North_American_1983 (NAD83), in order to preserve areas and work with homogeneous spatial data.

1.4.5.3. NDVI sampling: Automated and Manually

According to Chang (2013), a pure pixel is defined as the pixel whose its whole spectral signature is represented by a single material substance, a pixel containing unique spectral material.

In this case, a purity Pixel Model to obtain representative values of NDVI across the growing season of irrigated crops and native vegetation was created for each county, with the exception of York County in which the native vegetation sampling was done manually due to its small area of native species, basing upon 9- Mile Prairie located at UNL in Lancaster County.

The dryland Purity Model was run only for Box Butte. Its total dryland areas allow to run the model obtaining representative values. It was not possible to do in the rest of the counties. The dryland NDVI sampling for the rest of the counties was manually achieved.

Purity Pixel Model

Through the use of ArcMap GIS 10.2 software model builder tool, it was developed a model, capable to project layers, separate pure pixels of each ecosystem and measure its NDVI averages values for every 16 days.

It consisted of two Phases, 1 and 2.The first Phase (1) for creating single layers with representative pixels (80% confidence) for the specified type of ecosystem. The second phase (2) for averaging the NDVI values for these pixels previously selected in phase 1.The input data source required in Phase 1 were:

- USDA United States Department of Agriculture NASS Agriculture's National Agricultural Statistics Service CDL Cropland Data Layer product for year 2005, 30 m Resolution Dataset for Box Butte, Chase, Dundy, Holt and York counties ;
- County Boundaries TIGER/lines for Nebraska counties. created by U.S. Department of Commerce, U.S. Census Bureau, Geography Division (US Census Bureau, 2007),
- 2005 Nebraska Center Pivot Irrigation Systems and Nebraska 2005 Other Irrigated Areas 2005 dataset. Center for Advanced Land Management Information Technologies (CALMIT,2007)
- Nebraska Natural Resources District Boundaries (NRDs) shp. 1990 TIGER/lines dataset produced by US Bureau of Census (US Census Bureau, 1990).

  It was assumed that the NDVI in land use/ land cover change during 2000-2014 would not differ significantly to the land use/land cover of CDL 2005. The reason for this assumption was that the Irrigated Zones defined for "Center Pivot Irrigated Areas" and "Other types of Irrigated Areas" were done for 2005. This approach aimed to produce data as consistent as possible, working with tiles of the same year.

In the case of Irrigated Phase 1 (Figure 1-3) CDL 2005 tiles defined total crop area and the Center pivot/ Other Irrigated lands, defined Irrigated crop areas. These two delimited the part of the County which contains irrigated crops. Native vegetation tiles, only

required USDA NASS CDL 2005 tiles, since the model separates the pixels according to land use/ land cover classification. Figure
(1-4):shows model builder tool run for native vegetation.

For phase 2 the inputs used were:

- The outputs obtained in phase 1 which represent pixels of specific type of land use/ land cover.
- MOD13Q1 250m (16-days composites) product projected, described previously.

Two different layers containing native vegetation 2005 and irrigated crops 2005 were obtained for each county in Phase 1. Then, those outputs plus the NDVI-250m 16-days composites, previously projected, were combined to obtain representative pixels of both types of ecosystems.

Phase 2 (Figure 1-5) consists of a Model of basic GIS tools that are able calculate simultaneously 30 layers for a year. The results being 30 layers with NDVI data of DOY 97, 113, 129, 145, 161, 177, 193, 209, 225, 241 257, 273, 289, 305, 321 of which 15 layers correspond to native vegetation and 15 to irrigated crops.

The Model was run for each County for each year and County from 2000 to 2014. It meant a total of 2250 layers containing a sample of NDVI values.

Once the representative layers were done, the average value NDVI values were computed using the statistics viewer in each table of content of GIS ArcMap. (Figure 1-6) shows a spatial summary of the Model run (Phase I) and (Phase II)

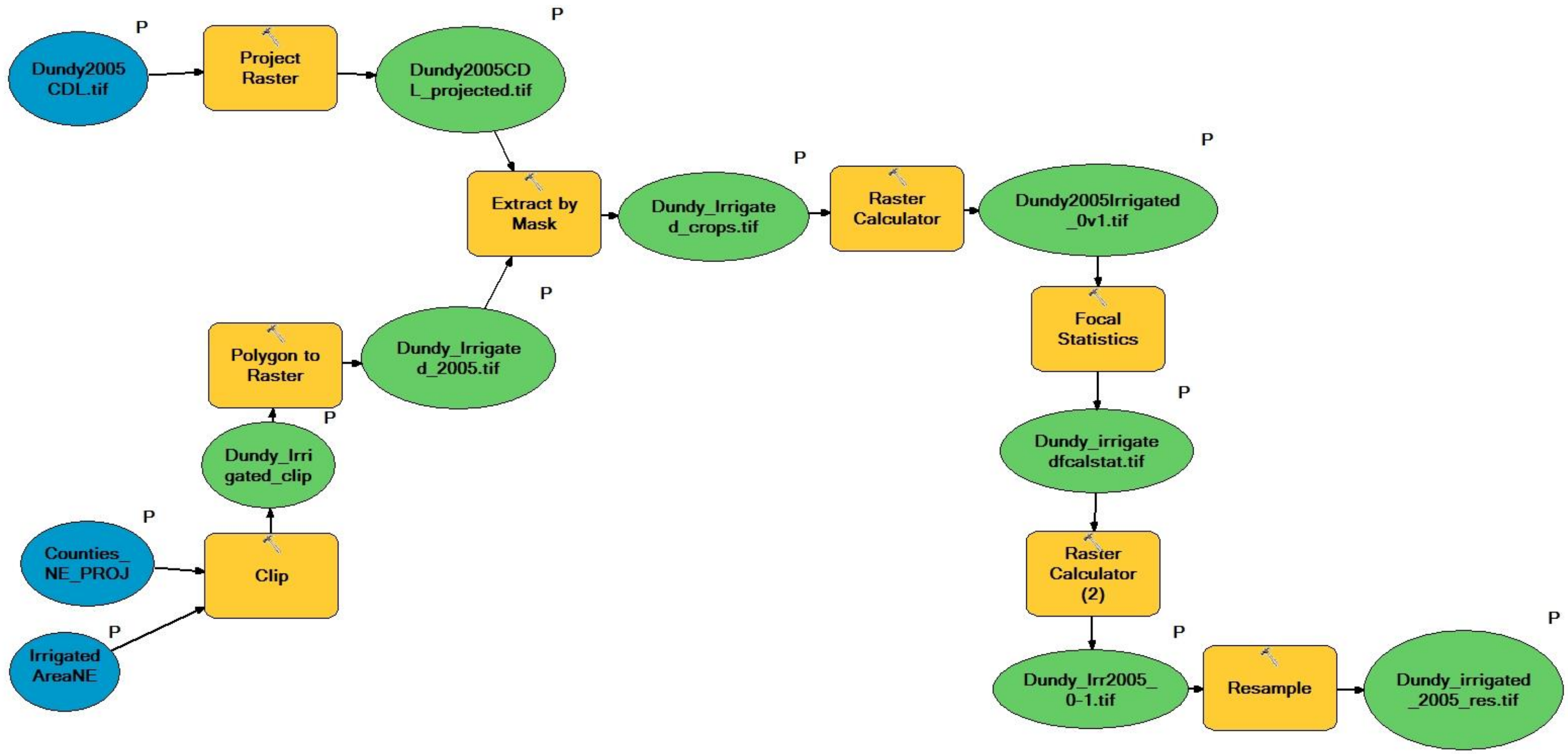

Figure1- 3. Phase 1 Model for Irrigated zones in Dundy County, Nebraska. Representative Irrigated Crops Pixels (80% confidence) in Dundy. Blue circles are inputs, yellow squares tools and green circles outputs, P letter means inputs/output parameters of the Model

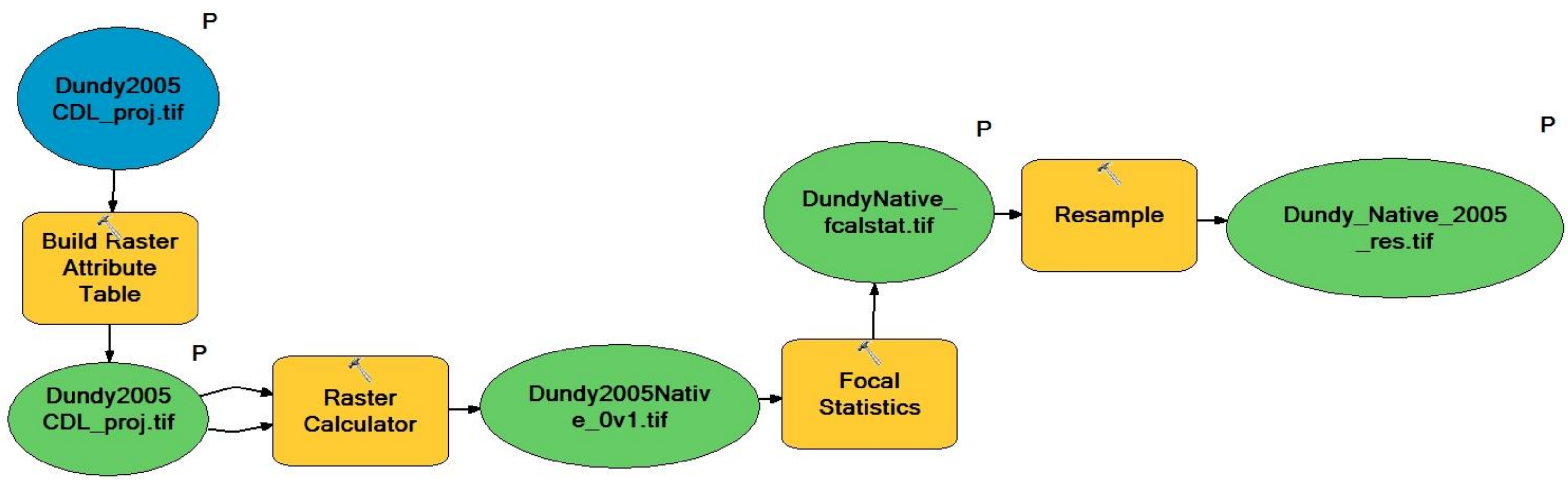

Figure1- 4. Model Builder Tool run for Native Vegetation (Phase 1) .Representative pixels in Dundy County. Blue circles are inputs, yellow squares tools and green circles outputs, P letter means inputs/outputs parameters of the Model

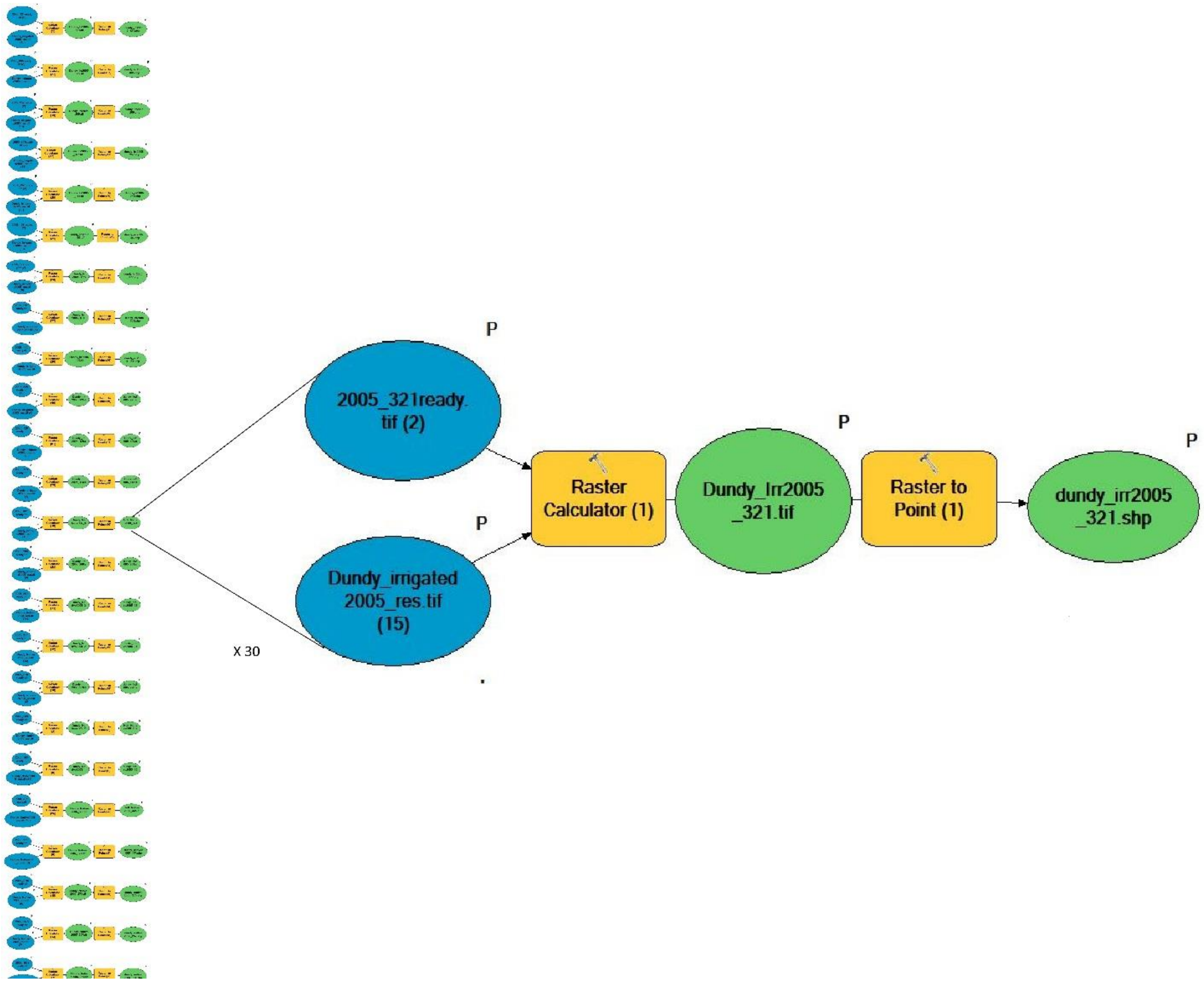

Figure1- 5. GIS Model Phase 2 for Dundy County. 30 NDVI layers processing at the same time(15 For Native /15 for Irrigated crops for year 2005). Blue circles are inputs, yellow squares tools and green circles outputs. P means inputs/outputs parameters of the Mode

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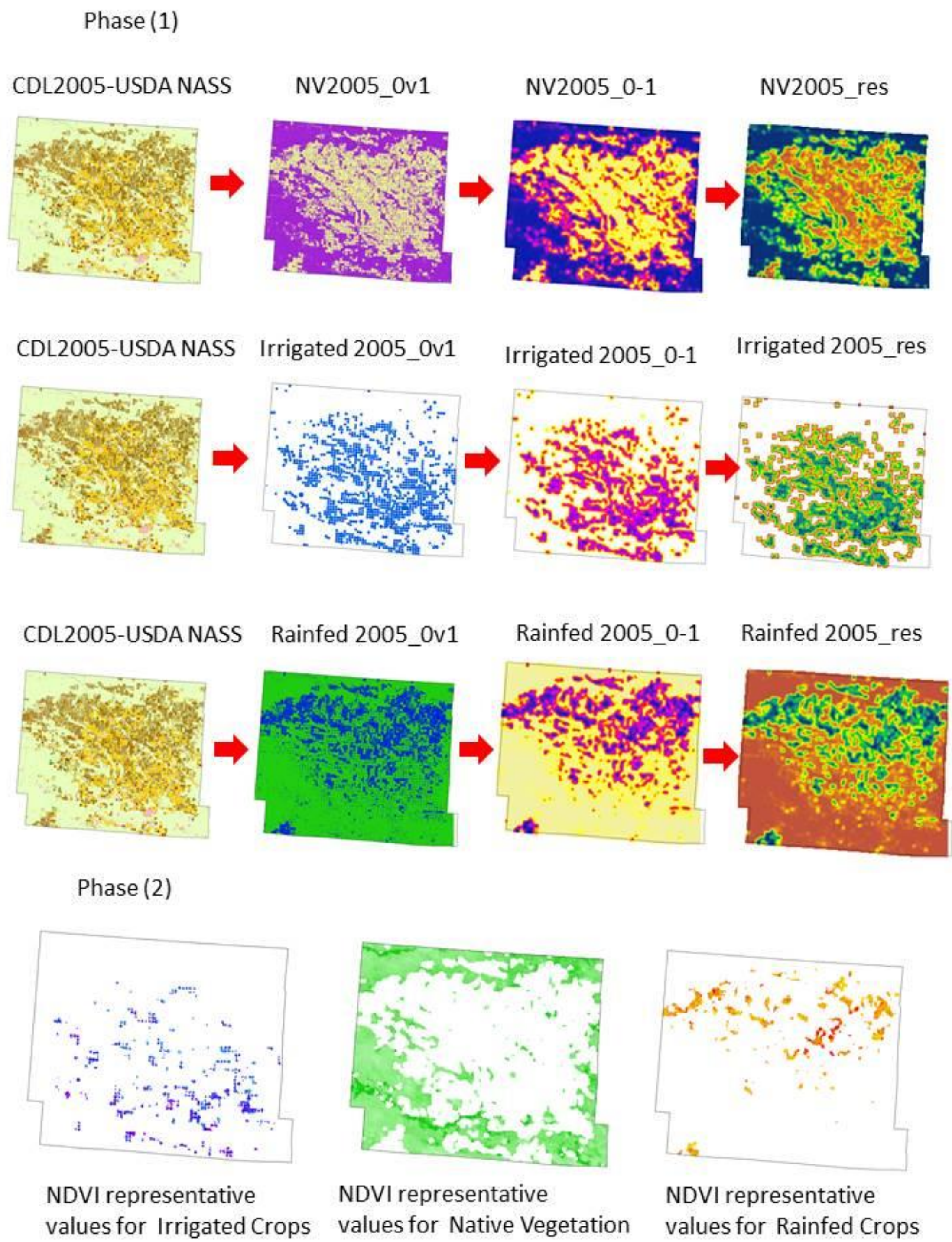

Figure1- 6. GIS procedures Spatially Summarized. Phase 1. Selection of Representative Pixels. Brown pixels in NV2005_res are Native Vegetation Pixels, Green pixels are Irrigated pixels in Irregated2005_res and Blue pixels are dryland pixels in Rainfed2005_res. Phase 2 . NDVI Applied to The Pixels

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Manual sampling NDVI

NDVI sampling in dryland Crops, was done manually, due to the fact that in some cases the crop strips in the wheat fallow crop rotation (strip cropping) are narrow and the location of the fields do not have not have a specific size, leading the model to make errors such as inappropriate pixel sampling. This was only possible in Box Butte County, where dryland is the main cropping system.

To search for dryland fields, it was used 15 m resolution imagery provided by Google Earth, using the tool “Historical Imagery” which allows to change yearly the Images and to check whether the land use has changed or remained the same. Once the sites had been identified, its latitudes and longitudes were exported to GIS ArcMap 10.2 shapefile, containing the points of interest.

In a second check step, the CDL 2005 Cropscape was displayed to identify iddle/dryland crops possible sites. Also, Center pivots 2005/ Other Irrigated Crops shapefiles, were used to certify that the selected places were not irrigated. Thus, with Google Imagery overlapped to CDL 2005 layers and 2005 Nebraska Center Pivot/ 2005 Nebraska Other Irrigated Crops layers (CALMIT ,2007) was possible to achieve a higher accuracy, that the locations selected were dryland crops.

Once the locations were selected, its NDVI values were computed for every pixel, for 15 years for every 16-days from DOY 97 to 321.

A total of 75 pixels were manually measured for 15 year time period. For Dundy County there were selected five different fields with dryland crops and four fields for Chase County. Five different fields were sampled from Antelope County to compute Holt NDVI values due to it have a greater area of dryland crops and make it easy to identify. For York County, four different samples from Polk County and one from Clay County were selected and computed.

For each field 3-5 pixels were selected.

The values for all the counties were averaged as a single value for every 16-day composite for each County.

As York county lacks of native vegetation, due to it is mainly an agricultural region, Native vegetation sample values were taken from the 9 mile prairie located East to York County, in Lancaster County. In Figure (1-7) is shown The 19 sampled points spatially distributed.

Sample	County	Latitude (º)	Longitude (º)
Sample1	Dundy	40° 19' 42.9204"	-101° 38' 12.4974"
Sample2	Dundy	40° 20' 55.6398"	-101° 32' 45.5388"
Sample3	Dundy	40° 1' 53.6916"	-102° 0' 25.2396"
Sample4	Dundy	40° 1' 8.0796"	-101° 50' 15.2484"
Sample5	Dundy	40° 10' 27.4008"	-101° 41' 46.4094"
Sample6	Chase	40° 23' 25.1586"	-101° 37' 16.8888"
Sample7	Chase	40° 40' 23.0586"	-101° 57' 36.5688"
Sample8	Chase	40° 40' 49.1196"	-102° 2' 40.2066"
Sample9	Chase	40° 39' 37.5582"	-101° 58' 24.4992"
Sample10	Antelope	42° 23' 52.7316"	-98° 15' 34.3008"
Sample11	Antelope	42° 23' 47.9184"	-98° 8' 25.101"
Sample12	Antelope	42° 23' 46.251"	-97° 58' 33.621"
Sample13	Antelope	42° 3' 45.021"	-98° 2' 52.4688"
Sample14	Antelope	41° 54' 59.58"	-98° 12' 43.7292"
Sample15	Polk	41° 14' 23.499"	-97° 26' 51.921"
Sample16	Polk	41° 13' 12.111"	-97° 28' 5.721"
Sample17	Polk	41° 9' 56.6496"	-97° 23' 5.7906"
Sample18	Polk	41° 7' 45.5988"	-97° 22' 54.4398"
Sample19	Clay	40° 32' 51.8706"	-97° 55' 31.53"

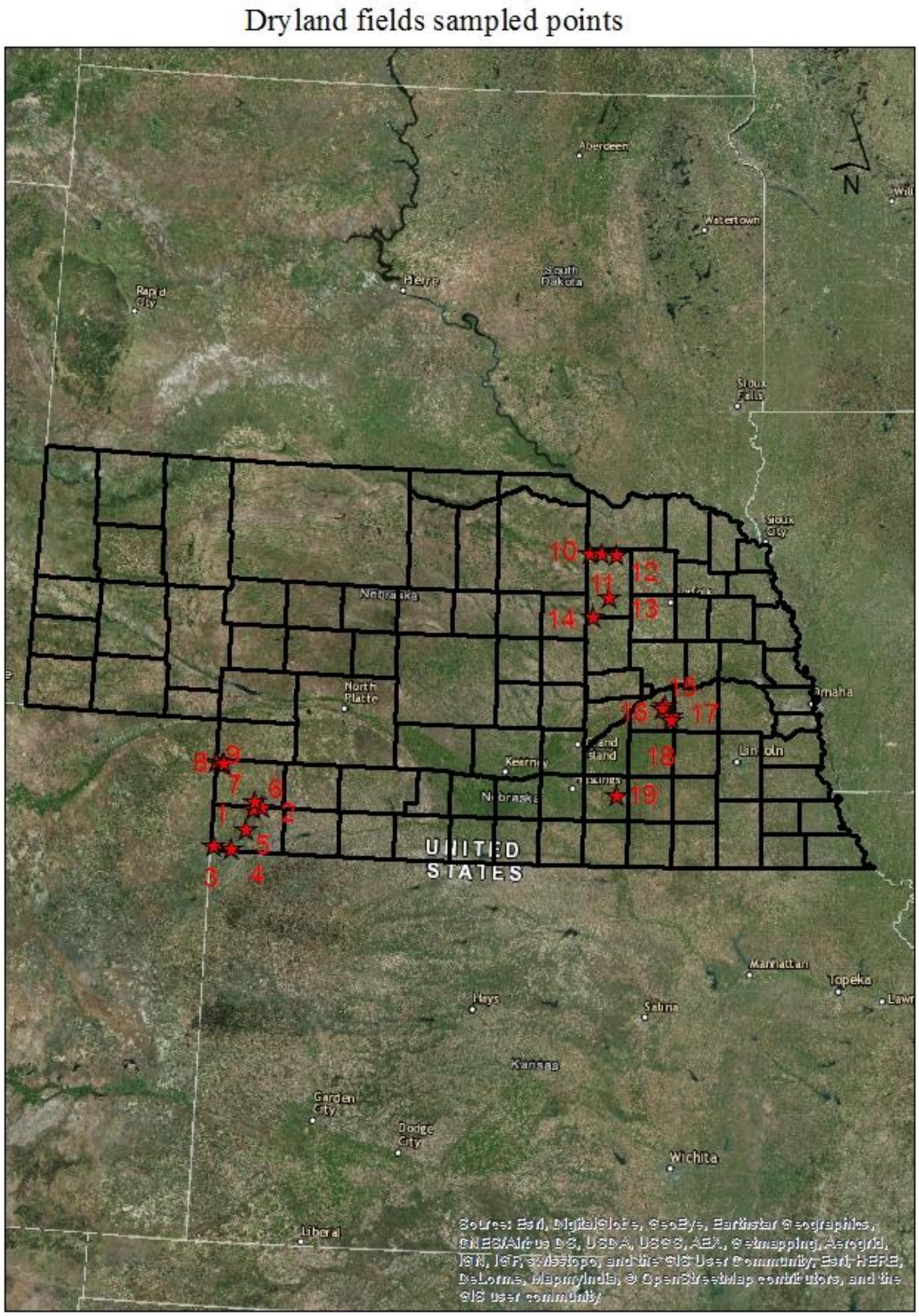

Figure1- 7. Site locations for 19 fields of dryland crops across Nebraska

1.4.5.4 Reference ETr Calculation

To calculate the Alfalfa reference ET variable, wide used across Nebraska , it was applied the ASCE standardized Reference Evapotranspiration Equation (ASCEsz Penman-Monteith) alfalfa based, developed by the Environmental and Water Resources Institute of the American Society of Civil Engineers. (Allen et al.,2005).

An EXCEL spreadsheet, non- published, for Alfalfa reference values was used for daily ETr values calculation. The spreadsheet followed the standardized equation and converts English units into Metric system Units (Burdette Barker. Personal Communication, November 2015). The Penman Monteith equation's goal is to bring commonality to the calculation of reference ET.

The basis of the standardized reference ET is the ASCE Penman Monteith (ASCE-PM) method of ASCE Manual 70 is shown in [Eq. 13]:

$$ETsz = -\frac{0.408\ \Delta(Rn - G) + \frac{\mathrm{Cn}}{\mathrm{T}+273} u2\ (es - ea)}{\Delta + (1 + Cd * u2)} \qquad \text{[Eq. 13]}$$

Where,

ETsz= standarized reference crop evapotranspiration for short (ETo) or tall (ETr) surfaces ($mm.d^{-1}$ for daily time steps or $mm.h^{-1}$ for hourly time steps)

Rn = calculated net radiation at the crop surface ($Mj.m^{-2}d^{-1}$ for daily time steps or $MJ.m^{-2}.h^{-1}$ for hourly time steps),

G= soil heat flux density at the soil surface ($MJ.m^{-2}\ d^{-1}$ for hourly time steps),

T = mean daily or hourly air temperature at 1.5 or 2.5-m height (°C),

$U_{2=}$ mean daily or hourly wind speed at 2 m height ($m.s^{-1}$),

e_s=saturation vapor pressure at 1.5 to 2.5-m height (kPa) calculated for daily times steps at the average of saturation vapor pressure at maximun and minimum air temperature,

e_a= mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ= slope of the saturation vapor pressure temperature curve (kPa.°C^{-1})

γ= psychrometric constant (kPa °C^{-1})

C_n= numerator constant tha changes with reference type and calculation time step (K mm.s^3 Mg^{-1} h^{-1}) and

$D_{d=}$ denominator constant that changes with reference type and calculation time step (s.m^{-1})

Untis for 0.408 coefficient are m^2 mm MJ^{-1}

The alfalfa "tall" crop is understood as an ideal crop with an approximate height of 0.5 m (similar to full-cover alfalfa) (ASCE-PM,2005).

The daily data required to complete the ASCE Standarized PM equation, for the time period 2000 to 2014, to use in the calculations were retrieved from HPRCC [http://www.hprcc.unl.edu] from automated stations located in near Box Butte, Chase, Dundy, York counties, and Upper Elkhorn river zone (Lower Niobrara-Holt) (Table 1-4).

Table 1- 4. HPRCC Stations located in Nebraska, placed near the zones under study.

County	Station	Latitude	Longitude	Elevation
Box Butte	Alliance North	42.1	-102.55	1213m
Chase & Dundy	Champion	40.4691616	-101.7485059	997m
Holt LNNRD	O'Neill	42.4594	-98.6564	606.5m
York	York	40.86	-97.6167	490.1m

The variables retrieved were: date, Maximum temperature Tx (°F),Minimun temperature Tn(°F), Average temperature Tav (°F), Relative humidity RH(%), Temperature od dew Tdew (°F), Wind speed WS (mph), soil temperature Tsoil (°F) and net radiation Rs (Langleys). The Excel spreadsheets convert the units into Metric system.

The daily ETr calculated values allowed estimate with accuracy specific dates for each type of ecosystem, applying it later to its Kc calculated value

1.4.5.5. Annual Evapotranspiration of Native Vegetation

To calculate annual native ET, based upon USGS (1984) Circular paper 2300 prepared by (Schopp and Bauersfeld 1984),it was obtained from the maps, the Runoff (mm) and its percentage (%)(Table 1-5), then, if Precipitation minus Runoff is ET, it can be obtained the relation shown in (Table 1-5) ETnv/Pa, where ETnv is ET of native vegetation and Pa is annual precipitation.

Table 1- 5. Runoff for each county, Percentage of Runoff and Decimal Fraction that corresponds to annual Native Vegetation ET in mm.

County	Annual Runoff (mm)	%Runoff	ETnv/Pa
Box Butte	25	6	0.94
Chase	19	4	0.96
Dundy	19	4	0.96
Holt LNNRD	50	8	0.92
York	50	7	0.93

$$P = ETnv + RO \qquad [Eq.14]$$

$$ETnv = P - RO \qquad [Eq.15]$$

$$ETnv = P - RO \qquad [Eq.16]$$

ETnv=P * ETnv/Pa [Eq.17]

From [Eq. 14], [Eq15] and, [Eq. 16], where P is Annual Precipitation (mm), RO is Runoff (%) and ETnv is annual native vegetation ET (mm)],it was obtained [Eq.17]. The ratios for every County multiplied by its Annual Precipitation represent the total native vegetation.

1.4.5.6. Annual ET for Dryland and Irrigated Crops

For this study, the Annual ET was calculated as the seasonal ET plus the ET during off season. It is challenging to obtain an annual ET result and there is not literature available for some specific zones. Thus, by following other studies conducted in the Great Plains and surrounding areas different relations were applied.

Different works of research in Central and Southern Great Plains (Musick 1970; Musick & Lamm, 1990) according to Unger & Howell, (1999) found out that exists significant relationships between residual ASW storage after harvest and preseason soil water storage from precipitation on Pullman clay loam soil, Southern Great Plains Texas. A test made in Texas s using different depths (125 mm,200 mm and 375 mm, respectively) of preplant irrigation only for continuous grain sorghum on Pullman clay loam soil , showed relatively low storage efficiencies at planting (42% and 32%) . Then, if the water storage for irrigated crops (sorghum) is considered to be ranging between 30-40%, the remaining 70-60% is ET. Furthermore, Hay & Irmak (2009) studied off season ET in South Central Agricultural Laboratory (SCAL) at

Nebraska at in a 3 year study. They obtained ET ranging between 133-167 mm for off season and $ET_{off\ season}/P_{off\ season}$ ranging between 0.41-1.21variating according to wet and dry years. Thus, by assuming that Western Nebraska conditions are similar to South and Central Great Plains conditions, ETa/Pa=0.7. For this research, it was only required only to calculate off season ET, like follows : $ET_{(off\ season)}/Precipitation_{(off\ season)}$= 0.7 for Box Butte, ET(off season)/Precipitation (off season)= 0.5 for Chase and Dundy which have similar climatic conditions . Hay & Irmak (2009) , ET(off season)/Precipitation (off season)= 0.4 for Lower Niobrara Holt and York which also have similar climatic conditions.

According to Unger & Howell (1999), the water storage efficiencies in fallow cropping systems for Great Plains after 20th century went up to 50% under some conditions (Smika, 1986). A study made in Akron, Colorado from 1976 to 1990 in wheat, in which 1976-83 tillage was minimum , and then no-tillage from 1983-90, achieved and overall water storage of 183 mm, % of precipitation 40%. (Greb, 1979). Thus, if water storage for Akron was 40%, the ET was about 60%. For this study, it was assumed similar values and calculated annual ET as the seasonal ET plus the off seasonal ET as; $ET_{(off\ season)}/Precipitation_{(off\ season)}$=0.6 for Box Butte , $ET_{(off\ season)}/Precipitation_{(off\ season)}$=0.4 for Dundy and Chase and , $ET_{(off\ season)}/Precipitation_{(off\ season)}$=0.3 for Lower Niobrara Holt and York. Table 1-6 summarizes the ETa/Pa for used for each County and ecosystem. Table (1-6) shows a summary of these values.

Table 1- 6. Summary of ET$_{(off\ season)}$/Precipitation $_{(off\ season)}$ estimated to calculate Irrigated and Dryland Annual ET.

	Irrigated	Dryland
Box Butte	0.7	0.6
Chase	0.5	0.4
Dundy	0.5	0.4
Holt LNNRD	0.4	0.3
York	0.4	0.3

1.4.6. Counties Areas

The county areas (Table 1-7) were estimated using the Census USDA (2012) reported areas for each county. For Low Niobrara-Holt area, the area was provided by the Lower Niobrara NRD. There is not official data about the area, but there are many reports and non-published data about the area provided by the NRD managers for this study

Table 1- 7. County area of Box Butte, Chase, Dundy and York. Lower Niobrara NRD inside Holt's boundaries

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County	Total area (km^2)	Total cropland area(km^2)	Irrigated crop area (km^2)	Dryland crop Area (km^2)	Native Vegetation area	%Irrigated	%Dryland	%Native
Box Butte §	2733	1365.77	573	793	1367	21	29	50
Chase§	2190	1176	646	530	1014	30	24	46
Dundy§	2107	844	384	460	1264	18	22	60
Holt LNNRD ¥	2507	1013	731	282	1495	29	11	60
York §	1374	1267	1021	245	107	74	18	8

§ USDA-NASS (2012) Census data

¥Lower Niobrara NRD data

1.4.7. Groundwater Level Declines

To estimate water levels variation for the time period 2000-2014, the kriging extrapolation method was applied to the areas of each county, based upon the difference resultant from two set points in time with groundwater levels of wells in spring season, 2000 and 2014. The data measures were provided by the Institute of Agriculture and Natural Resources of the University of Nebraska Lincoln (UNL IANR) and Arc Map 10.2 GIS software. Wells locations with its measures were converted into a point shapefile and krigged .Cell size for pixels were 250 m.

The kriging method (Figure 1-7) assumes that distance/direction between samples points are spatially correlated, so that can explain variations. Predicted values are derived from the measure of relationship samples through the weighted average technique (Childs 2004).

For this study, kriging Ordinary method, without a fixed radius and the Gaussian semivariogram was used.

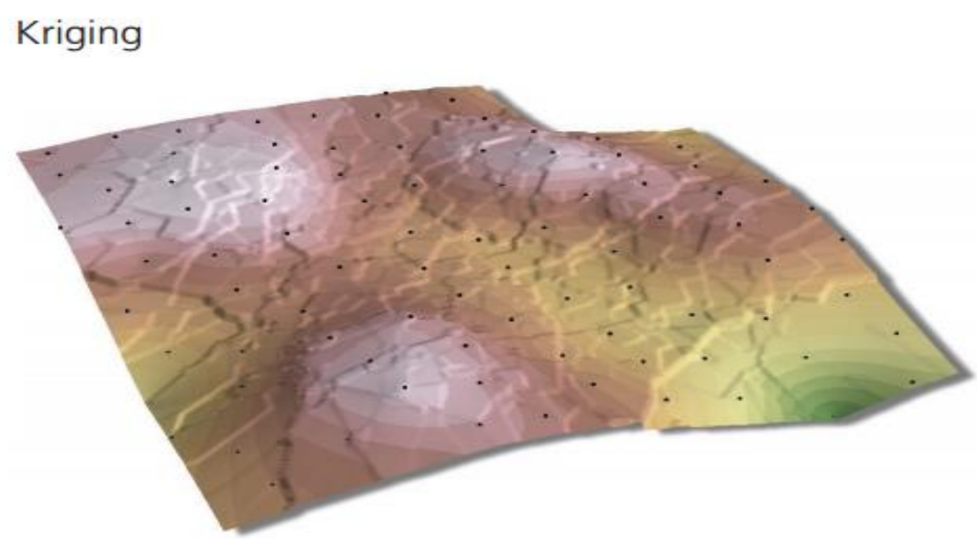

Figure1- 8.Example shown in Childs, 2004 for Krig Interpolation technique. Weighed average technique.

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1.4.8 Township scale Assessment

In order to evaluate how the scale impact results, five townships inside each county for 2000-2014 time period were evaluated. The criteria for the selection were townships with intensive use of groundwater irrigation inside each county.

Township evaluated were 25N 49 W in Box Butte, township 7N 40W in Chase, 2N 38W in Dundy, 31N 14 W in Lower Niobrara-Holt region and 10N 3W for York county (Figure 1-9).

Weighed ET and water level declines were calculated and also the sustainability index and change in water storage in order to assess data at different level scale.

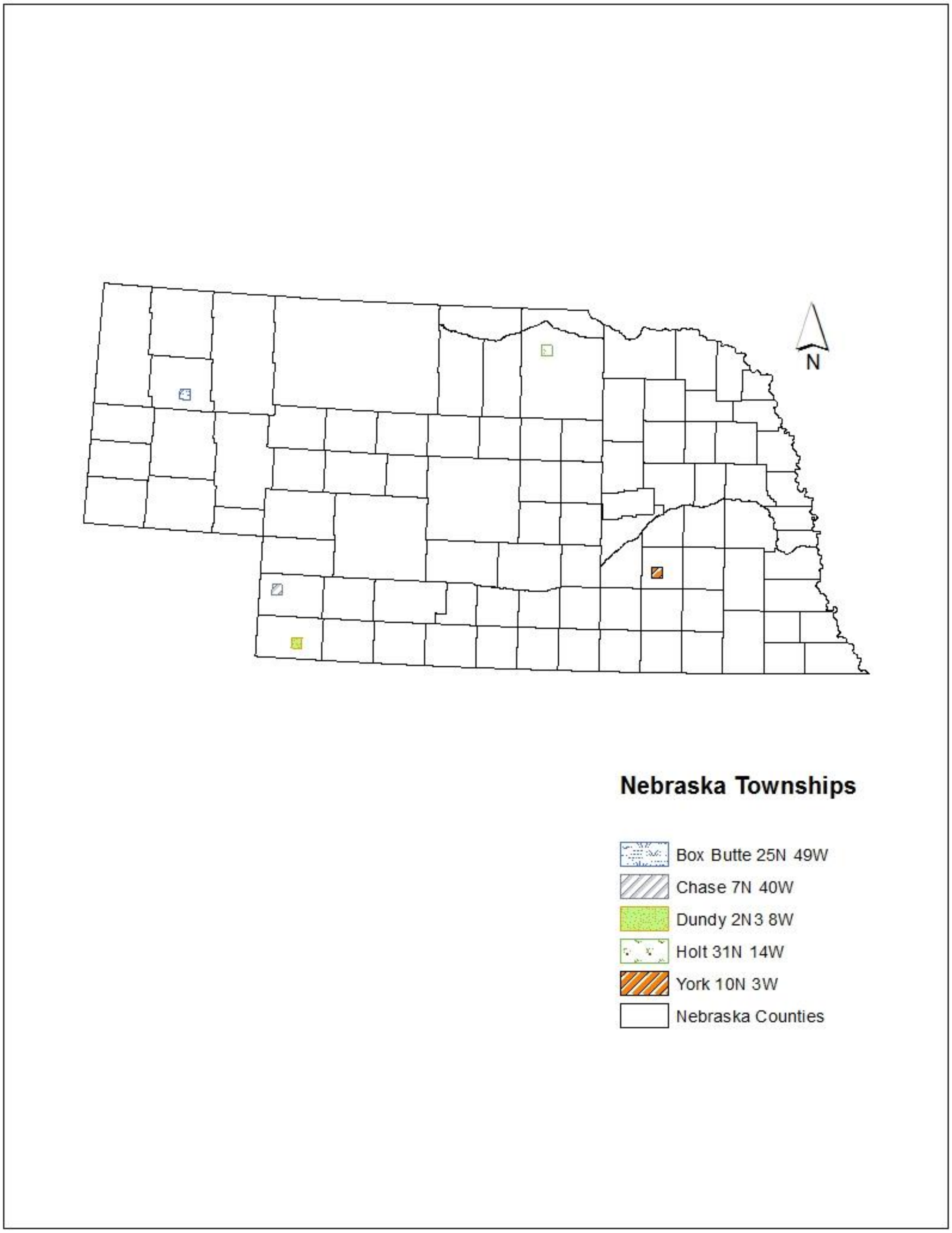

Figure1- 9. Township selection for each county.

1.5. Results and Discussion

The first objective of this work of research was to assess the impact of regional difference in ET on groundwater level changes. To address that, several variables related directly and indirectly to water balance equation such as precipitation, Seasonal and Annual ET, Kc and NDVI variations in time in different regions, water level declines, change in water storage were tested for the time period 2000-2014.

1.5.1 Annual Precipitation

Annual average Precipitation results are shown (Figure 1-10) for the five counties of this study. Nebraska precipitation increases West to East, then York and Holt counties showed the highest overall precipitations along the years due to they are located in the Eastern part of Nebraska. They presented average values of 655 mm/y and 693 mm/y, respectively. These values are followed by Chase and Dundy counties, 500 mm/y and 483 mm/y, respectively, which are located at South Western Nebraska. Box Butte reported the lowest precipitations values and achieved an average of 406 mm/y.

PRISM precipitation data for this research was also consistent with NOAA annual Precipitation reports for the time period 2000-2014. Alliance 19 NWN and Hemingford Stations located in Box Butte presented an average annual precipitation ranging between 394-427 mm, averaging 410 mm. Imperial Municipal Airport, Wauneta and Enders Lake Stations located in Chase County ranged between 471-524 mm/y, averaging 483 mm/y. Dundy NOAA Stations Max 1N, Parks 17 N and Benkelman ranged between 408-470 mm/y, averaging 482 mm/y. Holt County Stations O'Neill, Chambers and Ewing ranged between 624-699 mm/y , averaging 659 mm/y. York County Stations data for Bradshaw ,Gresham 3 W and Mc Cool Junction ranged between 656-688 mm/y, averaging 668 mm/y. It was observed that there exist differences between stations, even when they are in the same County. That might explain small variations with remote sensed data in the scale in millimeters.[https://www.ncdc.noaa.gov].

Normal precipitation values 1981-2010 (30 year-period) reported by PRISM Oregon State University Climate Group (2015) developed by (Daly et al. 2008) showed that , Box Butte County normal precipitation was 406 mm/y, Chase County 484 mm/y, Dundy County 494 mm/y, Holt County 637 mm/y and, York County 724 mm/y.

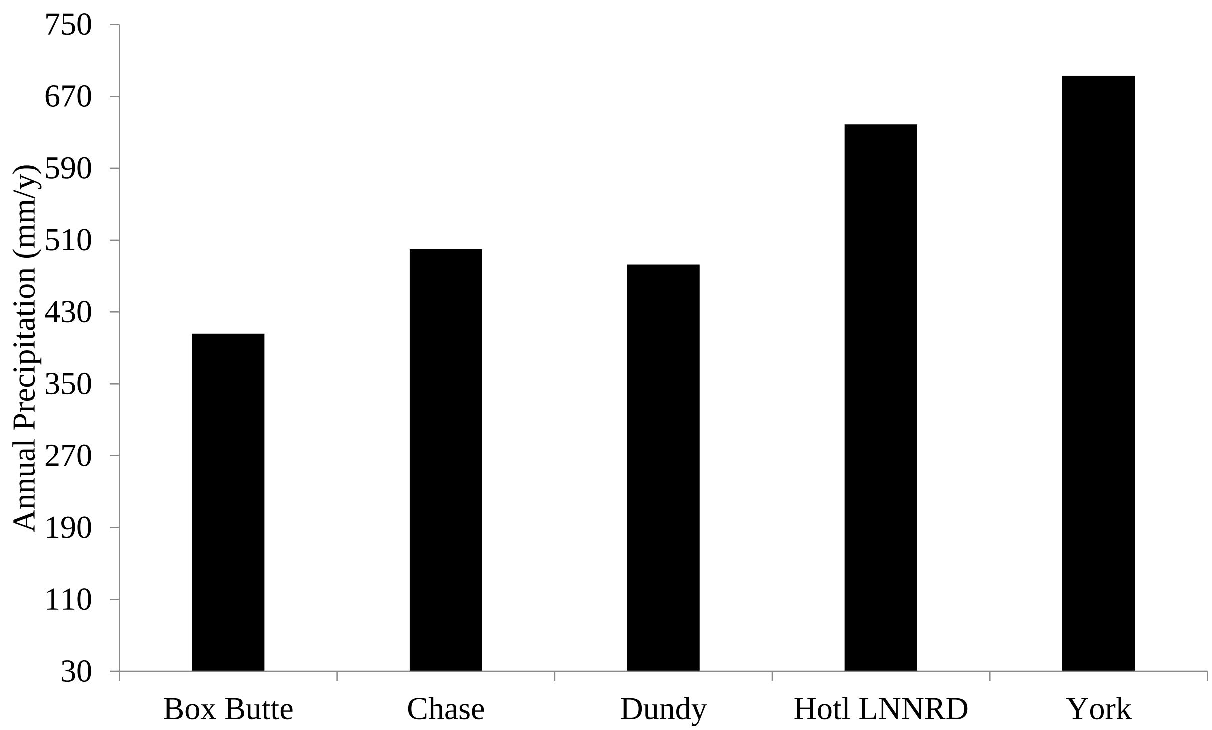

Figure1- 10 Annual Average Precipitation for 2000-2014 time period.

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According to Nebraska Statewide 2013 Report, Young et al.,(2013), 2007 to 2013 precipitations for Nebraska were reported to be near its normal values, followed by a significant drought in 2012, probably the most important in the last decades for Nebraska. It can be seen in (Figure 1-11) that 2012 year showed the lowest values for all the counties. In the case of Box

Butte, the average annual was 200 mm, for Chase 319 mm, for Dundy 343 mm, for Holt 390 mm and for York County 452 mm.

On the other side, 2009, 2010 and 2011 were reported as extremely wet years (Young et al., 2012). It can be seen in the graph, how these three years present high precipitation values in comparison with other years.

The annual averages for the 15 year period were equal or near the normal in most of the cases, Box Butte County had a deviation from normal of 0 mm, Chase County -16 mm, Dundy County + 11mm and, Holt County +18 mm. York County had the highest deviation below the normal, being 31 mm in the last 15 years. The comparison is also consistent with NOAA precipitation data for the same time period. It is detailed (Table 1-8) the annual millimeters of precipitation for every county.

Table 1- 8. Annual Precipitation Values. Time period 2000-2014 for Box Butte, Chase, Dundy, Holt and York Counties.

	Box Butte	**Chase**	**Dundy**	**Holt**	**York**
2000	444	386	391	468	530
2001	342	468	419	683	654
2002	225	266	276	467	576
2003	374	409	426	494	625
2004	405	551	568	678	621
2005	503	520	540	747	700
2006	342	491	463	584	714
2007	325	615	534	879	893
2008	402	577	525	832	989
2009	542	678	671	679	638
2010	501	651	553	845	678
2011	523	641	598	755	790
2012	200	319	343	390	452
2013	431	396	414	682	673
2014	531	538	518	642	863
Average	406	500	483	655	693

Overall precipitation annual values are summarized for all the years for each county (Figure 1-11).

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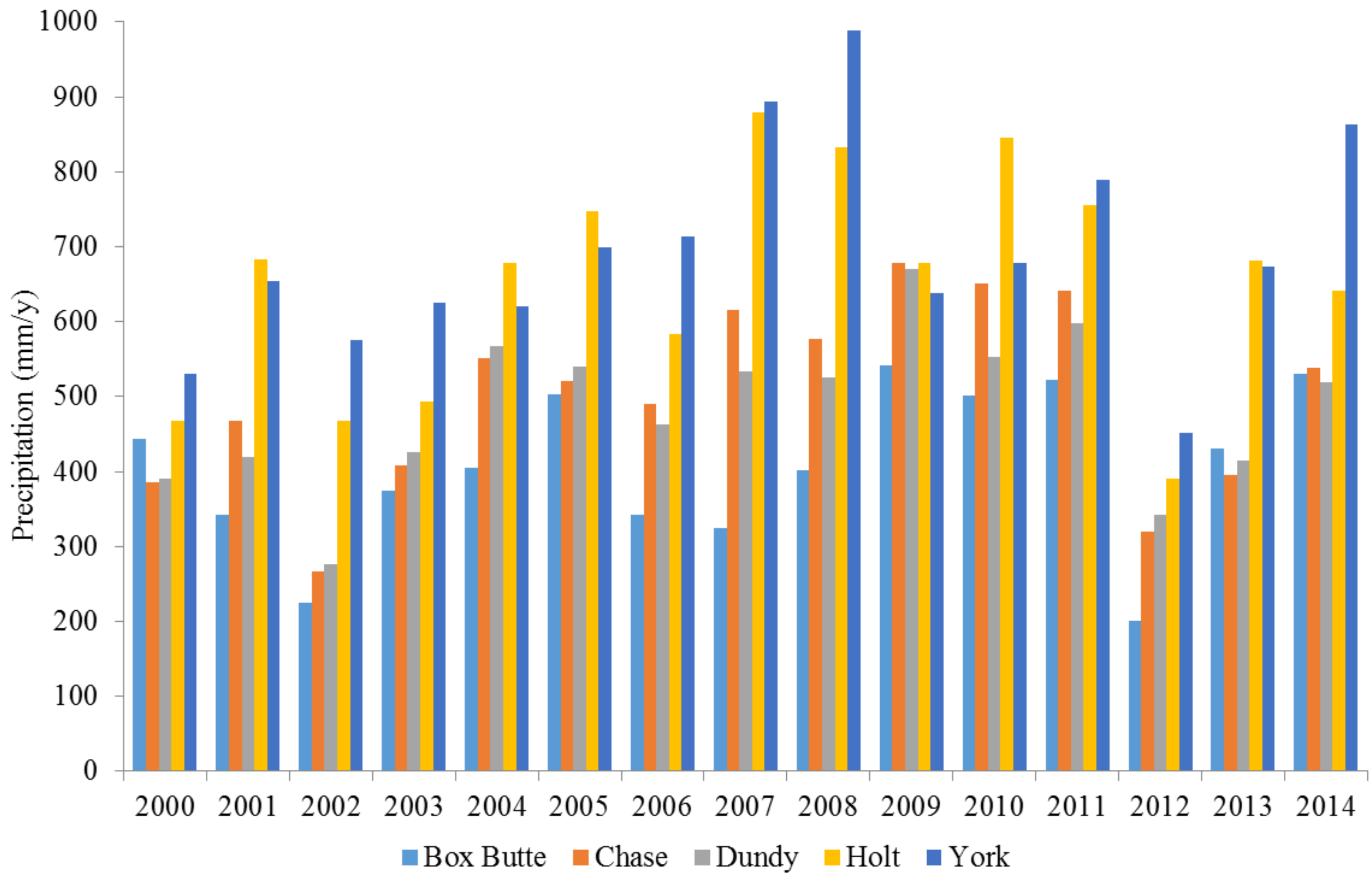

. Figure1- 11 Annual Precipitation for the time period 2000-2014 for from left to right Box Butte, Chase, Dundy, Holt and York

The first objective of this work of research was to assess the impact of regional change in ET on groundwater level changes. To address that, both variables calculated for the time period 2000-2014.

1.5.2 Evapotranspiration

Seasonal ET of each type of the cropping systems and native vegetation for each county, was obtained from remote sensed data and later calculated annually, following several author's estimates and results in surrounding areas. Then, the ET was applied to the area of each county to obtain weighed ET. Precipitation related to Seasonal ET, Kc average values and NDVI analysis over the time were also tested to evaluate trends that could impact later in Groundwater level changes.

1.5.2.1 Seasonal ET and Kc average values

Table (1-9) shows the seasonal evapotranspiration values obtained for each county and type of ecosystem.

Table 1- 9. Seasonal ET for Irrigated and Dryland crops and Native Vegetation foe each county for the time period 2000-2014.

	Seasonal ET (mm)		
County	Irrigated Crops	Native Vegetation	Dryland Crops
Box Butte	524	319	242
Chase	623	435	432
Dundy	605	401	435
Holt LNNRD	637	531	488
York	648	585	527

Box Butte County

The total Seasonal Actual ET shown in (Table 1-9) for native vegetation in Box Butte was 319 mm and it counts for the time period from 23rd May to 25th September. The total seasonal ET for irrigated crops was 524 mm (11th May to 9th September). The total seasonal ET for dryland Crops was 242 mm and it accounts for two periods in the year due to the crops planted (two different crops in almost all the cases) had different growing umbral .Dates were 15th April to 15th July and from 15th September to 18th October (Table 1-9).A study conducted by(Klocke et al. 1990) for Western Nebraska irrigated crops, obtained similar season ET values. The overall average ET for irrigated crops was 559 mm. The seasonal ET for Corn was 622 mm, Soybean 533 mm, Dry Beans 394 mm and Sorghum 483.

Schneekloth et al. (1991) compared water management systems, in North Platte at West Central Research and Extension Center of the University of Nebraska, measuring ET, precipitation, crop yields and its responses. It was reported for 1986-87-89 an average annual precipitation of 471 mm and growing season ET values of 640 mm in continuous irrigated corn and 389 mm for dryland corn and also 671 mm for irrigated winter wheat-corn-soybean rotation and 473 mm for dryland winter wheat-corn-soybean.

The Kc values (Figure 1-12) for native vegetation during the growing season ranged between 0.2- 0.4 achieving its highest peak on middle June, Kc= 0.5.In the case of irrigated crops, Kc increased from DOY 97 (Kc=0.25), ranging 0.5-0.75 between DOY 177-241. Its peak value was Kc= 0.74, in middle July (DOY 209). After DOY 321 values remain lower than 0.2.

Dryland crops ranged between 0.2-0.46, during all the growing season. It highest value was on DOY 145 (Kc=0.46), then, slows down ranging between 0.3-0.2 from DOY 193 to 273 and finally increase to Kc=0.3 on DOY 305 and 321.

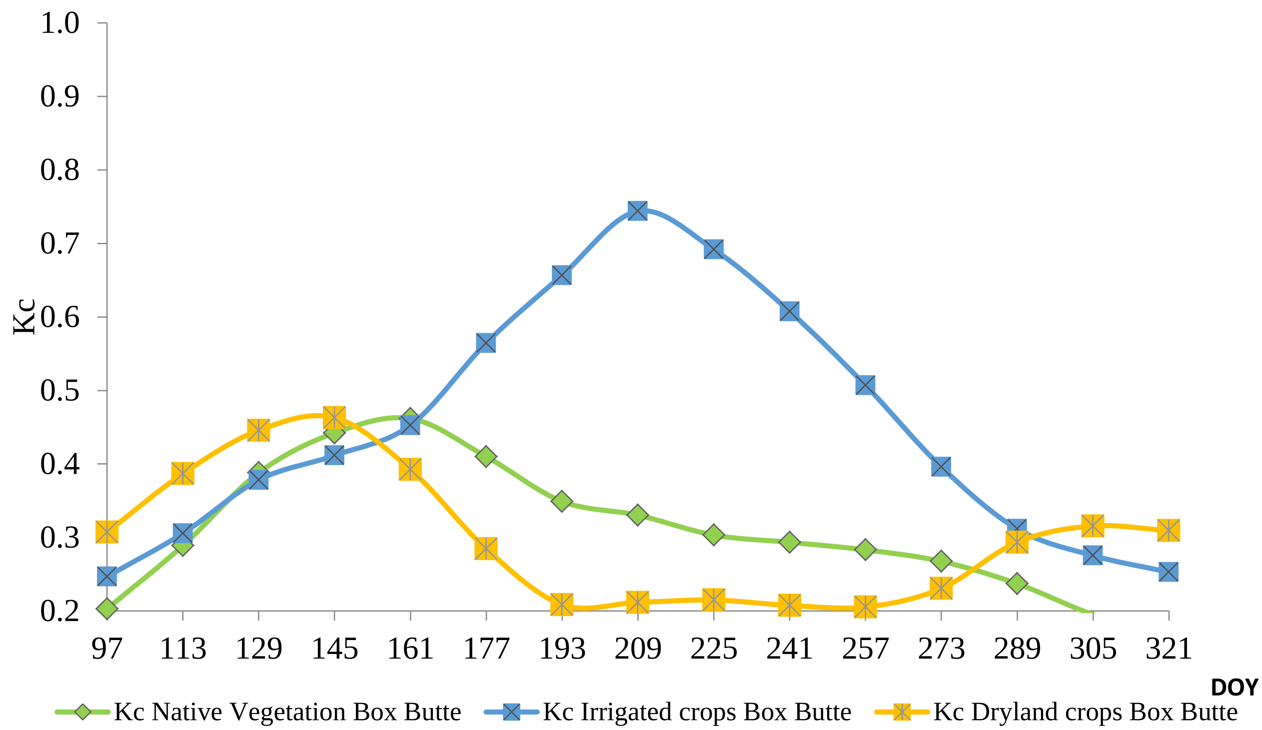

Figure1- 12. . Seasonal Kc Average Values For Native Vegetation, Irrigated and Dryland Crops In Box Butte County

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Chase County

The total Seasonal Actual ET in Chase shown in (Table 1-9) was 435 mm for native vegetation and it counts for the time period from 10rd May to 4th October. The total seasonal ET in irrigated crops was 623 mm and accounts from 3th May to 14th September. The total seasonal ET in dryland crops was 432 mm and it accounts from 11th April to 27th October. Results were similar to those obtained in Dundy County and will be discussed together in the following section (Dundy County).

The Kc values (Figure 1-13)for native vegetation of Chase County during the growing season ranged between 0.5-0.2 achieving its high peak on mid June Kc=0.5.From DOY 161-225 remained steady Kc=0.46, and decrease after DOY 189 to values under0.25.Irrigated crops increased after DOY 97 (Kc=0.25), ranging between 0.5 and 0.89 between DOY 177-241. It showed its peak 0.89 at the end of July DOY 2009. After DOY 273 values decrease from Kc=0.43 to 0.21 in DOY 321.Dryland crops ranged between 0.2-0.46, during all the growing season. It shows two peaks on DOY 145 (Kc=0.39) and DOY 209 (Kc=0.43)

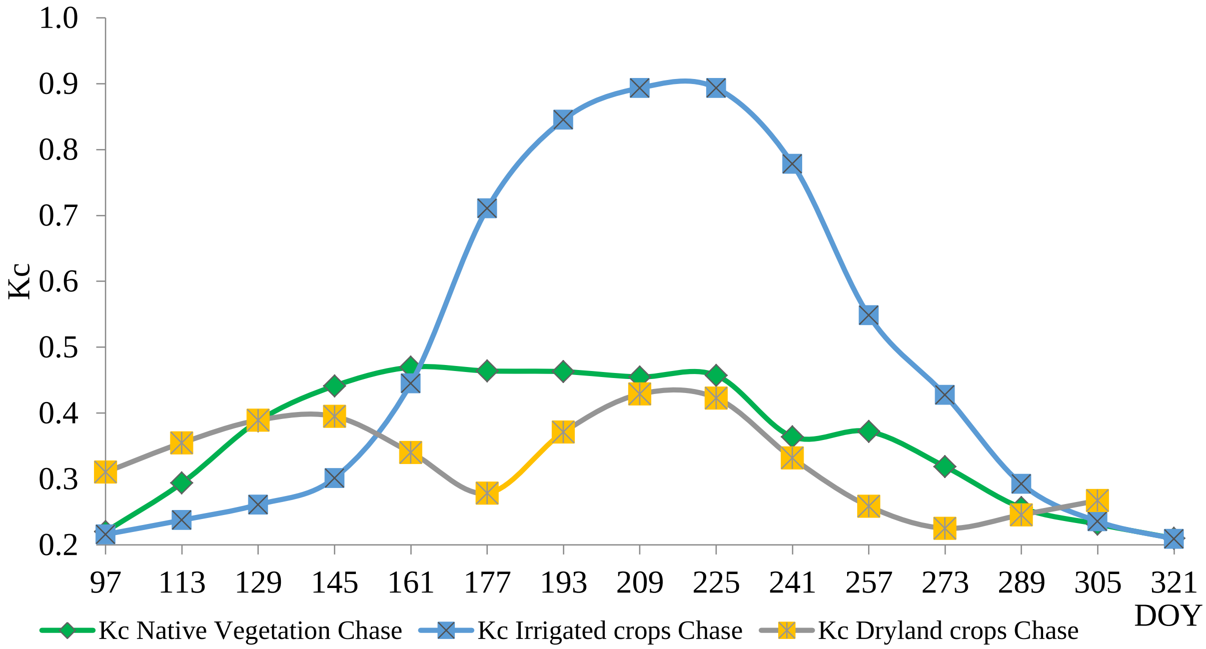

Figure1- 13. Seasonal Kc Average Values for Native, Irrigated and Dryland Crops in Chase County.

Dundy County

The total seasonal actual ET shown in (Table 1-9)for native vegetation in Dundy was 401 mm and it counts for the time period from 13rd May to 14th October. The total Seasonal ET in irrigated crops was 605 mm and accounts from 5th May to 13th September. The total seasonal ET in dryland croplands was 435 mm and it accounts from 11th April to 28th October.

The ET obtained in Dundy County is similar to those values obtained for Chase County. Both have similar precipitation values, although they have not the same precipitation during the time period of this study, and this might be the reason why Dundy presented overall smaller ET values.

Several authors have assessed it for Irrigated and Dryland Crops, but no studies have been done for native vegetation. Klocke et al. (1990) obtained for irrigated crops in Central Nebraska an average seasonal ET value of 649 mm. It included crops such as Corn (647 mm), Soybean (558 mm), Sorghum (520 mm), Winter Wheat (432 mm), Alfalfa (851 mm) and Sugar Beets (889 mm).

Other study, conducted in North Western Kansas Lamm et al. (1995,described in Suyker & Verma 2009) reported 586 mm for Irrigated Corn and 459 mm for Dryland Corn in 3 year of study . Moreover, Noorwood, (1999 as referred in Suyker & Verma,2009) for South High Plains region reported ET for a sub-humid climate, ranging between 395-601 mm for Dryland Corn with no till management and 385-505 mm inn conventional tillage over four growing seasons.

The Kc values (Figure 1-14) for native vegetation of Dundy County during the growing season ranged between 0.44-0.21, achieving its highest value on DOY 177 (Kc=0.44), then decreased to (Kc=0.31) on DOY 193 and made a second peak on DOY 209, Kc=0.44 .Irrigated crops increased after DOY 97 (Kc=0.2), ranging between 0.64 and 0.86 between DOY 177-209. It showed its peak 0.86 on DOY 209. After DOY 241 values decrease from Kc=0.71 to 0.23 in DOY 321.Dryland crops ranges between 0.2-0.4, during all the growing season. It ranged between 0.2-0.3 from DOY 07 to 161, then increase to Kc=04 from DOY 177 to 241 and finally decreased to Kc=0.2 in DOY 321.

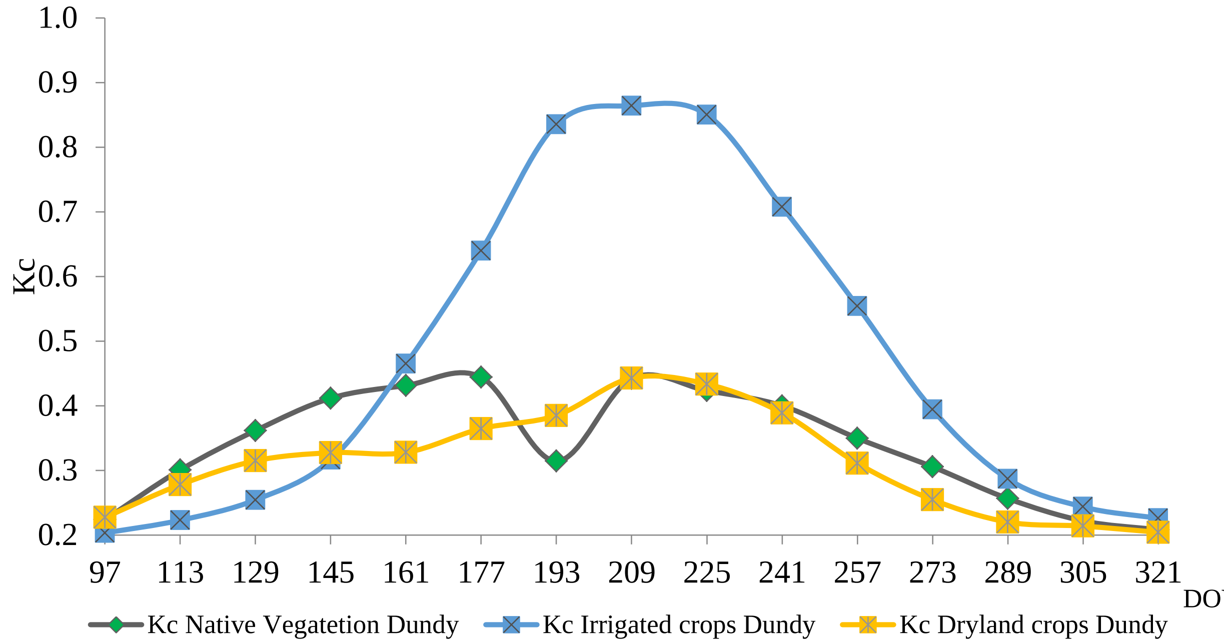

Figure1- 14. Seasonal Kc Average Values for Native, Irrigated and Dryland Crops in Dundy County

Holt LNNRD

The total seasonal actual ET shown in (Table 1-9)for native vegetation in Box Butte was 531 mm and it counts for the time period from 12rd May to 4thOct. The total seasonal ET for irrigated crops was 637 mm and accounts from 3rd May to 12th September. The total seasonal ET for dryland croplands was 488 mm and it accounts for 3th May to 12th September.

The Kc values (Figure 1-15) for native vegetation during the growing season ranged between 0.3 and 0.7 achieving its high peak on mid June were it was 0.7 .Irrigated crops increased after DOY 97 (Kc=0.21), ranging between 0.83 and 0.86 between DOY 177-241.It showed its peak 1.01 the DOY 209 and 225. After DOY 321 values remain lower than 0.2. Dryland Crops ranged between 0.25-0.7, during all the growing season. It shows a peak on DOY 209 (Kc=0.74), then slows down steadily from DOY 225 to 321 ranging between 0.72 to 0.24.

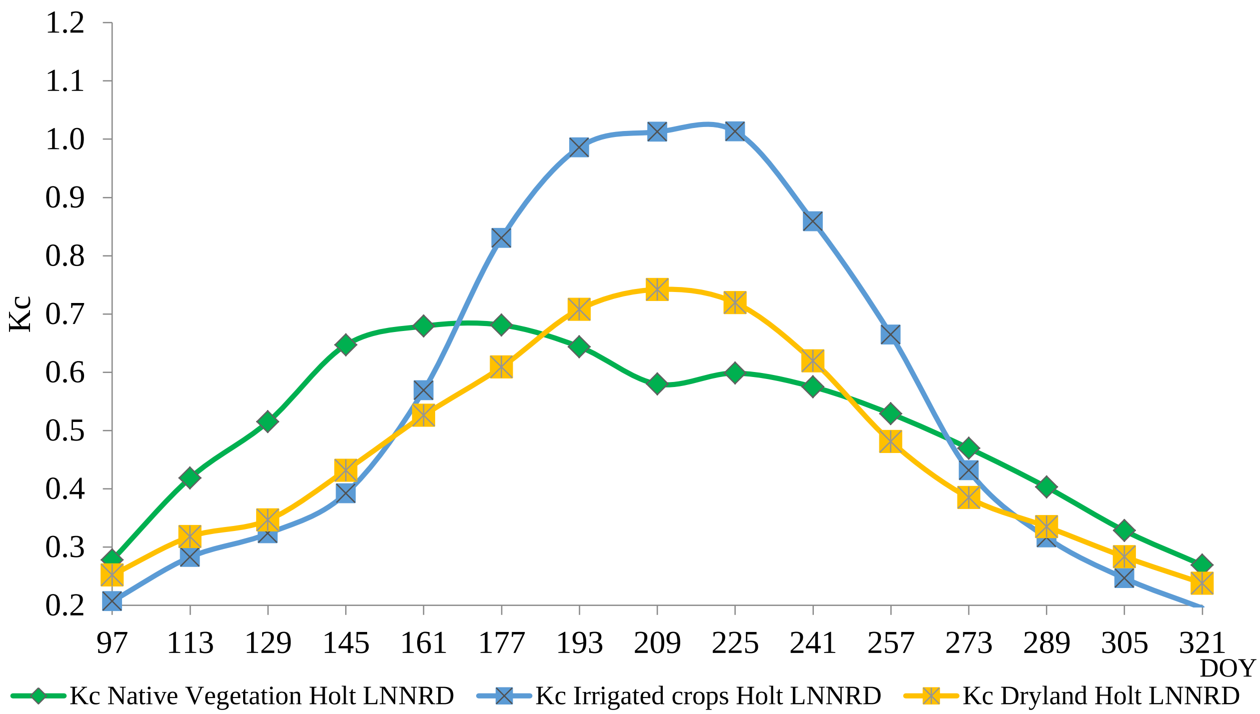

Figure1- 15. Seasonal Kc Average Values for Native, Irrigated and Dryland Crops in Holt LNNRD.

York County

The total seasonal actual ET shown in (Table 1-9)for native vegetation in York was 585 mm and it counts for the time period from 10rd May to 4th October. The total seasonal ET for irrigated crops was 648 mm and accounts from 3th May to 14th September. The total seasonal ET for dryland croplands was 527 mm and it accounts from 11th April to 27th October. Burba & Verma (2005) obtained similar seasonal (May-Oct) native vegetation ET values of 531mm for Tallgrass Prairies species in, a three year study. Concerning Irrigated and Dryland crops, results can be generally compared with several studies done in the region, Klocke et al. (1990), obtained an average ET value of 627 mm for irrigated crops, including Corn (673 mm), soybean (597 mm), sorghum (546 mm), winter wheat (432 mm) and alfalfa (889 mm).

On the contrary, lower values of ET were presented by (Suyker & Verma, 2009) by measuring ET with Eddy Covariance towers for Eastern Nebraska. They obtained seasonal ET of 552 mm for Irrigated Corn and 482 mm for Dryland crops, during a three year period. Also, they measured during two years Irrigated Soybean and Dryland Soybean, obtaining ET of 452 mm and 430 mm, respectively.

In a more recent research done by Djaman ,(2011), during 2009-2010 period, done at South Central Agricultural Laboratory in the University of Nebraska Lincoln, obtained ET seasonal values of 645 mm for full Irrigated Corn and 509 mm For Dryland Corn during 2009 and, 748 mm and 690 mm during 2010, respectively

The Kc values (Figure1-16) of native vegetation in York County during the growing season ranged between 0.4-0.8, achieving its highest value on mid June Kc=0.8 on DOY 161.Irrigated crops increased after DOY 97 (Kc=0.21), ranging between 0.97 and 1.1 between DOY 177-241. It showed its highest value Kc= 1.1 in July on DOY 193. After DOY 257 values decrease from Kc=0.51 to 0.17 in DOY 321. Dryland Crops increased from Kc=0.21 to 0.95 from DOY 97-209. In DOY 209 achieved the highest value Kc=0.95 and then, decreased steadily from 0.87 to 0.2. from DOY 225 TO 321

Singh & Irmak (2009),obtained similar values by assessing Kc for specific irrigated and dryland crops in Southcentral Nebraska, using different remote sensing data and energy balance equation (SEBAL) combined with automated stations data and ET reference equation. It was obtained Kc=0.23 for Irrigated Corn and Kc=0.3 for Dryland Corn during the beginning of the growing season (DOY 139) .In mead-season Kc for Irrigated Corn was 0.9 and 0.76 for Dryland Corn (DOY203). Values of Kc for end of the season were Kc=0.24 for both, Irrigated and Dryland Corn.

Overall Kc for irrigated crops values averages have shown to be between the suggested Kc range ,cited in FAO 56 (Allen et al., 2077), estimated for sub-humid climates, Kc_{ini} (0.35-0.4),Kc_{mid}(0.9-1.15) and Kc_{end} (0.4-0.95) according to the specific crop measured . It is important to point out that Kc can variate according to climate conditions. Moreover in this study, all the crops are measured together, since the linear equation allows it. Thus these are average Kc values.

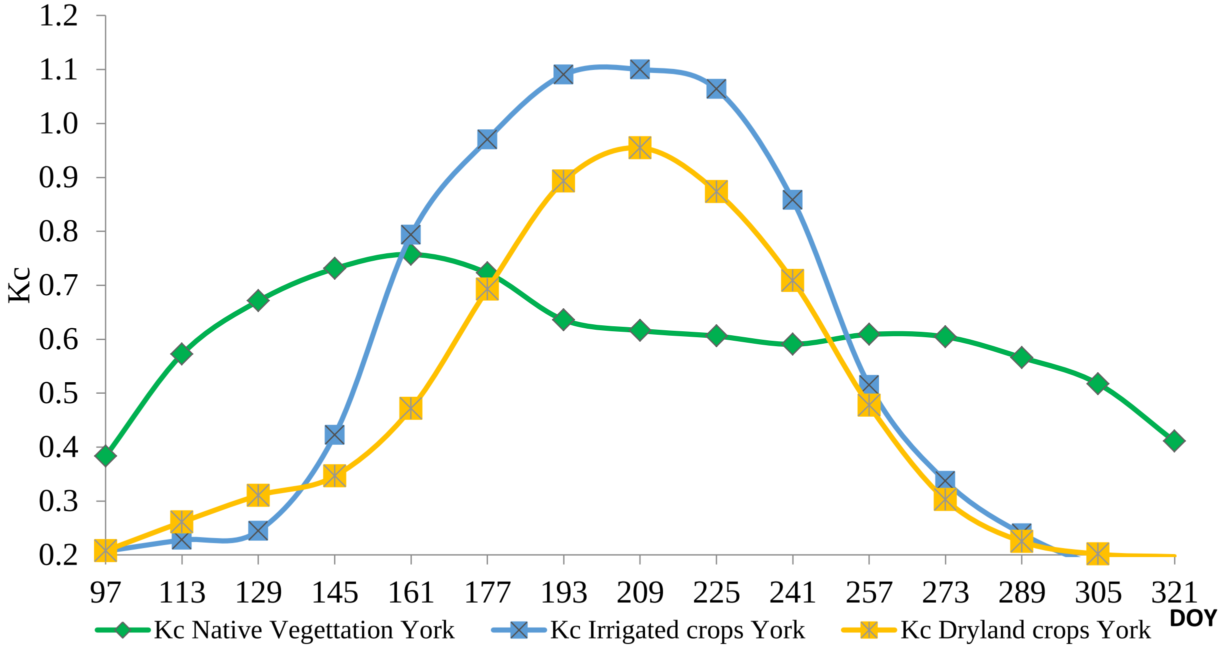

Figure1- 16. Seasonal Kc Average Values for Native Vegetation, Irrigated and Dryland Crops in York County

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1.5.2.2 NDVI Values

NDVI values in Box Butte showed differences among ecosystems. native vegetation values from early growing season DOY 97 to DOY 161 increased from 0.26-0.43(maximum NDVI) and then decreased from DOY 177 to 321 ranging between 0.4-0.23.(Figure 1-18.A). On the contrary, irrigated crops started the season with lower values in comparison with native vegetation. NDVI values for DOY 97 to 209 increased from 0.25 to 0.74(maximum NDVI value) and then decreased from NDVI=0.69 to 0.25 from DOY 225 to 321. For dryland Crops NDVI, there were observed two peaks and lower values in contrast with the other ecosystem types. The maximum values were NDVI=0.43 in DOY 145 and NDVI=0.33 in DOY 305, respectively. The rest of the values ranged during the season between NDVI= 0.26-0.43. It has to do with the fact that Box Butte County has several zones with dryland eco-fallowing farming, presented in the shape of stripes, which has different NDVI over the year, and as the satellite includes both, they mark a trend reflected in the average values.

For Chase (Figure 1-18.B) and Dundy Counties (Figure 1-18.C) NDVI trends were similar. Native vegetation from DOY 97 to 177 NDVI ranged between 0.27-0.44 (maximum value). Dundy showed 2equal peaks NDVI=0.44 on DOY 177 and 209. Then values decreased ranging from NDVI=0.42-0.21 DOY 225 to 321.

In contrast, irrigated crops increased later than native vegetation for both counties. Irrigated lands increased from NDVI-0.25-0.69 on DOY 97-193 for both counties, then achieved its maximum value on DOY 225 NDVI=0.72 (Chase) and DOY 209 NDVI=0.71 (Dundy).And finally decreased from 0.69 to 0.25 from DOY 225 to 321.

Dryland crops ranged from NDVI0.26-0.42 for both counties. Chase NDVI greatest value was on DOY 225 NDVI=0.42 and also for Dundy on DOY 209. Then values decreased for both ranging between 0.41-0.26 from DOY 241-321.

NDVI values for Holt LNNRD area (Figure1-18.D) for native vegetation ranged between NDVI=0.3-0.6 from early growing season period DOY 97 to 257.Then, decreased from 0.4 to 0.3 from DOY 273 . Irrigated crops followed a Gaussian bell (Figure 22.D). It was observed NDVI=0.26-0.8 for DOY 97 to257 (maximum peak achieved on DOY 225 NDVI=0.8). Later values decreased from 0.41 to 0.25 from DOY range 273 to 321. Dryland crops showed a Gaussian bell, similarly to irrigated crops but with lower values. It started ranging in early season from 0.29-0.62 for DOY 97 to 225 ranges. Its greatest value was achieved when NDVI=0.62 on DOY 209. Then it decreased from 0.54 to 0.28 between DOY 241-321.

York County (Figure 1-18.E) native vegetation increased from NDVI= 0.38-0.63 on DOY 97 161(maximum value) and then, decreased ranging between NDVI=0.5-0.4 from DOY 177 to 321. Irrigated crops increased at lower rate than native vegetation in early season ranging from NDVI =0.26-0.86 for DOY 97 to 241(maximum value NDVI=0.86 for DOY 193 and 209) .Later, decreased from DOY 257 to 321 ranging between NDVI=0.51-0.17 followed a Gaussian bell. Similarly, Dryland crops followed this trend increasing from NDVI=0.26 to 0.73 on DOY 97 to 193. Its higher value was achieved on DOY 209 NDVI=0.77. Finally, NDVI decreased from 0.72 to 0.25 from DOY 225 to 321. Singh & Irmak, (2009) obtained similar results when comparing native vegetation with irrigated crops in Southeastern Nebraska. During early season, when field crops have been planted, have emerged or starting to develop, presented lower NDVI rather than native rangeland/natural vegetation. In addition they reported greatest peaks For Irrigated Corn NDVI=0.77 and Dryland Corn NDVI=0.69 by July (DOY 203) respectively, NDVI=0.86 for Irrigated Soybean and NDVI=0.81 for Dryland Soybean . The values are still similar even when it is compared NDVI for different irrigated crops with the NDVI values for corn. It is important to observe that irrigated and dryland in this zone follows a similar pattern, more evident on DOY 219, after that Dryland Crops starts diminishing gradually at higher rate.

Tieszen et al.,(1997) conducted a survey in Great Plains using AVHRR Advance very high Resolution Radiometer data collected from 1989-93 for 13 layers of grassland for different sectors of the Great Plains. Biweekly measurements for the entire year were done, creating a time integrate NDVI curve, in which NDVI values ranges between 0.15-0.52. The values are comparable to those obtained for native vegetation in the Western zone of Nebraska (Figure 1-17).

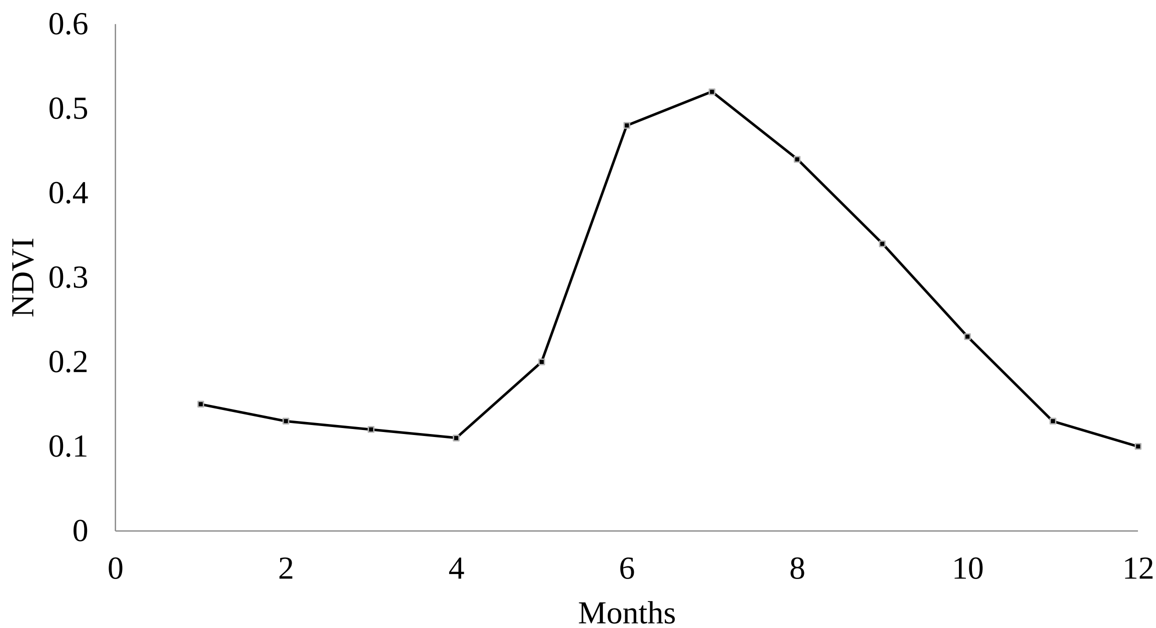

Figure1- 17.Shows time integrated NDVI values for Great Plains for the entire year

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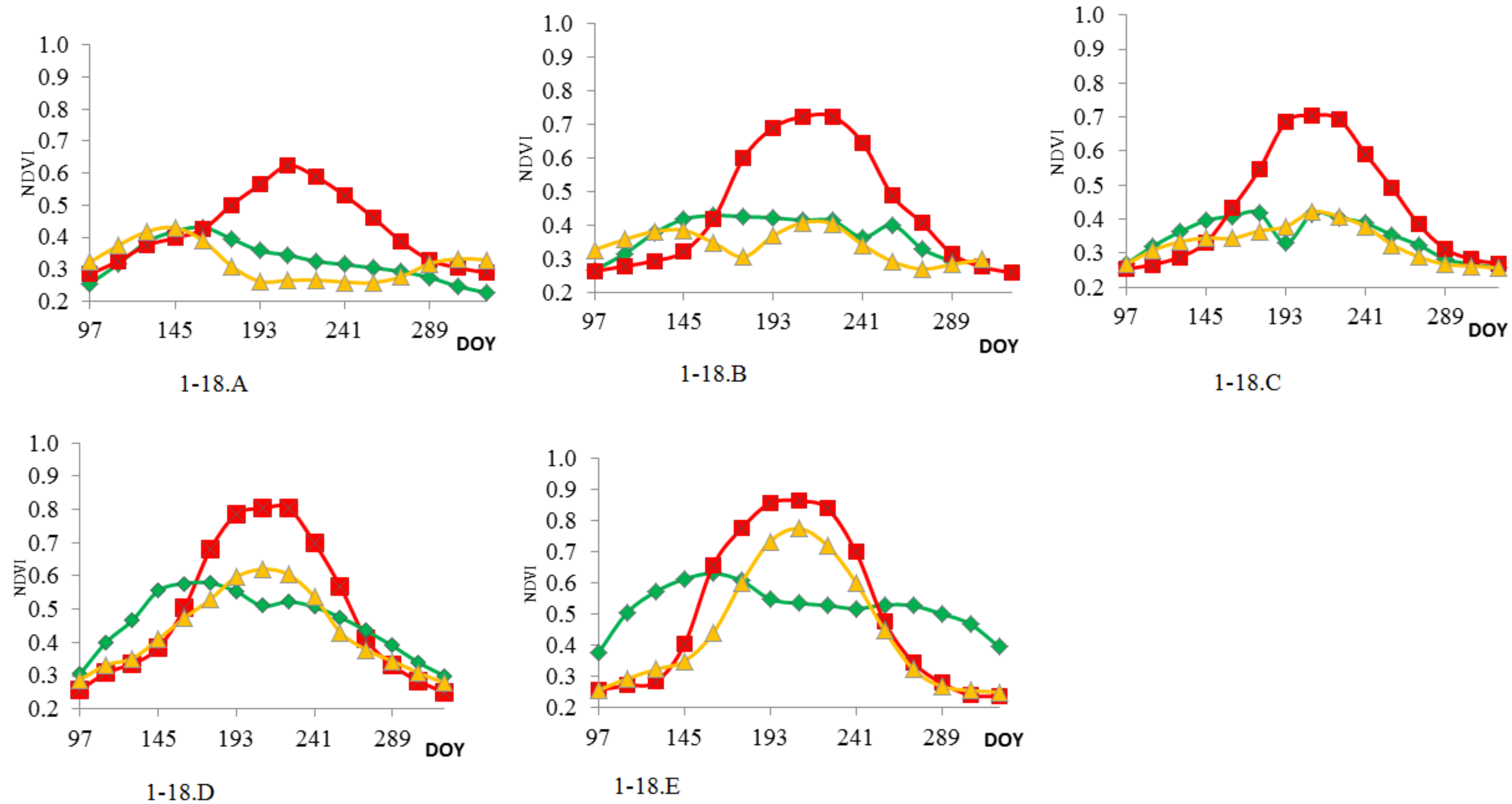

Figure1- 18. NDVI Average Values from DOY 97 to DOY 321. Lines with Squares represent Irrigated Crops, lines with Rhombus represent Native Vegetation and lines with Triangles represent Dryland Crops
. Where figures 1-22 A Box Butte County 1-22.B Chase County 1-22.C.Dundy County 1-22.D. Holt LNNRD 1-22.E. York

. 1.5.2.3. Annual ET

Through the off season precipitation values obtained from NOAA stations in the time period 2000-2014 plus the Eta/Pa off season estimated, it was calculated the annual ET (Table 1-10).

Table 1- 10 Summary Of Seasonal ET, Off Season Precipitation and Annual ET For each County for Native Vegetation, Irrigated Crops and Dryland Crops, during Time Period 2000-2014.

	Seasonal ET (mm)			**Off Season Precipitation (mm)**			**Annual ET (mm)**		
County	Irrigated Crops	Native Vegetation	Dryland Crops	Irrigated Crops	Native Vegetation	Dryland Crops	Irrigated Crops	Native Vegetation	Dryland Crops
Box Butte	524	319	242	147	144	132	627	382	320
Chase	623	435	432	183	140	107	715	480	475
Dundy	605	401	435	187	177	70	699	465	463
Holt LNNRD	637	531	488	269	253	269	745	601	568
York	648	585	527	267	260	267	755	644	606

*Note Holt LNNRD term refers to the part of Holt County inside Lower Niobrara NRD boundaries, where is located the major part of the agriculture practiced in the county.

To assess both variables, ET and Precipitation together is of major importance since ET is in Nebraska the 90-93% of annual precipitation (Irmak, 2010a) and more than 75% of the total ET occurs during growing season (Burba & Verma, 2005).

Box Butte County Annual ET obtained for native vegetation was 382 mm, for irrigated crops 627 and for dryland crops 320 mm (Table 1-10). . The average annual precipitation (406 mm) showed to be 24-86 mm higher than ET of native vegetation and dryland crops, respectively, and 221 mm lower than irrigated crops. (Figure 1-19).A work of research, done by Szilágyi (2013), using the CREMAP ET mapping Based upon surface temperature using MODIS sensor 1km resolution dataset, obtained for the time period 2000-2009, an average annual ET range for Nebraska of 250-500 mm (Figure 1-24)

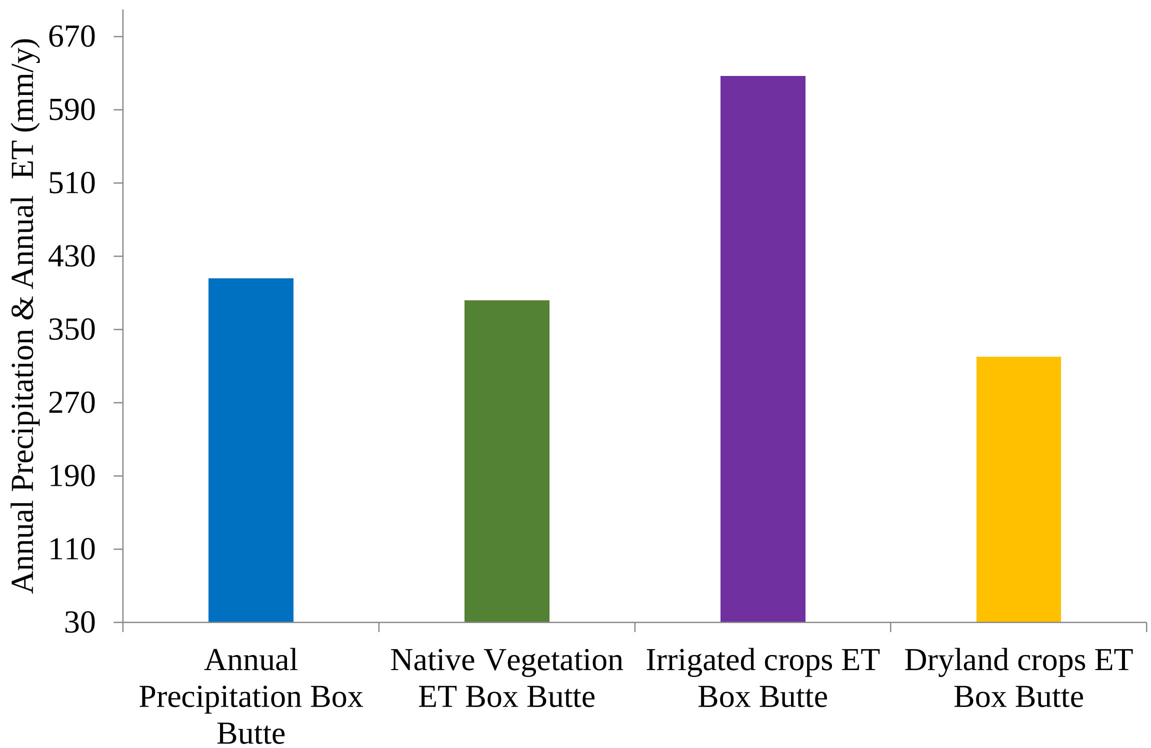

Figure1- 19 Annual Average Precipitation and Annual average ET for Native, Irrigated and Dryland Crops for Box Butte County during 2000-2014 .

By quantifying ET/P It is possible to estimate the amount of water that is going to the atmosphere and how much is destined to water storage and runoff. It suggests how sustainable the ecosystems are being and allows to plan practices to manage it.

In the case of Chase County, annual ET for native vegetation was 480 mm, for irrigated crops 715 and 475 for dryland Crops (Table 1-10). Similarly, Dundy County annual ET for native vegetation obtained was 465 mm, 699 mm for irrigated crops and 463 mm for dryland crops. The average annual precipitation (500 mm) showed to be 20-25 mm higher than ET of native vegetation and dryland crops, respectively, and 215 mm lower than it irrigated crops. (Figure1-20).

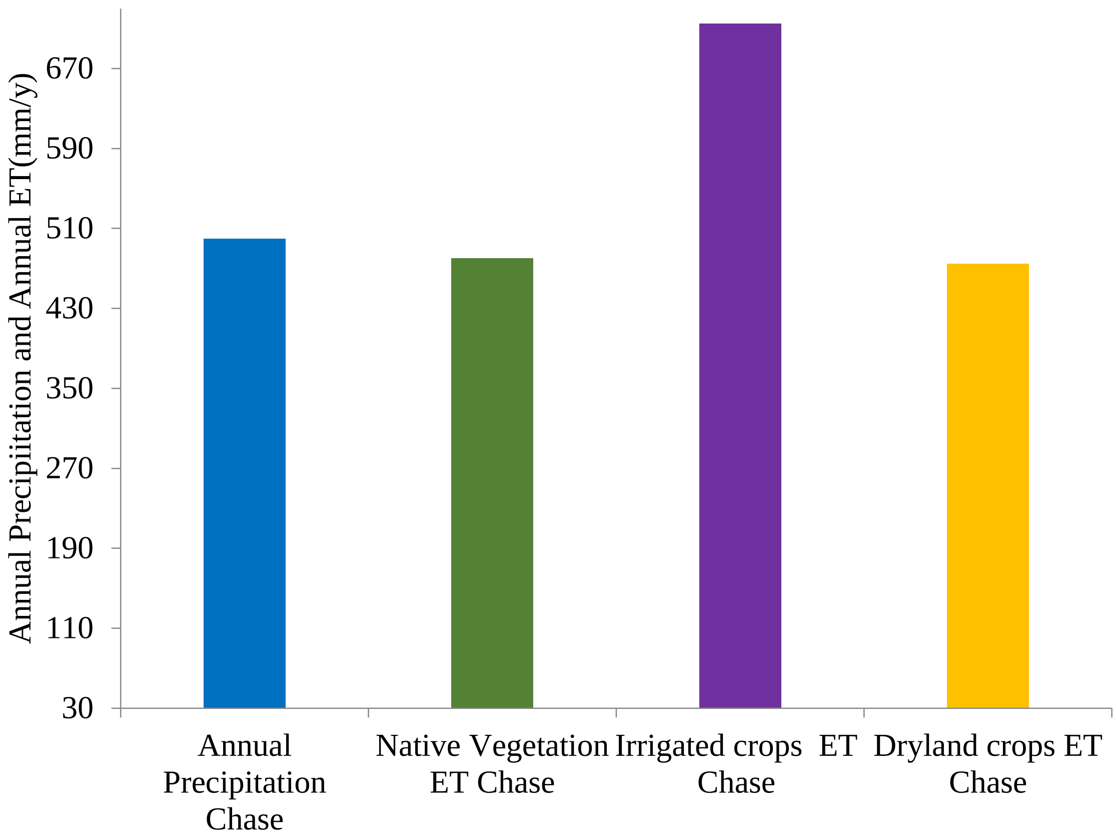

Figure1- 20 Annual Average Precipitation and Annual average ET for Native, Irrigated and Dryland Crops for Chase County during 2000-2014.

Dundy County annual ET obtained for native vegetation was 465 mm, for irrigated crops 699 and for dryland crops 463 mm (Table 1-10). The average annual precipitation (483 mm) showed to be 18-20 mm higher than ET of native vegetation and dryland crops, respectively, and

216 mm lower than it irrigated crops. (Figure 1-21) Results for both, Chase and Dundy generally comparable to those obtained by Szilágyi (2013), which defined for middle of the state region an annual ET ranging between 500-650 mm (Figure 1-24).

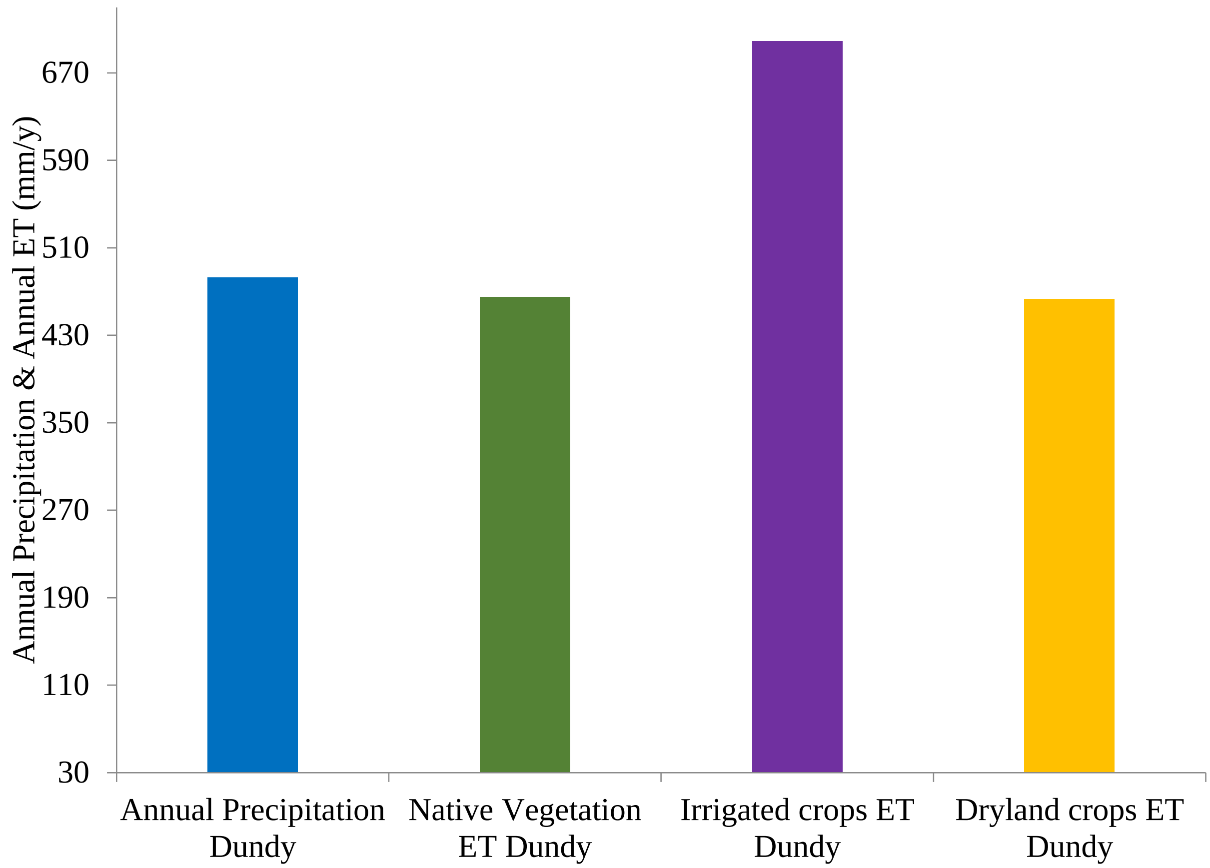

Figure1- 21 Annual Average Precipitation and Annual average ET for Native, Irrigated and Dryland Crops for Dundy County during 2000-2014.

Holt LNRD ‘s annual ET for native vegetation was 601 mm, for irrigated crops 745 mm and for dryland crops 568 mm (Table 1-10). The average annual precipitation (655 mm) showed to be 54-87 mm higher than ET of native vegetation and dryland crops, respectively, and 90 mm lower than it irrigated crops. (Figure 1-22).

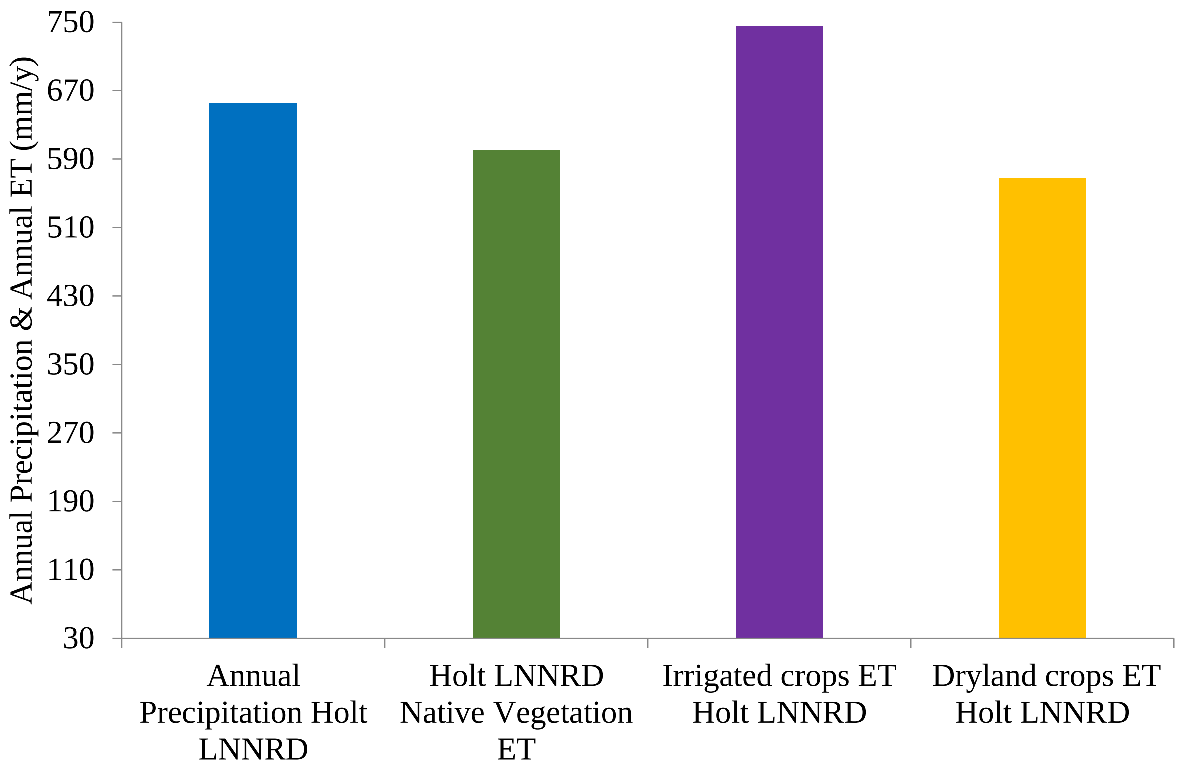

Figure1- 22 Annual Average Precipitation and Annual average ET for Native, Irrigated and Dryland Crops for Holt LNNRD during 2000-2014 .

York County annual ET for native vegetation was 644 mm, 755 mm for irrigated crops and 606 mm for dryland crops (Table 1-10). The average annual precipitation was 693 mm, and showed to be 49-87 mm higher than ET of native vegetation and dryland crops, respectively, and 62 mm lower than it irrigated crops. (Figure 1-23).

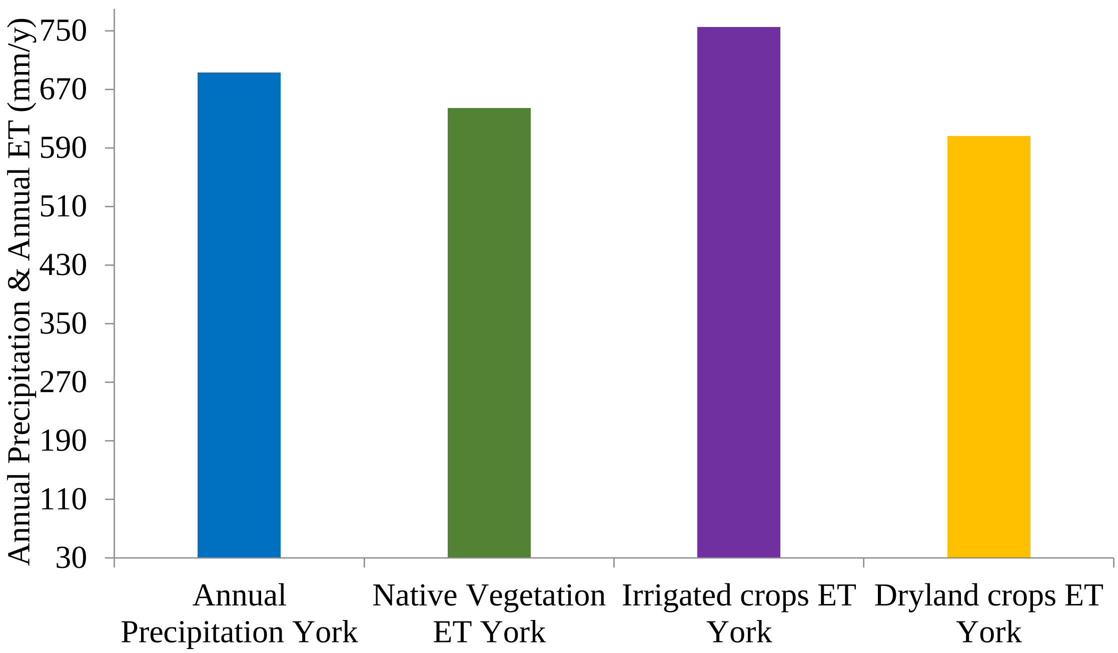

Figure1- 23 Annual Average Precipitation and Annual average ET for Native, Irrigated and Dryland Crops for Box Butte County during 2000-2014.

Szilágyi, (2013), described for Eastern Nebraska an average annual ET equal or more than 650 mm/y (Figure 1-24).To make the results comparable to those obtained for other authors, it is important to remark that the CREMAP method is an actual ET calculation method, done for 10 years period while the method used in this study is a NDVI-Kc based equation, described preferably to be used in no stressed, well irrigated crops. Then ET values can be overestimated in some mm (Kamble et al., 2013; Szilágyi, 2013).

In other study done by Suyker & Verma, (2009), in eastern Nebraska, for time period 2001-2006 in irrigated corn and 2001,2003 & 2005 for dryland corn it was reported annual ET of 667 mm and 631 mm, respectively.

For native vegetation, specifically for tallgrass prairie Burba & Verma, (2005) reported for North Central Oklahoma Great Plains region seasonal ET values mentioned previously, and annual ET values of 712 mm (ranging between 640-810 mm), with an annual precipitation average of 1170 mm in the 1997-99 time period.

In addition, Djaman, (2011), attributed variations in ET year to year to differences in temperature and precipitation. Thus, for a warmer and wetter year, the values presented for ET are higher. As discussed previously York County showed to be 31 mm below its normal values for the time period 2000-2014. Thus, Holt LNNRD and York have shown similar ET/P ranges, even when York is expected to receive higher quantities of precipitation.

In this research, annual precipitation was higher than annual ET for native vegetation and dryland crops. In the case of irrigated crops, Annual ET overpassed annual precipitation in all the counties.

*Note that dryland sampling Holt LNNRD and York were extrapolated for Antelope and Polk and Clay dryland, due to difficulties to find representative samples. Also, native vegetation of York was sampled based upon 9-miles prairie managed by UNL, which contains tallgrass prairie species like York would be.

The higher ET areas correspond themselves with irrigation wells across the state (Szilágyi, 2013)

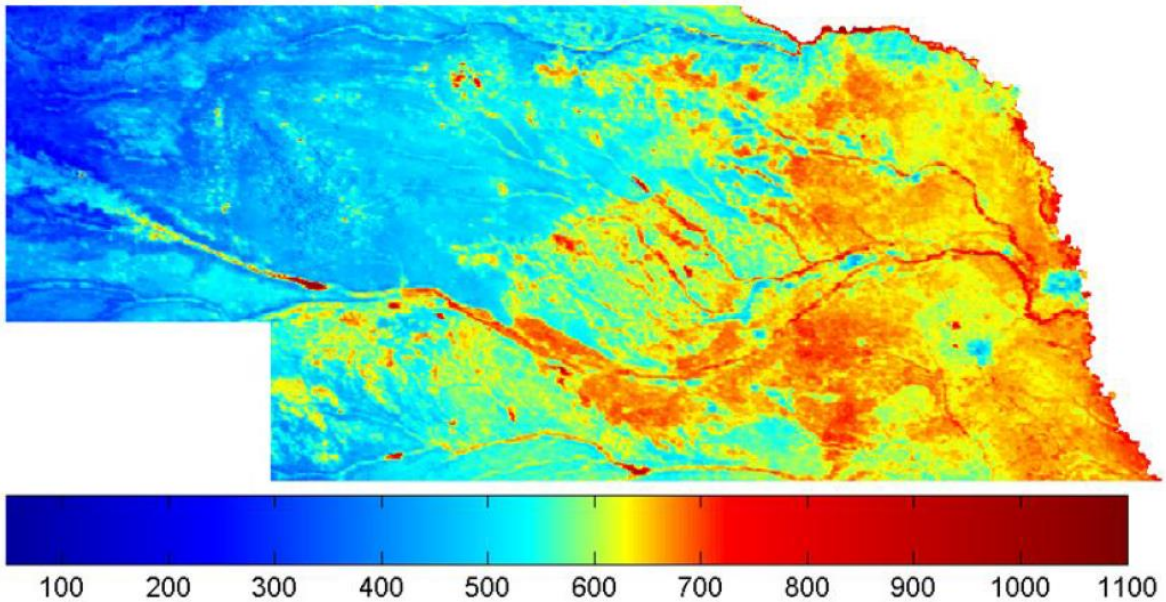

Figure1- 24. Annual ET across Nebraska using CREMAP method by Joe Szilágyi for the time period 2000-2009

1.5.2.4. Weighed Annual ET

The weighed annual ET was calculated for the five counties in this research. Table 1-11 shows the different locations and areas regarding its total land use and its total annual ET calculated before. Table 1-12 shows the total weighed ET in volume units (m^3) for Native Vegetation, irrigated crops and dryland crops for each county. Also the total weighed ET for each county as if it was just native vegetation (Natural ET) and the annual average ET according to the county land use for the time period 2000-2014. Annual average ET were in metric units in both, (m) and (mm)(Table1-12).

Table 1- 11 Counties areas destined to Croplands and Native vegetation, Annual Evapotranspiration for Native Vegetation, Irrigated and Dryland crops.

County	Area					Annual ET		
	Total area	Total cropland area	Irrigated Crop Area	Dryland Crop Area	Native Vegetation Area	Native ET	Irrigated ET	Dryland ET
	(km^2)	(km^2)	(km^2)	(km^2)	(km^2)	(mm)	(mm)	(mm)
Box Butte	2733	1366	573	793	1367	382	627	320
Chase	2190	1176	646	530	1014	480	715	475
Dundy	2107	844	384	460	1264	465	699	463
Holt LNNRD	2507	1013	731	282	1495	601	745	568
York	1374	1267	1021	245	107	644	755	606

Table 1- 12 Weighed ET for each Ecosystem, croplands weighed ET, Natural weighed ET, and Total weighed ET and Average County ET.

County	Weighed ET						ET	
	Native Weighed ET	Irrigated Weighed ET	Dryland Weighed ET	Croplands Weighed ET	Natural County Weighed ET	Total County average ET Weighed	Average County Annual ET	
	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	(m)	(mm)
Box Butte	522383090	359195760	253721600	612917360	1044006000	1135300450	0.42	415
Chase	486794400	462068750	251726250	713795000	1051200000	1200589400	0.55	548
Dundy	587680950	268269210	213063340	481332550	979755000	1069013500	0.51	507
Holt LNNRD	898194500	544855750	159892000	704747750	1506773110	1602942250	0.64	639
York	69114080	770855000	148694220	919549220	884856000	988663300	0.72	720

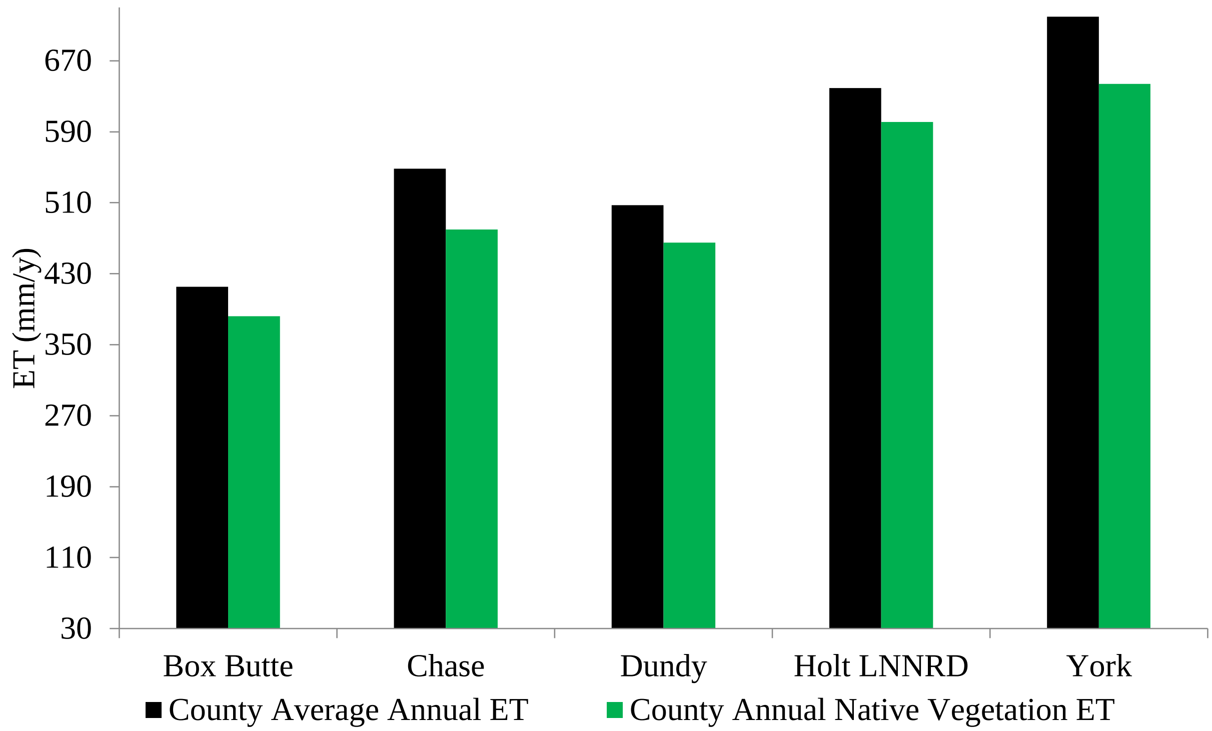

Figure1- 25. County Annual Average ET and Average Native Vegetation ET for each County for the time period 2000-2014).

Results have shown(Figure 1-25) that Box Butte had the smallest County Annual Average ET value (415 mm) and the smallest native annual vegetation ET (382 mm)and York the greatest ones(639 mm) and (631 mm), respectively. The annual County average for Chase resulted into 548 mm and 480 mm for native vegetation, 507 mm and 465 mm, respectively for Dundy County and 639 mm and 601 mm, respectively for Holt LNNRD Results have shown that final ET is influenced by the total area destined to each use in the counties.

About 29% of Box Butte area is dryland Crops in which the practice of wheat-fallow is very common. Figure (1-26.C) shows dryland cropping in stripes. Also the 50% Figure (1-26.B) of its total area is native vegetation, and the remaining is Irrigated agriculture (Figure 1-26.A) that might explain the low overall ET average value in contrast with the other counties (Figure-1-

25). Box Butte, located in Western Nebraska and, as mentioned before it received a lower average precipitation of 405 mm/y and consequently had lower ET.

Chase and Dundy Counties, located in South Central Nebraska, have similar climatic conditions. The 46% (Chase) and 60% (Dundy) is native vegetation. About 30% (Chase) and 18% (Dundy) total surfaces are irrigated crops and, 20% and 24%, respectively, are dryland crops in which the eco-fallow practice is common. Precipitation showed to be 80-100 mm greater than in Box Butte County, that explain why overall ET was higher (83-98 mm), even when the great area of native vegetation might have an influence in the total county average ET. (Figure 1-27.A, Figure 1-27.B, Figure 1-28.A.Figure 1-28.B) show examples of native, dryland and irrigated agriculture across Chase and Dundy.

Holt LNNRD is located near Elkhorn River, a huge area is destined to agricultural purposes. The 30% of its area are irrigated crops, mainly center pivot irrigation Even when USDA Census (2012) reported the 11% of its surface as dryland crops, it is not very common to find dryland agriculture, due to it is located near the river and farmers prefer to irrigate. However, the 60% is native vegetation. Therefore, the average County ET for the time period 2000-2014 was lower in contrast other Eastern Counties like York, in which Native Vegetation is not common and there is a great area destined to crop production (Figure 1-29 A, Figure 1-29 B).

York has the smallest area of the five counties under study. Also, the main activity is the irrigated farming, specifically corn and soybean. Approximately the 74% of its total area are irrigated croplands, while the remaining is dryland and native vegetation (Figure -29 C).Moreover, as Holt, it is located at Eastern Nebraska where precipitation is higher and consequently ET is higher. This evidence could address its greatest County Average values.

Figure1- 26.A. Box Butte Irrigated Crops

Figure 1-26 B. Box Butte Native Vegetation

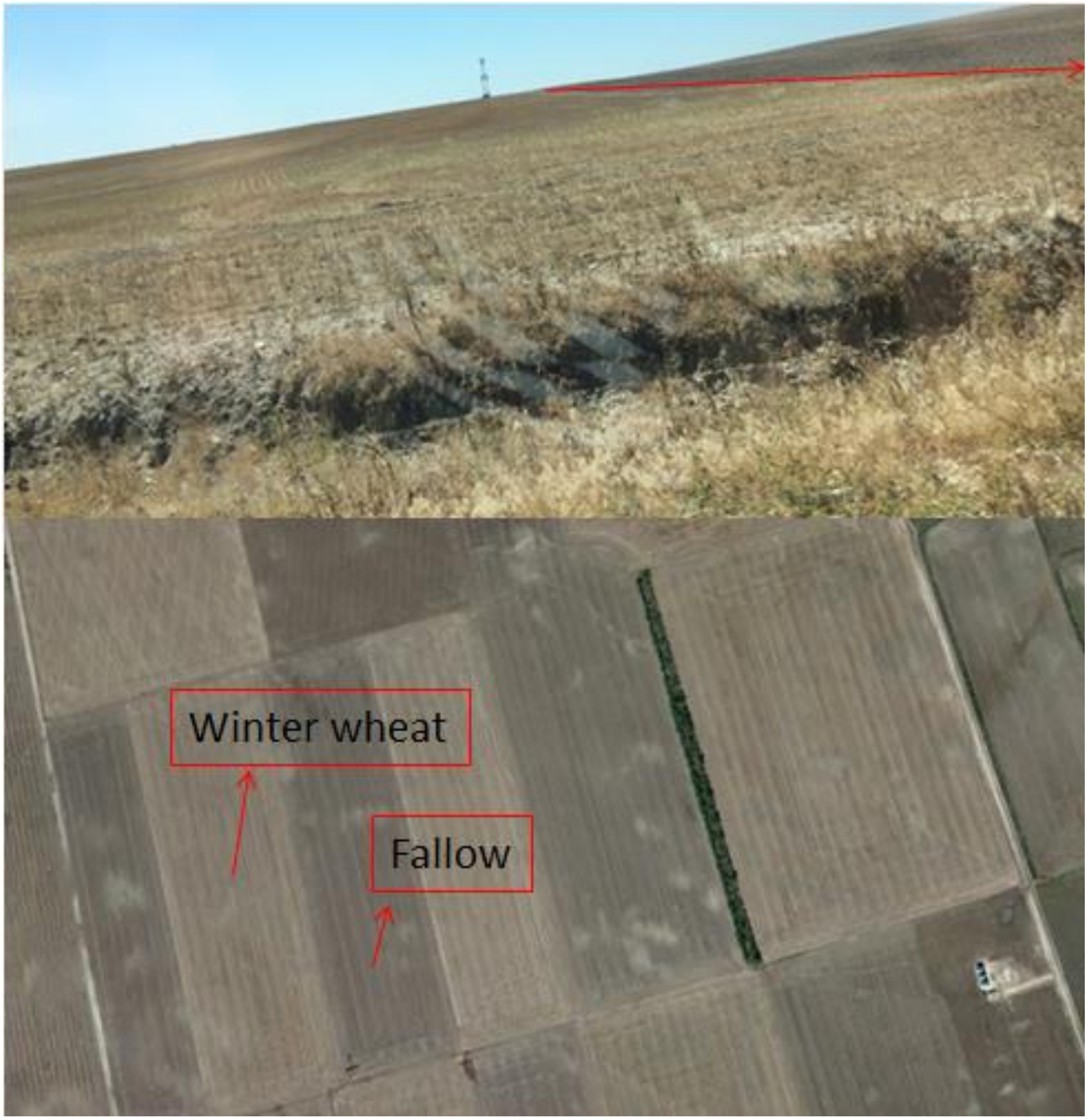

Figure 1-26 C .Box Butte Dryland Cropping, Wheat-Fallow stripes from Dryland, Summer 2015 and .Box Butte Wheat-Fallow stripes from the ground (Google Earth Imagery) .

Figure1- 27. A Wauneta Native Vegetation, Western Chase County, Summer 2015.

Figure1- 27.B.Irrigated Crop Center Pivot in Chase County (Google).

Figure1- 28. A Irrigated Agriculture in Dundy County from Google Images.

Figure. 27. B. Dryland Farming in Dundy County from Google Images

Figure1- 29. A.Native Vegetation, Holt County, Summer 2015.

Figure 1-29.B. Irrigated Soybean, Holt County, Summer 2015.

Figure 29.C. Irrigated Corn,York County, Summer 2015

1.5.3. Groundwater Level Changes and Groundwater Storage.

As table (Table1-13) indicates, Box Butte average annual level changes are -0.26m,-0.24m for Chase County, -0.26m for Dundy County, -0.12m for Holt LNNRD area and York -0.26m.

A 10 year period test from Spring 2004 to Spring 2014, showed on the Nebraska Groundwater level report, Young et al.,(2014), declines for Box Butte, Chase and Dundy of 1.5 m as general result, and declines of 7.5m in the worst parts. When applied to normal specific yield of Nebraska assuming Sy=15% from USGS Paper 1400-B (Gutentag et al.,1984), the change in water storage would be 0.225 m/y, . In this study (Table 1-13) the change in water storage obtained was -0.039 m for Box Butte County,- 0.036 m for Chase County and -0.039 m for Dundy County. Results might be consistent considering that account for the entire area of each county and not only in observation wells contours incorporated to a map in areas where principal aquifer is continuous, have a good hydraulic connection and high density of data (Young, Burbach, and Howard 2013)

Concerning Holt LNNRD, it has been reported by Young et al.,(2013) declines nearly to 0.6 to 3 m in the Elkhorn River Basin zone m for the time period between 2008-2013. That means a change in water storage nearly 0.09 m. No detailed data has been specified for Holt area not in Lower Niobrara-Holt boundary. However, the results do not differ too much from the ones obtained in this study, where change in water storage for Holt LNNRD area was -0.018 m/y (Table 1-13). Some factors and different methods used in both studies, as well as scales might have an influence on the final results. The study is weighed for the entire Holt LNNRD while the contours were calculated for specific zones.

For York County region (Southeastern Nebraska), there has been reported declines ranging between 3-6m from predevelopment (1953) to 2013(Young et al., 2013).

On the contrary, in some zones there were observed rises in water levels instead of declines since 2007 to 2012(Young et al., 2012) The NRD website Upper Big Blue for York shows average rises of 0.3m after 2012 drought [http://www.upperbigblue.org/]

Results for York showed an average change in water storage of -0.039 m/y (Table 1-13) for the time period 2000-2014. That change in water storage is comparable with the ones observed for Box Butte, Chase and Dundy Counties. It has to do with long and short time trends, where in long-term period York County declines have not been historically as high. However extreme climatic events such as, the drought of 2012 caused a drop down in the water table. Whittemore, Butler, & Wilson, (2014), attributed distribution of rainfall within the period measured as the major driver of water declines. When precipitations are below normal, it might cause a great effect on short term aquifer’s water table (Whittemore et al. 2014; Young et al. 2013).This study showed York County precipitation to be 693 mm/y, 31mm below its normal precipitation (724 mm/y for the time period 1981-2010) which could have an influence on its groundwater levels declines.

The well recorder data (Figure 1-30) measured by the Institute of Agriculture and Natural Resources measured groundwater levels according to distance from the surface. York situation could be clarified through these data. It can be observed how water levels declined from 2000 to 2007 from 24.2 m to 27.1 m and then, rose up from 2007 to 2012 from 27.3 to 25.7 m. After 2012 water levels declined from 25.7 to 27 m.

Table 1- 13. Groundwater Level Changes for each County, Specific yield, and Changes Groundwater Storage .

County	Groundwater Level changes 2000-2014(m)	Specific Yield (Sy)	Changes in Groundwater Storage (m/y)	Changes in Groundwater Storage (mm/y)
Box Butte	0.26	0.15	0.039	39
Chase	0.24	0.15	0.036	36
Dundy	0.26	0.15	0.039	39
Holt LNNRD	0.12	0.15	0.018	18
York	0.26	0.15	0.039	39

*Sy=15%

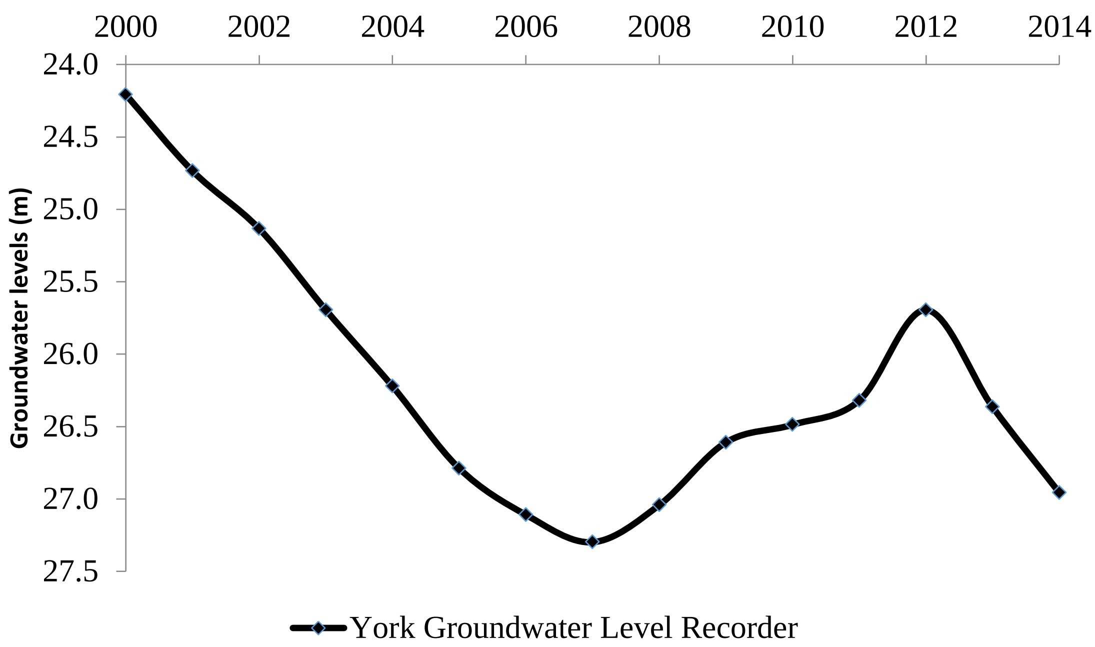

Figure1- 30. York Groundwater Level Recorder. Spring Season. Well located in York County, measured from 4th April 2000 to 16th April, 2014.

A recent study made by UNL researchers, shows spatially projected the water level variation during the 2000-2009 time period for Nebraska (Figure 1-31). At first glance, declines are observed. However, there are some parts which experimented rises in water levels .It can be observed how important were the level declines produced in certain zones in Western Nebraska and also in some zones of Southeastern Nebraska. Generally results showed depletion ranging between 1-25m, and rises mostly in Northeastern Nebraska ranging between 0.3-4.5m

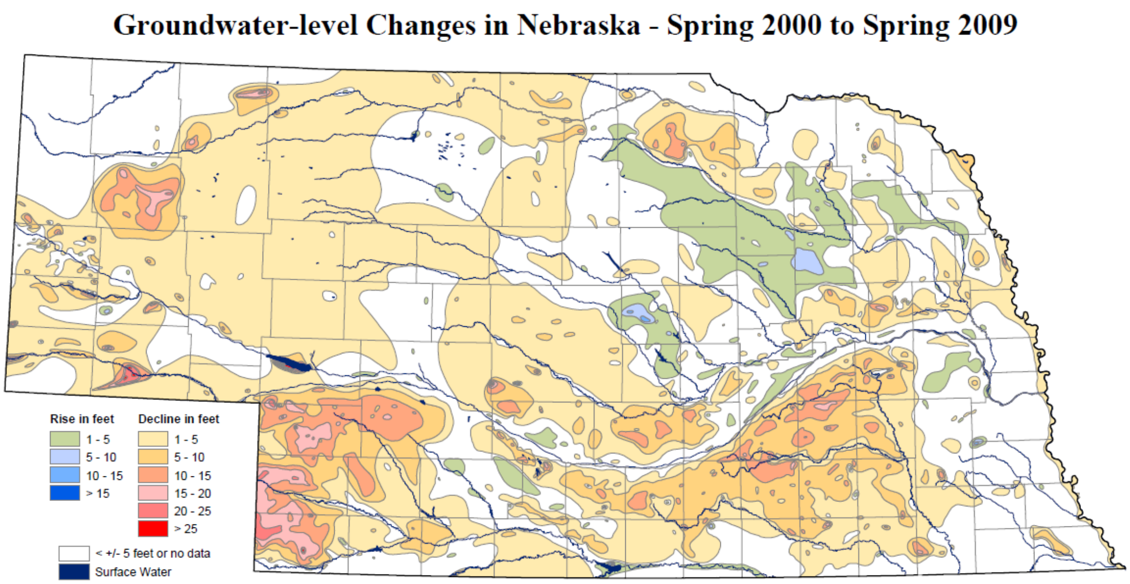

Figure1- 31. Groundwater Level Changes for Nebraska Spring 2000-2009 period.

1.5.4. A Sustainability Index

One of the objectives of this study was to develop and evaluate a groundwater sustainability index (SI) for climatically diverse groundwater irrigated regions in Nebraska .To evaluate the index, SI was calculated using the ET of native vegetation in each County and dividing it by the county average ET.

The sustainability index is intended to explain how sustainable water is being consumed across each county. The nearer to one, the more sustainable is the water use/consumption. No previous studies have been reported for Nebraska using a SI of this type.

Chase County (Table 1-14) had the lowest index value, SI=0.88, followed by Box Butte SI=0.92, Dundy SI=0.92 and York SI=0.90. The greatest index value was for Holt LNNRD, SI=0.94 The SI is strongly influenced by two things, the density of irrigation in county and the local climate For instance, York County has a high density of irrigated agriculture (74% of the land area in York is irrigated cropland) which leads to a relatively large county average ET, resulting in a lower SI. In contrast, a county such as Chase County has much lower percentage of land irrigated, 29% but because of the drier climate, the ET of native vegetation is much lower than in York County. The lower ET of native vegetation leads to a lower SI in Chase County. However, the percentage of land use (as calculated from data shown previously in Table (1-11) do not explain the index in all the cases.

Table 1- 14. Sustainability Index for each County

County	Sustainability Index
Box Butte	0.92
Chase	0.88
Dundy	0.92
Holt LNNRD	0.94
York	0.90

1.5.5. Township scale assessment results

The weighed annual ET volume, was calculated for the selected townships in each county, using annual ET for each type of ecosystem and the associated area (Table 1-15).

Water level declines in mm/y and decreases in groundwater storage inn mm/y were calculated for the townships for the time period 2000-2014 (Table 1-15).

The increase in ET (Table 1-15) was obtained through the difference between township annual average ET and ET.

Table 1- 15 Townships Area, Weighed ET, Sustainability Indices, Groundwater Level declines, Changes in Water Storage and Increase in ET calculation

County	Township	Area				Weighed ET					
		Total area	Irrigated Crop Area	Dryland Crop Area	Native Vegetation Area	Natural Township	Total Township	Sustainability Index	Groundwater Declines	Changes in Water Storage	Increase in ET
		(km^2)	(km^2)	(km^2)	(km^2)	(m^3)	(m^3)		(m/y)	(mm/y)	(mm/y)
Box Butte	**25N 49W**	93	48	31	15	35613860	45334220	0.79	0.33	50	104
Chase	**7N 40 W**	93	62	31	1	44750400	59075700	0.76	0.35	52	154
Dundy	**2N 8W**	93	44	29	21	43351950	53477640	0.81	0.37	55	109
Holt LNNRD	**31N 14W**	93	63	1	29	56031230	65052620	0.86	0.14	21	97
York	**10N 3W**	93	83	7	3	60040120	68988640	0.87	0.29	44	96

1.5.6. Correlations between Sustainability Index and Increase in ET to Reduction in Groundwater Storage.

Several climatic indices such as Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) have been created to assess its influence on groundwater levels, taking into account variables such as precipitation, soil moisture, potential evapotranspiration, and other factors concerning plant growth (Palmer, 1965; Heim, 2002) cited in Whittemore et al., (2014). However, no sustainability indices based upon the ET of native vegetation and the actual ET across an area has been reported, neither for a zone nor in Nebraska. In order to assess a relation between variables two different correlations were evaluated, SI and reduction in groundwater storage and increase in ET (county average actual ET minus the ET of native vegetation) and reduction in groundwater storage.

As shown earlier, actual ET was higher than ET of native vegetation in each of the five counties due to irrigated cropland in each county. This resulted in an SI less than one in all cases.

Increased ET ($ET = ET - ET_{nv}$) and reduction in groundwater storage (mm/y) was found to have a significant positive correlation (0.62) at p-value < 0.05 level confidence, n=10 using one-tailed Pearson's r critical values. Thus, greater ET increases result in greater reductions in groundwater storage

Moreover, the negative correlation (Table 1-16) between SI and reduction in groundwater storage (mm/y) proved to be significant at p-value< 0.025, n=10 using one-tailed Pearson's r critical values. Therefore, for a higher SI a lower reduction in groundwater storage is expected.

Table 1- 16 Linear correlations between Sustainability Index and Change in water storage and Increase in ET and Change in water storage. Pearson's r critical values.

Variables	n	df	r	P value
SI and Reduction in Groundwater Storage (mm/y)	10	8	-0.69	<0.025
Increase in ET and Reduction in Groundwater Storage (mm/y)	10	8	0.62	< 0.05

The data suggested that SI is negatively related with groundwater storage reduction and that the increase in ET is positively related with groundwater storage reduction. Thus, by applying alternate agricultural techniques and more sustainable practices groundwater depletion could be reduced. However, there are those who attribute changes in water storage to more than one factor, placing ET as only a part of the change.

According to the literature, groundwater levels could respond not only to anthropogenic but also natural factors. Limiting the extraction may not prevent depletion. Water depletion's major drivers in heavily stressed aquifers are long term groundwater pumping, prolonged drought, which are primarily, function of meteorological conditions such as precipitation and potential ET (Young et al., 2014; Whittemore et al., 2014; Bredehoeft, 1997).

Bredehoeft, (1997) cited in Young et al.(2014),interpreted rate of recharge as "sustainable limit" on the rate of groundwater extraction from an aquifer as a common misconception. On the contrary, there must be taken into account other factors such as discharge (such as to baseflow) recharge as well as aquifer properties, that would make groundwater storage response different according to these other factors.

Other authors stated that conversion of ecosystems as is key factor on water storage increase. Recent studies made by Scanlon et al., (2005) in the High Plains Region in Texas, suggested that recharge occurs in dryland agriculture whereas it does not occurs in rangeland ecosystems. Water level rises are associated with cultivation factors, so by converting natural rangeland into dryland crops might increase water storage. Increase in recharge in dryland areas can be attributed to the lower ET of dryland cropping compared to native vegetation especially during fallow periods. The importance of fallow periods was shown in the Northern Great Plains when a change of crop-fallow rotations into perennial alfalfa reduced recharge Halvorsen & Reule, (1980) .In addition, water level rises of less than 6 m in 50 years were observed in dryland agriculture in a study conducted in Oklahoma in a Great Plains area, Luckey & Becker,(1999), proving that conversion to dryland cropping caused rises in groundwater levels. Both studies were cited by Scanlon et al., (2005).

Fallow periods also caused an increase drainage and water storage in comparison with continuous cropping in Australia O'Connell et al.,(2003) cited in Scanlon et al., (2005).

Therefore, changes in groundwater storage depend on land use/land cover of ecosystems and their influence on ET, natural and anthropogenic factors (including aquifer properties, saturated thickness and lateral movement, precipitation, potential ET, and also water pumping, manmade water bodies, etcetera), agricultural practices (i.e:fallowing, plowing) among others. This research proved the actual ET as a factor of major importance. Thus, to manage ET reducing total ET of a region so that it approaches that of native vegetation, which kept water levels in balance in the past, could be a good approach for improving groundwater use sustainability.

Therefore we partially accept our hypothesis that states that groundwater use can become sustainable if the regional ET is managed so that it equals the ET of native vegetation.

A sustainability index such as used here might help in a better understanding of irrigation management, in order to decrease water consumption .Further studies about sustainability Indices are required in Nebraska to better understand their potential for wide spread use.

1.6. SUMMARY AND CONCLUSIONS

This research dealt with the impact of regional change in ET on groundwater level change and the development and assessment of a groundwater sustainability index for climatically diverse groundwater irrigated regions across Nebraska during the time period 2000-2014.

Precipitation was measured through remote sensed data analysis. Western Nebraska average annual precipitation was 406 mm/y. Precipitation in southwestern Nebraska counties varied from 483 to 500 mm/y. Eastern Nebraska counties had annual precipitation that ranged between 655 to 693 mm/y. The latter value corresponded to York County, which had the highest deviation,-31 mm below normal during 15 year period. Box Butte County had a deviation from normal of 0 mm, Chase County -16 mm, Dundy County + 11mm and, Holt County +18 mm.

Seasonal and annual ET, NDVI and NDVI-based Kc trends were calculated and analyzed for each region through remote sensed data, NDVI-Kc linear equation ,GIS pixel purity models, HPRCC Stations data, ASCE Standarized Penman Monteith method, established growing season dates and indices for those regions, for the time period 2000-2014. The seasonal ET and annual ET for native vegetation, irrigated and dryland ecosystems for Western Nebraska ranged between 242-524 mm and 320-627 mm/y, respectively. For Southwestern Nebraska seasonal ET ranged between 432-623 mm and annual ET 463-715 mm/y. Eastern Nebraska's ET ranged between 488-648 mm seasonal and 568-755 mm for annual ET .

Kc and and NDVI maximum values for Western Nebraska were Kc=0.5;NDVI=0.43 for native vegetation, Kc=0.75;NDVI=0.74 for irrigated crops and Kc=0.46;NDVI=0.43 for dryland crops. Southwestern counties showed Kc=0.5;NDVI=0.44 for native, Kc=0.89;NDVI=0.72 for irrigated crops and Dryland Kc=0.46;NDVI=0.42. Eastern counties presented maximum values of Kc=0.8 ;NDVI=0.63 for native; Kc=1.1 ;NDVI=0.86 in irrigated crops and Kc=0.5;NDVI=0.73 in dryland ecosystems. As expected, Kc increased according to land use and from West to East. The same linear equation that relates NDVI to Kc was used to all the ecosystems. Thus, variations in NDVI showed to be affected mainly by phenological differences in vegetation and length of growing season for each area.

The use of remote sensing proved to be quite helpful working at regional scale. By automating procedures through the creation of GIS models it can be used to obtain quick results for large areas, generating a higher accuracy working at higher resolutions to avoid interference of features.

Groundwater level declines and groundwater storage were calculated using interpolation with kriging analysis. Water levels declines ranged between 0.12-0.26 m/y and changes in water storage between 18-39 mm/y at the county level and 0.14-0.37 m/y and 21-55 mm/y, respectively at the township scale. Results were consistent with reported data in all the cases except York County, where changes were greater than expected. Reported data related this issue to other factors such as lower precipitation, drought period and extensive ground water pumping.

In all counties the annual ET of native vegetation was lower than annual precipitation, the ET of dryland cropping was less than that of native vegetation, and the

ET of irrigated cropping systems was greater than that of both native vegetation and dryland cropping.

The higher ET of irrigated cropping systems resulted in a county average actual ET greater than that of native vegetation.

The SI proved that Holt LNNRD currently has the most sustainable use of groundwater and Chase County currently has the least sustainable use of groundwater, regardless the scale selected, county or township. York County had the least difference between the county scale SI and the township scale SI probably due to widespread and relatively uniform distribution of groundwater irrigation within the county.

The positive correlation between increased ET (ET=ET-ET*nv*) and reductions in water storage showed a significant correlation (0.62) at p-value < 0.05 level confidence, n=10. In general greater increases inn ET caused greater reductions in groundwater storage.

The negative correlation between SI and reduction in groundwater storage (-0.69) proved to be significant at p-value< 0.025, n=10. Therefore, for a greater SI the general trend is for less reduction groundwater storage.

Our results suggest that, managing ET, reducing the county ET, so that it approaches that of native vegetation, groundwater sustainability is possible, even in regions that rely on irrigation for crop production.

In this assessment the hypothesis that groundwater use can become sustainable if the regional ET is managed so that it equals the ET of native vegetation could only be accepted because none of the counties or townships studies demonstrated perfect groundwater sustainability.

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2. CHAPTER 2: GENERAL CONCLUSION AND RECOMMENDATIONS FOR FUTURE

Groundwater resource is of major importance in agricultural irrigated regions like Nebraska. Moreover, Evapotranspiration is the most important variable in the water budget and have a great influence in groundwater level variations. However, ET variable by itself it not enough to explain all the changes in groundwater levels.

Even though the relation between Sustainability Index based upon SI=ETnv/ET and changes in water storage did not show a good agreement, it suggests that managing ET so that it equals the ET of native vegetation could be a good approach to reduce water use, in detriment of other anthropogenic and natural factors;

The creation of a Sustainability Index is helpful for better understanding of irrigation management in a quick and simple way.

2.1 Future Research

Improved Indices not only for ET but also Precipitation and Drought for Nebraska should be done, in order to refine current data and improve accuracy of estimates.

A range for sustainability index should be implemented in future research. Reference ET could be a key factor while searching for a no arbitrary limit.

Other factors rather than only ET should be assessed and compared with the current studies available.

The creation of improved GIS models to separate ecosystems might be quite helpful to address changes in ET at regional scale. Further evaluation and improvement of these models must be done.

Future studies about native rangeland to dryland cropping systems for Nebraska are suggested in order to assess if there is an increase in groundwater storage and a greater Sustainability in water consumption.