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Quantifying historical impact of groundwater irrigation practices to the ecological environment and the availability of the High Plains Aquifer

The quantitative analysis of historical impacts of irrigation to the volumetric sustainable availability of the High Plains Aquifer and to the environmental flow requirements from 1901 to 2018

Jinmoo Lee
Student number: 6393896
j.lee5@students.uu.nl

Supervisor: Dr. L.P.H. van Beek
2nd Reader: Prof. dr. ir. Marc Bierkens

Water Science and Management
Faculty of Geosciences
Utrecht University

Universiteit Utrecht

Table of Contents

Abstract

The High Plains Aquifer (HPA), one of the largest groundwater systems in the world, has sustained the regional food production industry since the nineteenth century. It has provided a great number of agricultural products which were worth 35 billion US dollar in 2007, but at the same time, the aquifer has experienced severe depletion. A number of studies have pointed out that the overexploitation for agrarian purpose is responsible for the groundwater depletion by providing information of the regional historical trend of groundwater use. But it needs to be more studied, especially to figure out where, when the excessive consumption occurred and its impact on environment. In order to better conduct an impact analysis on spatial basis, this study first divided the entire HPA area into 27 ecoregions which have similar geo-, hydro- and ecological- features. Based on the spatial division, zonal groundwater replenishment and zonal baseflow to streams estimated from PCR-GLOBWB hydrologic model were obtained. Then the acquired values were compared to the irrigated area by the groundwater footprint method. The result of this steps indicates the historical trend of regional hydrologic situations and consequently how excessively irrigation practices have affected the groundwater dynamics and regional riparian ecosystems. As a result, the groundwater recharge rate in most ecoregions of the study area is enough to sustain streams and riverine ecosystems. However, the abstraction availability for the sustainable use, the difference between groundwater recharge and its outflow to streams, differs from 0 to 0.4 m for each ecoregion, and the abstraction history has been greater than the sustainable availability. Recently, groundwater usage in some ecoregions has frequently intercepted the amount that would have sustained the environmental flow requirements. This implies that a better resource management could be established when it was specified in a smaller areal unit level such as ecoregion or county.

Key words: groundwater depletion, groundwater footprint, high plains aquifer, zonal impact assessment, irrigation practices

1. Introduction

1.1 The emerging threat of groundwater depletion

Historically groundwater has contributed to economic growth by providing a safe and reliable source of water. Prominently, it has supported the expansion of irrigated agriculture over the 20th century and was facilitated by more efficient and cheaper drilling and pumping technology and driven by the greater global demand for food to feed the growing population. According to hydrologists, groundwater resources supply approximately 1,400 km^3 of the irrigation water demand annually worldwide, which accounts for 40% of the total of the annual global irrigation demand of 3,500 km^3 (Sundquist, 2010; Wada et al., 2012). This withdrawal has more than doubled since the 1960s whereas the total irrigation water demand per year has increased seven to eight-fold from 500 km^3 to 3,500 km^3 showing the increasing dependence on groundwater to maintain food security (Siebert and Döll, 2010; Wada et al., 2010) and the share of groundwater has risen more quickly since the year 2000 (Konikow, 2011). Over a growing number of regions in the world, groundwater abstraction rates approach and exceed long-term groundwater recharge rates. This development, which stems from human consumption, threatens the security of connected riparian ecosystems and environment through lessening groundwater contribution to streams and the water content in soil, and eventually risks the available groundwater volume itself. In this context, numerous studies have focused their attention on the limits of sustainable groundwater use and its improved management.

1.2 Dynamics of groundwater systems

Groundwater does not a discrete storage of water but, instead, interacts with surface water bodies with various degrees of connectivity in a form of flux from the recharge areas to the discharge areas taking the respective volumetric balance.

Typically, this underground resource is recharged by precipitation. As soon as precipitation percolates below the root zone where it is presumably out of the influence of evapotranspiration process, it moves downwards to the groundwater table and finally replenishes the aquifer (Sophocleous, 2005). This process can simply be expressed as:

$$R = ASW + P - SRO - AET - SC \quad (1)$$

where R is potential recharge (deep percolation), ASW is the antecedent soil water within the root zone, P is precipitation, SRO is the surface runoff, AET is the actual evapotranspiration, and SC is the storage capacity of available soil water in the root zone (Sophocleous, 2005). The formula implies that the degree of groundwater recharge differs according to spatial-temporal variability. For example, arid areas where feature low ASW, P and high SRO, AET, have a low recharge rate.

Once the water entered the system, it flows out vertically as well as horizontally supporting environment in diverse ways; for example, as flow to streams and reservoirs, as soil water content for phreatophytic vegetation, as evaporation from playas and areas of shallow water tables, as leakage to adjacent aquifers or as flow to the sea (Sophocleous, 2010; Narasimhan, 2009; Gleeson and Richter, 2018). Under natural conditions or the virgin conditions, groundwater systems take a volumetric balance between the amount of water entering and the amount of water leaving the system, so called the natural equilibrium state. However, after human intervention has taken place and has become excessive, the natural volumetric balance will collapse and shift towards a new equilibrium state (Chaminé, 2015). Based on the understanding of groundwater systems, the amount of abstraction (additional loss to the natural outflows) must be compensated by recharge as well. However, the recharge rate normally does not increase dramatically, for it is strongly dependent on steady

conditions such as soil type that governs the infiltration rate and regional climatic condition. Therefore, in most cases, the loss is compensated by a reduction of the amount of discharge, known as the baseflow. Eventually, the groundwater system establishes a new equilibrium taking the human intervention in the form of consumption as well as, importantly, lessening groundwater's environmental contribution.

Particularly in terms of the interaction with surface water, groundwater reportedly exchanges flux with streams (Winter, 1999), and its direction is determined by hydraulic head differences which is often decided by the altitude of groundwater table with respect to the stream altitude (Alley et al., 1999). Generally, the flow direction changes seasonally. For example, when a precipitation event is great in summer and the amount of surface runoff and interflow increase leading to a higher hydraulic head in surface water than groundwater, streams start infiltrating its banks and bed, and consequently recharge the aquifer (Alley et al., 1999). However, during a dry season or in arid areas, groundwater flow may have relatively higher pressure compared to a stream flow, so it compensates for a decrease in stream discharge (Sophocleous, 2002; Dingman, 2015). Some places in which surface water is disconnected from groundwater by an unsaturated zone wedging between solely recharge groundwater. In these areas, groundwater pumpage does not affect the amount of stream discharge (Alley et al., 1999) unlike other places. But, in most riparian areas, groundwater abstraction influences a stream flow in a form of a decrease in the amount of flux exchange as well as its direction sometimes (de Graaf et al., 2019). Assuming a groundwater well was installed near a river body, firstly the well intercepts groundwater flux towards the river. Then with an increasing rate of pumping, it takes much water than the amount of groundwater discharge to a stream, and it eventually reverses the flow direction from riverwards to landwards, i.e. hydraulically groundwater baseflow to river water infiltration (de Graaf et al., 2019). Therefore, it implies that groundwater is intimately connected to surface water, and hence a water loss such as groundwater pumping lessens surface water flux as well.

1.3 Sustainable groundwater use

Since the ancient era, groundwater and water-related issues regarding the sustainable use have been a topic among people of various professions including militaries, philosophers, scientists and engineers (Biswas, 1970; Bono and Boni, 1996). Mostly groundwater studies have looked into finding out the maximum and optimum groundwater development for securing its perennial amount (Meinzer, 1946). Until the industrialized beginning of groundwater development with high capacity pumps in the late 1940's – 1950's, groundwater resource was thought of as isolated from surface water sources, so hydrologists believed that the aquifers would be preserved unless the amount of abstraction exceeded the volume of percolation, known as 'water budget myth' (Bredehoeft et al., 1982; Alley et al., 1999; Winter, 2001). Like the disconnected formation of groundwater-surface water in Section 1.2, people believed groundwater abstraction never affects other hydrologic features such as river discharge. In this context, 'water budget myth' had led to overexploitation of water resources as well as to misorientation of the water-related policies (Sophocleous, 2010). However, with a better understanding of groundwater systems, the concept of the safe yield was elaborated upon, and the definition of the sustainable groundwater use was clarified (Sophocleous, 2005): the groundwater development and use need to assure that there is enough capacity for future generations as well as, more importantly, for the natural environments such as stream flows, riparian ecosystems, aquatic ecosystems and wetlands which are dependent on groundwater's environmental contribution (e.g. baseflow and capillary rise). Recently the environmental flow which groundwater sustains started to be considered as an important element of the sustainable use for its attributions of supporting surface waters and ecosystems (de Graaf et al., 2019).

Groundwater accounts for 40 – 50% of the river discharge in small and medium size rivers, and naturally a considerable proportion of the mainstream (Alley et al., 1999), but sometimes in a dry season, the river water is merely from groundwater due to bare precipitation. As riparian ecosystems

and its services are sustained by stream flows, so called environmental flow, groundwater contribution to streams in a dry season is critical. When the necessary amount of the environmental contribution of groundwater, also known as environmental flow requirements, was not fulfilled, the riverine ecosystems starts to collapse. In this manner, the sustainability of groundwater use has to be approached while taking into account of the meeting these environmental flow requirements (de Graaf et al., 2019).

1.4 High Plains Aquifer

The High Plains, referred to as the "grain basket of the U.S.", is traditionally famous for food production in the States. Approximately 39% of the land is utilized for agricultural use, and among them 30% is irrigated (Scanlon et al., 2012). The proportion of groundwater accounts for 48.6% of the total amount of water use for irrigation which is higher than the global average rate of 40% showing high dependency on groundwater (Wada et al., 2012; Dieter et al., 2018). Groundwater plays an important and indispensable role in food production in the High Plains, and the recent findings have warned groundwater depletion over the region induced by excessive groundwater irrigation practices (Döll and Siebert, 2002; Siebert and Döll, 2010).

According to multiple authors (Alley et al., 1999; Sophocleous, 2005; Whittemore, 2012), the aquifer was able to provide enough amounts of environmental flow keeping its water cycle balanced until the predevelopment era, up to the 1940s. However, after a number of high capacity pumps had been installed from the late 1940s to the 1980s, it underwent a great decline of the water table of over 30 meters in Kansas, New Mexico, Oklahoma, and Texas (Sophocleous, 2005). In particular, some southern HPA regions including Texas have reportedly been experiencing reductions in the saturated thickness of the aquifer, with rates as much as 50 percent in comparison to the predevelopment stage. Due to its increasing rate of abstraction and its high evaporation rates, the region from the central to the southern HPA has not yet reach a new equilibrium state between recharge and discharge in the groundwater system (Alley et al., 1999). Besides the report of degradation of the groundwater system, deterioration of the riparian environment and its ecosystem has been outlined as well. As a result of the decrease in the water table, several streams and its ecosystems such as cottonwood riparian zones have been deteriorated across the central and southern HPA as well as a decrease in the amount of aquatic species diversity along the adjacent streams has been reported (Sophocleous, 2000). This kind of environmental degradation has highlighted the need for best management practices for the "environmentally sustainable development of groundwater" (Sophocleous, 2010).

In order to provide scientific information towards the sustainable development of the High Plains Aquifer (HPA), various studies have been conducted. Sophocleous (2005) investigated the recharge rate variation under the conditions of different soil and land use over the central HPA. He described the groundwater recharge rate at different scales of a range from counties to regions taking the soil-water budget into account. In 2010, he also studied the sustainability of groundwater development projects and suggested science-based groundwater management recommendations such as an interstate groundwater commission (Sophocleous, 2010). Gleeson et al. (2018) also proposed a new standard towards the sustainable groundwater resource management with the findings of the response time of environmental flow to groundwater abstraction. In the study, they emphasized that the impact of pumping practices is critical under ecologically sensitive conditions such as high evapotranspiration rates, arid climates and less precipitation. In addition to it, de Graaf et al. (2019) have specified the location in which the environmental services have collapsed in their global scale study and also identified the flow limits that guarantee the thrive of riparian ecosystems. Regarding abstraction, Deines et al. (2019) studied changes in the irrigated area during 1984-2017 and provided a dataset of groundwater depletion maps linking to the increment of irrigation practices. Moreover, Esnault et al. (2014) identified the correlation between a crop species and the degree of its distinctive effect on water use linking to aquifer depletion as well as the regional riverine ecosystem,

further suggesting the best way forward in quantifying the impact of a specific crop to the aquifer was through the "groundwater footprint". This indicator relatively explains how much a crop has consumed water with respect to the groundwater availability. Esnault et al. (2014) indicated that irrigation practices for corn, hay and haylage, cotton (in the south HPA) and wheat (in the central HPA) spend groundwater up to 10 times more than the aquifer capacity, and in aggregation, the total consumption for irrigation is more than the 10-fold greater than the amount of water the HPA can affords.

1.5 Knowledge gap and research objective

The preceding studies have captured the attributions of the High Plains Aquifer and revealed that consumptive water use of irrigation practices have historically been so excessive that groundwater cannot afford the environmental flow requirements, which is responsible for the current state of environmental degradation. Furthermore, this historical trend is difficult to be compensated by groundwater recharge, and as a result, the HPA is under depletion phase. Also, from the findings of research studies, the impact of abstraction on groundwater storage and connected ecosystems is known to vary in space (geological variation) and in time (meteorological variation) (de Graaf et al., 2019; Sophocleous, 2002). Despite of these numerous and rigorous studies, knowledge gaps still exist on the degree of the impact of groundwater abstraction to the environmental sustainability along with the time period as well as in small spatial divisions. Furthermore, due to the constraint of the time lag between abstraction and its impact to baseflow and thus the difficulty of measuring the transient impact of groundwater use to baseflow, temporal analysis of the impact to the environment has barely been conducted. But it is possible to analyze by comparing the extraction with the availability in the system which excludes environmental flow requirements (i.e. the groundwater footprint), and it indicates the impact potentially affecting the riverine environment and its ecosystems. Also, for the spatial analysis for the impact, the study area, the High Plains Aquifer region, needs to be divided into sub-regions which have similarity in geological, ecological and hydrological features. In this manner, this study focuses on quantifying the impact of groundwater use to the aquifer system as well as dependent streams, and subsequently analyzing changes in the impacts in time and space.

Considered the main consumer of groundwater, as described in earlier chapters, agricultural irrigation practices were chosen to represent the increasing demand across the High Plains. This water demand, then, is annually compared to the net availability of the groundwater system volumetrically, specifically recharge minus environmental contribution. The aggregated outcome of the entire time-series is designed to reveal at what point and when the agricultural demand exceeded the sustainable availability of abstraction volume and quantify the related disturbance of the water balance. Hydrologic variables and datasets necessary for the groundwater footprint analysis are from the global scale hydrologic simulation from PCR-GLOBWB. Particularly, it provides hydro features which are difficult to observe such as groundwater recharge or river discharge under hypothetical natural condition.

The results of this study are expected to be valuable information to establish explicit agricultural guidelines for the sustainable management of groundwater systems as well as environment. In this regard, the objective of this study becomes to find:

1. The degree of the historical impact of the groundwater irrigation practices over the High Plains Aquifer affecting the groundwater dynamics and dependent streams
2. The potential for a more sustainable development

In order to conduct the research properly, several sub-research questions follow:

(1) How does the geological features and climate trends vary over the ecoregions, and how do groundwater recharge rates alter its variation?

(2) How has the regional groundwater recharge rate changed over time? What are the factors?

(3) How could the computer model secure reliability? And what are the uncertainties of the model?

(4) How do the environmental flow requirements vary spatially?

(5) What are the major crops in HPA? And what are the patterns of agricultural irrigation, especially for the major crops?

(6) What are the current groundwater management schemes and how has it historically changed?

2. Study Area

2.1 Physiography

2.1.1: Geology

The High Plains Aquifer (HPA), an unconsolidated sand and gravel aquifer, composed of Tertiary (formed in 63 to 2 million years ago) and Quaternary (formed in 2 million years ago to present) geologic units which are hydraulically connected to each other (Gutentag et al., 1984). The upper Tertiary layer, again, is mainly divided into three formations: the Brule Formation, Arikakee Group, and Ogallala Formation, while the Quaternary deposit is categorized as alluvial, dune-sand, and valley-fill deposits (Condra and Reed, 1943; Gutentag et al., 1984). The Ogallala Formation which accounts for 80% of the High Plains Aquifer contains a heterogenous combination of clays, silts, sands and gravels deposited mostly by aggrading streams easterly flowed. The calcium carbonated zones in the Ogallala Formation form the boundary of the aquifer due to their resistance to weathering. The Brule

Table 1 Geologic units in HPA and the physical features (From Weeks and Gutentag, 1981), the blue cells mean aquifer extent whereas the brown cells mean a consolidated bedrock

System	Series	Geologic Unit	Max. Thickness	Physical features
Quaternary	Pleistocene And Holocene	Valley-fill deposits	60 ft (18.3 m)	Gravel, sand, silt, and clay associated with the most recent stage of weathering and accumulation along present streams. Hydraulic link to underlying Quaternary and Tertiary layers.
		Dune sand	300 ft (91.4 m)	Sand with a small portion of clay and silt forming hills and ridges. Recharge area of the High Plains Aquifer
		Loess	250 ft (76.2 m)	Silt with little amounts of fine sand and clay formed by windblown dust
	Pleistocene	Unconsolidated alluvial deposits	550 ft (167.6 m)	Gravel, sand, silt, and clay partially cemented into caliche or mortar beds. Hydraulic link to Tertiary layers.
Tertiary	Miocene	Ogallala Formation	700 ft (213.4 m)	Forms over 80% of the entire High Plains aquifer. Poorly sorted clay, silt, sand, and gravel generally unconsolidated. Locally calcium carbonate-cemented into caliche or mortar beds.
		Arikaree Group	1000 ft (304.8 m)	Generally, deposits with massive fine to very fine - grained sandstone, and local beds of volcanic ash, silty sand, siltstone, claystone, sandy clay, limestone, marl, and mortar formed.
	Oligocene	White River Group (Brule Formation)	700 ft (213.4 m)	Upper unit, the Brule Formation, mainly consists of massive siltstone with sandstone beds. Locally lenticular beds of volcanic ash, claystone, and fine sand. The portion of the Brule Formation connected to joints, fractures and solution openings is considered part of the High Plains aquifer Lower unit, Chadron Formation, consists of bentonite and loosely cemented clay/silt.

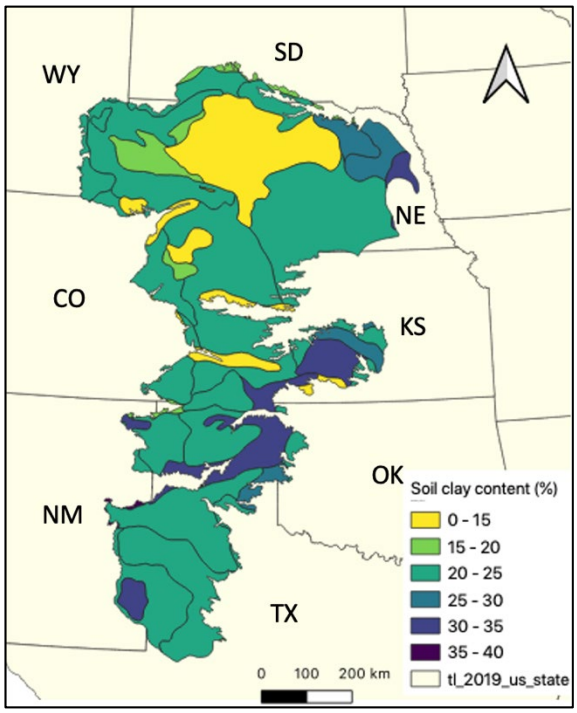

Figure 1 Clay content in soil over the High Plains (Sanchez et al., 2009)

Formation which underlies much of western Nebraska, northern Colorado, south-western South Dakota and south-eastern Wyoming generally consists of a massive siltstone layer containing sandstone and sand deposits. But locally, lenticular beds of volcanic ash, claystone, and fine sand are also found in the formation. Due to its geological distinction, this formation has generally little permeability. However, in some areas of joints of geologic units, fractures and solution openings are found, hence the permeability is high. The Arikaree formation laying over Nebraska, South Dakota and Wyoming is formed with a fine-grained sandstone that contains localized beds of volcanic ash, silty sand, and sandy clay. The Quaternary layers, unconsolidated alluvial deposits, are reportedly generated by the cycle of erosion and accumulation of streams, and it builds connections to the Tertiary layers (Gutentag, 1963). Dune sand deposits, the yellowish features shown in the *Figure 1*, have distinctive features such as high permeability, and it is considered important for recharge areas of the aquifer storage (Condra and Reed, 1943; Gutentag et al., 1984). The deposits predominantly consist of very fine to medium wind-blown sand, and its annual recharge rate is reportedly 15.2 cm in the west-central Nebraska (Gutentag et al., 1984; Scanlon et al., 2012). As *Figure 1* indicates, sand dune area accounts for 19 per cent of the HPA extent, as large as 85,000 km2. The most substantial area of dune sand extends over west-central Nebraska state covering an area of 51,800 km2 and having saturated thickness of about 91.4 m at maximum (Weeks et al., 1988).

2.1.2: Climate

Most of areas over the High Plains Aquifer have a distinctively mid-latitude dry inland climate with rich sunshine, moderate precipitation, low humidity and a high evaporation rate (Gutentag, 1984; Crosbie et al., 2013). The climate over the High Plains displays a spatial gradient vertically as well as horizontally.

The mean annual precipitation is uniformly distributed from south-west to north-east as 475 mm/year – 501mm/year (Scanlon et al., 2012) increasing eastwards by about 25 mm every 40 km. The precipitation varies from less than 400 mm in the west states such as Colorado, New Mexico, and Wyoming to about 710 mm in the north-east states such as eastern Nebraska and central Kansas (Gutentag et al., 1984). In addition to the general variation in space, the precipitation pattern varies with a large degree from year to year due to variability in its local climate rain systems, and local storm occurrences. Furthermore, the vast amount of the rainfall is concentrated in the growing season through the April – September window. The evaporation potential induced by the regional high summer temperatures and strong winds grow from about 1520 mm in northern Nebraska and southern South Dakota to about 2660 mm in western Texas and southern New Mexico (Gutentag et al., 1984). Compared to the summer season, the winter season over the HPA is drier and windier, and snowfall is very light (Gutentag et al., 1984).

2.1.3: Geomorphology and hydrography

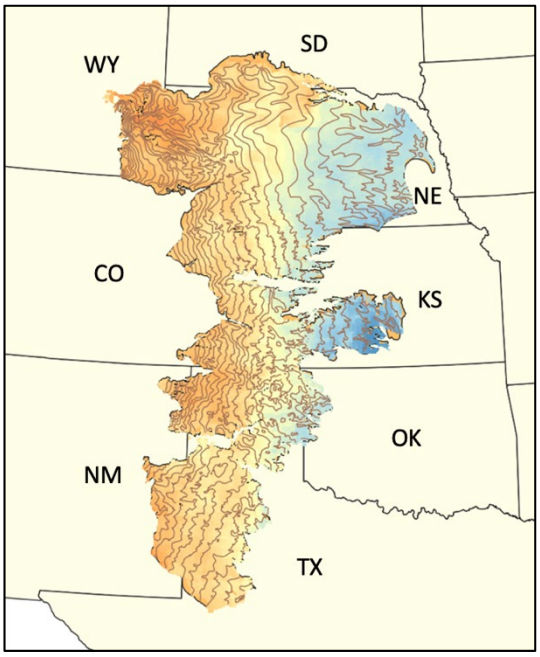

Figure 2 Groundwater depth contour map (Houston et al., 2013)

The extent of the area where the High Plains aquifer is laid over stretches to the Rocky Mountains in the west, the Central Lowland to the east, southern South Dakota to the north and the northern Texas to the south. The area which has been formed by deposition of easterly flowing streams is mostly an extensive plateau making a slight declining gradient to the east and south (Weeks et al., 1988). Due to its extremely flat topography, surface waters such as rivers and lakes are generally supplied by ephemeral lakes or playas, and then those integrated water currents confluence in a few major rivers such as the Platte, Arkansas, Missouri and Republican river (Scanlon et al., 2012).

As groundwater flow is governed by several regional factors such as geological formation, aquifer topography (saturated thickness, aquifer base elevation), etc., its flow in the region reportedly departs from the west, especially in the mountainous area of the Rocky, and run towards the east of the region as described in *Figure 2* (Houston et al., 2013; Peterson et al., 2016).

2.1.4: Vegetation

Riparian areas such as flood plains and streambanks have distinctive features compared to other High Plains land areas; unique fertile soil and vegetation species which are easily influenced by water (Montgomery, 1996). Since the riparian zones are situated in lowlands in the landscape, the groundwater table is found nearer to the soil surface, and its greater accessibility to water resources promotes the reproduction of vegetation. In the Platte River, *Populus deltoides* Marsh., also known as cotton wood, and *Salix amygdaloides Anderss*. are the dominant species (Johnson, 1994). The patterns of vegetation spread are found densely in central Nebraska but become thinner westwards along the increasing aridity gradient. Similar to the floodplains of Platte River, the riverine zones of Missouri River are well forested with *Populus* and *Salix* including *Fraxinus* in dominant areas (Johnson, 1992). These species cover almost three fourths of the riverine areas of the Missouri River, and the remaining quarter consists of wetlands, grasslands and shrublands (Hesse, 1996). However, due to the increasing number of reservoirs and unregulated developments, the flows of streams have greatly declined, and consequently natural point-bar formations have disappeared where the vegetation thrived. As a result, the patterns of riparian vegetation are changing species, and decreasing in numbers. For example, *Populus* and *Sali*x in Missouri River have been replaced by *Fraxinus*, *Ulmus* and *Acer* (Johnson, 1998).

2.1.5: Ecoregions

According to the Environmental Protection Agency (EPA, 2013), an ecoregion is a region defined as an area characterized with environmental similarities including climate, water, land, biota and humans. Besides, especially in this study, the river catchment is added as the key factor in order to delineate riparian ecoregions, since the ecosystem and the natural environment or riverine area

are sustained by the environmental flow requirements (de Graaf et al., 2019). The river catchment map provided by USGS (WBD, 2013) and the EPA ecological map are overlapped, and this combined map is generally used for analyses in this groundwater recharge and impact study. The combined ecoregion map is shown as *Figure 3* below. The well-known three divisions of the North High Plains Aquifer (NHP), the Central High Plains Aquifer (CHP) and the South High Plains Aquifer (SHP) are matched to ecoregion as followed; NHP: ecoregion No. 1 to No. 12, CHP: ecoregion No. 13 to No. 22, SHP: ecoregion No. 23 to No. 27.

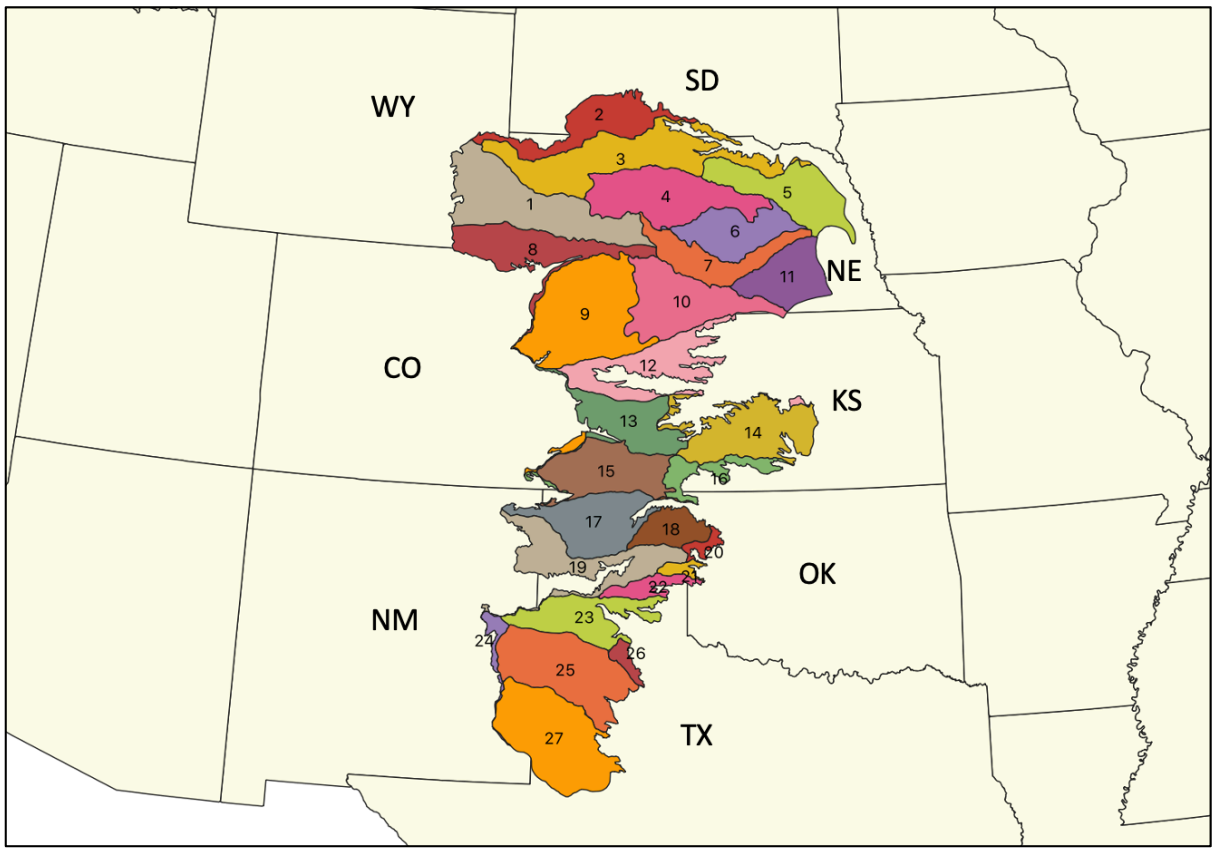

Figure 3 The Ecoregion divisions in the High Plains Aquifer which feature similar geological, ecological and hydrological characteristics

2.2 Human activity

2.2.1 Crops and Irrigation requirements

Groundwater irrigation use over the study area was first introduced in the late 19th century. However, it had remained scarce until 1940's, since farmers extracted surface water such as rivers and reservoirs with less cost than groundwater abstraction (Weeks et al., 1988). However, due to the industrial development leading to the mass production of high capacity pumps with low cost and increasing food demands, groundwater abstraction schemes and associated irrigation systems spread out across the High Plains. Specifically, according to the USGS High Plains Aquifer study (Weeks et al., 1988), the groundwater irrigated agricultural area had increased from 8,093.71 km^2 in 1949 to 56,655.99 km^2 in 1980, and the pumpage had grown 4.5-fold from 4.93 km^3 in 1949 to 22.20 km^3 in 1980. As of 2015, the annual pumpage is reportedly 22.50 km^3 which accounts for 47% of the total water irrigation (Dieter et al., 2018).

Since 1960s as shown in *Figure 4*, increasing food demands have induced rapidly growing groundwater abstraction rates, subsequently resulting in a great deduction in groundwater storage.

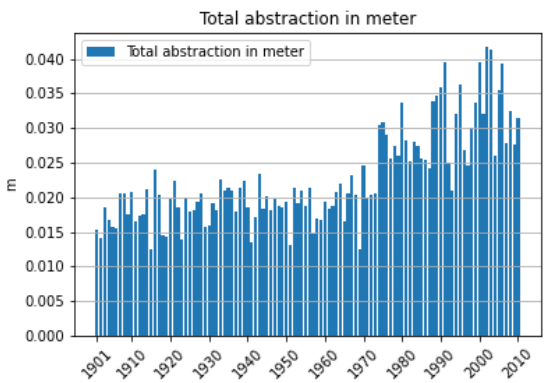

Figure 4 Total amount of abstraction in meter for the entire HPA

Specifically, groundwater has been depleted by 330 km^3 during the 1950 – 2007 time period, which accounts for 8% of the total estimated volume of the aquifer (Scanlon et al., 2012). Consequently, the declines of the water table have resulted in low well yield capacity as well as a decrease of the amount of baseflow which sustains river discharge (Weeks et al., 1988).

2.2.2 History of regional groundwater management strategies

In order to manage the groundwater resources in the aquifer efficiently and sustainably the eight High Plains states have chosen different approaches according to their geological, environmental and industrial contexts. Among those aspects, the groundwater renewability, also known as recharge rate, is the key reference for their determination of the resource management strategy between 'safe yield' and 'planned depletion' (Sophocleous, 2000). For example, Texas, Oklahoma, Wyoming and New Mexico, where very low recharge rates are seen in, take 'planned depletion' rather than sustainable use of groundwater resource, while Nebraska, Kansas, South Dakota and Colorado adopt a 'safe yield' strategy regulating water withdrawal as well as novel groundwater developments (Sophocleous, 2010). Nevertheless, the groundwater table still declines continuously, since the management schemes and governances have been set as political and economic goals rather than a hydrologic objective (Emel and Maddock, 1986).

3. Theory

3.1 Groundwater footprint: Quantification of irrigation impact on the groundwater system

The water footprint, the theoretical motivation of groundwater footprint idea, was firstly discussed in the International Expert Meeting on Virtual Water Trade in Delft, the Netherlands (Hoekstra, 2003). The concept of the water footprint, similar to the ecological footprint suggested by Rees (1992), denotes the volume of the freshwater required to sustain an ecological population in cubic meter per year (Hoekstra, 2009). Based on the concept of water footprint, groundwater footprint quantification methodology was proposed by Gleeson et al. (2010). The theory of this novel assessment deals with the volumetric water requirement that may affect the quantity of the groundwater and is subsequently expressed in an area required to sustain the groundwater use. It is theoretically expressed as:

$$GF = \frac{C}{R - E} \times A_{aq} \tag{1}$$

where GF, C, R, E and A_{aq} are the groundwater footprint, the amount of area-averaged abstraction, groundwater recharge, the groundwater contribution to environmental stream flow and the areal extent of an aquifer respectively. From the term of $\frac{C}{R-E}$, it is easily interpreted in a fraction depicting just how excessive a current abstraction practice is. More specifically, when a numerator is greater than a denominator, in other words the term is greater than 1, the GF would have a larger area than the actual aquifer area. Indicating an aquifer size required to fulfill the amount of water abstraction without environmental damage, the area of GF could be a reference to explain the level of overexploitation of an abstraction practice as well as environmental impact. In the research conducted by Esnault et al. (2014), it was used for volumetric analysis of aquifer depletion of the Central Valley and the High Plains. The study concentrated on a transient analysis and indicated both aquifers are currently under high stress in terms of sustainable use. In the study, the groundwater footprint explicitly delivered the information of groundwater overexploitation compared with the current capacity of an aquifer. Similarly, the volumetric analysis in this study employs the term $\frac{C}{R-E}$ from the GF methodology as an indicator of the groundwater use.

3.2 Environmental flow requirements

As water demand for intensive food production as well as industrial development has increased, concerns about the water amount required to sustain riverine environments and the riparian ecosystems has emerged (Pastor et al., 2014). For example, the annual flow amount of the Yellow river basin in China shrank by almost 25% over the past 30 years (Changming and Shifeng, 2002). Furthermore, due to considerable reduction in river flow, riparian species have reportedly decreased by 36% during 1970 – 2000 globally (Loh et al., 2010). The environmental flow requirements are the quantified water resource necessary to sustain the ecological environment over river basins, and it is acquired from environmental flow (EF) methods.

There are reportedly more than 200 EF methods in use, and these methods are generally categorized into four types: hydrological, hydraulic, habitat and holistic systems (Tharme, 2003). In this study, the Q90, one of the hydrological models, is used to find the environmental flow requirements. Based on the assumption that the discharge in dry season is the minimum flow to

sustain riparian ecosystems, the Q90 method considers environmental flow requirements as the flow exceeding 90% of the period of time series that is normally longer than five consecutive years. It is frequently used as a measure to obtain the amount of the low flow as well as groundwater baseflow needed to maintain a necessary minimum flow for riparian ecosystems (Gleeson and Richter, 2018) under the condition that groundwater head is above the low flow (de Graaf et al., 2019). In some areas which have significant discharge as well as highly permeable riverbanks or riverbeds, river water infiltration might dominantly occur even in dry season.

3.3 Hydrologic model: PCR-GLOBWB

Generally, groundwater storage and its dynamics are known to be difficult to measure and monitor due to its low velocity as well as limited accessibility. In order to compensate for these difficulties, computer modeling schemes have widely been used, for example hydraulic and hydrologic modeling. While hydraulic simulations such as Modflow provide indications and analyses of groundwater flow, hydrologic simulations such as PCR-GLOBWB delineate the water balance and water circulation in a regional environment.

PCR-GLOBWB, a widely used hydrological simulation schemes, is a global scale hydrological-modeling program developed in Python programming language firstly by van Beek and Bierkens (2009) and later modified by Sutanudjaja et al. (2018). This macroscale hydrological simulation technique has a 'leaky bucket' concept applied on a grid basis (5 arc-minute resolution ≈ 10km). It calculates the amount of water stored in two soil layers (or three layers) which vertically connects together every grid cell and every time step by processing several environmental variables and forcing variables such as meteorological data (rainfall, snowmelt, evapotranspiration, etc.), land cover, hydrologic properties and water use (van Beek and Bierkens, 2009). Among those forcing variables, anthropogenic factors are simply able to be applied by assigning land cover datasets and a water demand dataset. Since developed, PCR-GLOBWB has been used for several hydrological analyses such as groundwater depletion studies (Wada et al., 2010), water temperature mapping (Wanders et al., 2019), and safe yield securing environmental flow requirement studies (de Graaf et al., 2019), etc.

3.4 Validation: Kling-Gupta Efficiency (KGE)

This measuring methodology for fitness of two different datasets, developed by Gupta et al. (2009), is widely used to validate hydrological models and to find the correlation between two datasets (Knoben et al., 2019). It was designed to help analyses of the relativeness of two different datasets by providing a diagnostically interesting decomposition of Nash-Sutcliffe efficiency (NSE) and hence the mean squared error (MSE) (Gupta et al., 2009). The KGE value of one represents the exact same tendency as well as the same magnitude of two components, two identical data, since r, Pearson coefficient (see *Eq 3*), α, the ratio of standard deviation of both datasets, and β, the ratio of mean values, go one. It can be obtained with the *Eq 2*:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \tag{2}$$

$$r = \frac{Cov_{so}}{\sigma_s \cdot \sigma_o} \tag{3}$$

where Cov_{so}, σ_s and σ_o stand for the covariance between the simulated and the observed values, the standard deviation of the simulated dataset and of the observed dataset respectively. Due to the distinct features of MSE and NSE, the components of KGE, such as the correlation, the bias and a

measure of variability, anomalies in KGE values indicate that those constraints exist in the modeled data (Gupta et al., 2019)

4. Method

4.1 Data requirements and sources

To better understand the regional groundwater dynamics and impact of irrigation, as *Table 2* and *Figure 5* show below, four analyses have to be conducted: the temporal and spatial trend of groundwater replenishment, the environmental contribution of groundwater over ecoregions, historical irrigation practices and finally the groundwater footprint analysis. And, consequently, the final products of this study are (1) the trend of groundwater in time and space, (2) regional environmental flow requirements (EFRs), (3) temporal and spatial variation of irrigated area per crop and finally (4) the groundwater footprint (GF) analysis over sub-regions, ecoregions.

Table 2 List of required analyses, the relevant datasets and its sources

Analysis		Changes in Groundwater recharge in time and space	Zonal analysis of Environmental Flow Requirements	Temporal irrigation trend	Groundwater Footprint
Required datasets		Groundwater recharge under pristine and historical conditions	Groundwater recharge (gain), Groundwater contribution (potential loss)	Total irrigation data, Crop specific irrigation data	Results of previous analyses
Sources		PCR-GLOBWB	PCR-GLOBWB	PCR-GLOBWB, USDA Census, USGS Water report	Previous analyses
PCR-GLOBWB	**Simulations**	Pristine condition, Historical condition	Pristine condition	Pristine condition, Historical condition	-
	Variables	Groundwater recharge	Total groundwater abstraction	Groundwater recharge, River discharge, Total runoff	-

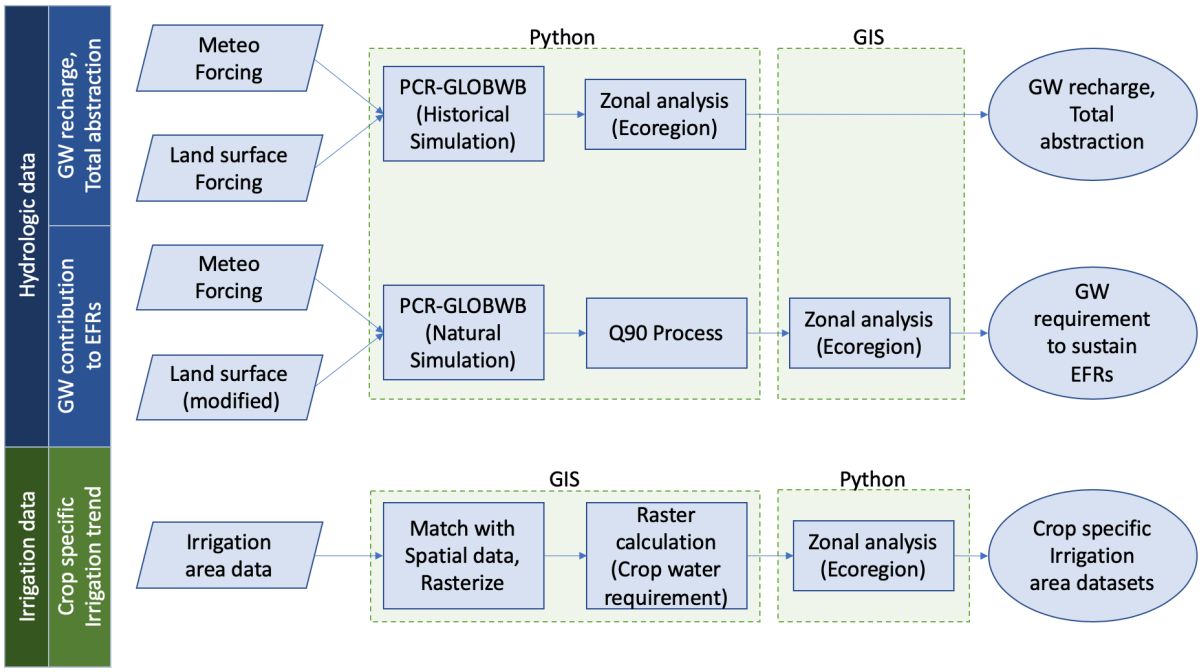

Figure 5 Data process flow chart

As *Table 2* shows, each analysis implanted with several datasets, acquired from relevant sources. Generally, the required datasets are divided into two parts according to its properties: hydrological datasets and non-hydrological datasets. Hydrologic datasets such as groundwater recharge and groundwater contribution to stream baseflow, are obtained by PCR-GLOBWB modeling, and other datasets are available from the U.S. governmental organizations for example USDA and NOAA. Especially for the hydrologic model simulated by PCR-GLOBWB, the model setup again has to be specialized for dataset's attributions. Since the potential groundwater contribution to EFRs has to be calculated with variables of the natural condition, its setup has to be adjusted similar to the pristine condition. In terms of observation datasets such as irrigation area dataset and climate index, this information is available from the public web pages of each organization and agency.

4.2 Hydrologic model: PCR-GLOBWB

Table 3 Model setup for PCR-GLOBWB simulations

Simulations	Distinctive setup options of the model				Output
	Resolution	Temporal extent	Artificial reservoir	Irrigation	
Natural condition	5 arc min	1961-1990	Disabled	Disabled	Groundwater recharge, River discharge, Total runoff
Historical condition	5 arc min	1901-2010	Enabled	Enabled	Groundwater recharge, Total abstraction

The main goal of using PCR-GLOBWB in this study is to secure the hydrologic values necessary for the groundwater footprint calculation as well as the groundwater recharge analyses. As stated in the previous section, due to the different purpose of datasets, PCR-GLOBWB has to be run twice with different conditions: the natural condition and historical condition.

The natural condition option in the program mimics primitive environmental conditions such as 'no groundwater abstraction', 'no reservoirs' and 'no landcover disturbance'. Thus, this condition ensures that the output data of the model are of a completely natural potential. In this paper, for the natural condition model, the main options were set as follows: temporal extent was set as 1961 – 1990 for 30 years, artificial reservoirs and irrigation practices were excluded. From this run, three kinds of datasets, groundwater recharge, river discharge, total runoff, were finally obtained.

The historical condition option simulates the real-world water exchanges in the regional environment as similar as is possible. It takes an account of variables such as land use, land cover, artificial dams, and groundwater abstraction, so that the model provides the most plausible values of observations. In this model, the time extent was set as 1901 – 2010 which covers the extent of the agricultural dataset and other options were set as default. This simulation was applied to acquire the real-life historical trend of groundwater recharge and its usage. However, both simulations shared other common parameters, for example meteorological forcing with CRU-TS 3.23 processed by ERA-CLM. Other modules were set identically in both models.

4.3 Data processing

As soon as all the datasets were required for this study were obtained, the data had to be properly processed using computer tools. As *Figure 5* describes, each data set required a different approach. Once all the hydrologic raw datasets had been generated by PCR-GLOBWB modeling, the output from the historical simulation was grouped into the 27 ecoregions. Subsequently the

groundwater recharge and the total abstraction values were averaged in respect to the area of each ecoregion. Since the irrigation datasets from USDA historical census archive are a county-based value, it cannot indicate the variability sufficiently over the land. Therefore, the groundwater dataset has to be aggregated and rescaled to the size of an ecoregion. Otherwise, some areas where the irrigation history does not exist may cause an error. While the groundwater recharge and the total groundwater abstraction under the historical setup are secured after the zonal analysis for each ecoregion, other hydro values under the natural condition require an additional procedure before the zonal analysis: namely the Q90 process. The Q90 flow was acquired from the 90th percentile of monthly river flow dataset from 1961 to 1990. Subsequently the groundwater baseflow is finally derived by the calculation as shown below:

$$Groundwater\ baseflow = Q_{90} - total\ runoff \tag{4}$$

However, from the distinctive dry and flat climatic and topographic features of the study area, the assumption can be applied that the surface runoff during low flow is negligible. Therefore, Q90 flow is the same as the groundwater baseflow in this study.

The numerical datasets of irrigation information from USDA, as mentioned previously, are county-aggregated areal data for each crop. Thus, in order to convert the unit of these data into water depth in meter like other data, it requires a calculation with several variables:

$$Irrigation\ depth = \frac{A_{irr}}{A_{co}} \times WR_c \times f_{gw} \times e \tag{5}$$

where $A_{irr}, A_{co}, WR_c, f_{gw}$ and e mean the irrigated crop area, the size of a county, annual crop water requirement, groundwater-irrigated area proportion over the total irrigated area and irrigation efficiency. In *Eq 5*, the irrigation efficiency is the integrated efficiency of conveyance system efficiency, application system efficiency and managing factor (Esnault et al., 2014). Throughout the irrigation depth equation above, the areal datasets become irrigation depth datasets. For this calculation GIS techniques were applied, since it is easy for spatial calculations. Like *Figure 6* below, the data handling for irrigation datasets had been implemented.

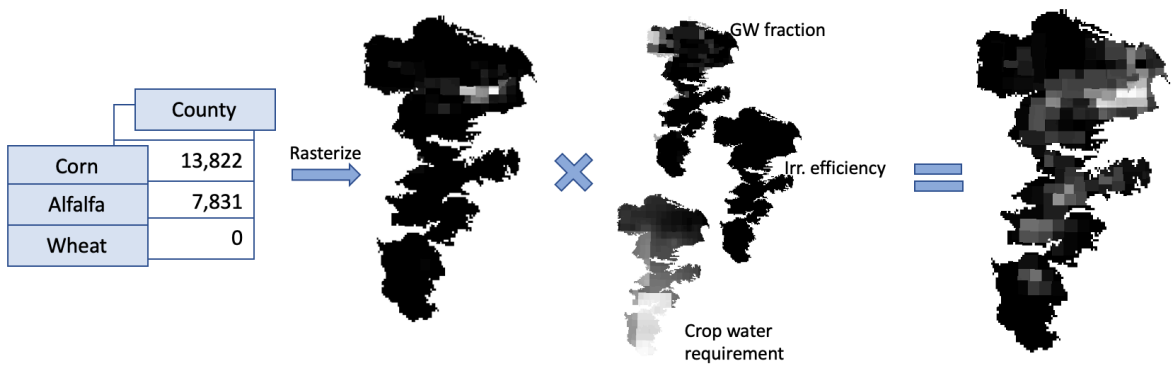

Figure 6 Data process of irrigation datasets

4.4 Analysis

In order to better understand the correlation of groundwater dynamics in time and space and excessive consumptive water use, four sub-analyses are required (see *Table2*): (1) groundwater recharge analysis in time and space, (2) zonal analysis of environmental flow requirements, (3) historical trends of the water consumptive use for irrigation and (4) groundwater footprint analysis.

The primary purpose of these analyses is to calculate the historical changes in groundwater availability securing the environmental flow requirements in regard to agricultural practices.

4.4.1 Validation

Among the datasets acquired for the research, the simulated datasets from PCR-GLOBWB require validation. Although two different simulations were conducted in PCR-GLOBWB, the validation work is only needed for one simulation. Compared to the historical modeling, the natural modeling is far from the realistic values due to several setup options being disabled. More specifically, in order to better delineate the natural condition of regional water balance in the model, three main arguments such as 'land cover', 'water abstraction' and 'artificial reservoir' were ignored. Thus, the natural condition's outputs of hydrologic values and levels, e.g. river discharge and groundwater recharge, are much closer to the primitive condition than that of the realistic modeling. Instead of direct validation, indirect validation is still possible to apply on the natural simulation through the validation work on the historical simulation. It is because the forcing datasets and the arguments of both modeling are the same, which implies that the input data and the main algorithms are the same. Therefore, the validity of the historical simulation could ensure the validity of the other simulation.

The model was validated for not only parameterization part (with input data) but also output part. The input data validation can assure the quality of the parameterization in the model, while the output data validation indicates how much other factors and the algorithm suit enough to describe the real world. As an input data for the validation the USDA census of irrigated area during 1964 – 2007 was applied, and the validation for the internal computation was implemented by comparing river discharge data with groundwater recharge data. River discharge data was validated by the GRDC observation dataset, whereas groundwater recharge output was verified with the observations of the USGS groundwater study of 2000 – 2009.

As a validation scheme, two different concepts have been used. River discharge values and irrigation values were validated by applying Kling-Gupta efficiency score method (KGE), while the simulated groundwater values were verified by the residual sum of squares (RSS) scheme due to the data type of ground truth data. Both the Kling-Gupta efficiency score method and the residual sum of squares are widely used to indicate the degree of the discrepancy (therefore, the similarity) of the data trends of the simulation and observation. A small RSS or KGE scores close to one indicates a tight fit of the model to the observed data.

4.4.2 Zonal analysis of environmental flow requirements

The definition of the environmental flow requirements, as discussed previously, is the 90th-percentile flow of river discharge (known as the Q90) historical dataset over the time period. And this river discharge in the definition has to be the flux under pristine conditions. However, due to river flows being regulated by artificial reservoirs in the real world, it is not feasible to derive the Q90 under the real-life conditions. Hence, in this study, three desirable variables including EFRs, Q90 and the relevant river discharge were acquired from the natural condition simulation. Specifically, the model excluded reservoir factors and irrigation effects. The obtained Q90 flux, the low flow as well as baseflow, was put on the ecoregion map, and consequently the gain (or loss) in flux inside of the ecoregion was obtained. This gain (or loss) directly indicates the regional groundwater contribution to EFRs by the assumption.

4.4.3 GW Recharge

Groundwater availability, the primary research object, is closely related to groundwater recharge, and this groundwater recharge rate to an aquifer is affected by land cover and precipitation patterns. Therefore, in order to understand the dynamics of groundwater recharge, groundwater recharge under different land cover conditions and the relationship between groundwater and climate change are necessarily pursued.

The rate of groundwater recharge through precipitation is reportedly affected by land cover (Scanlon et al., 2005). In the High Plains Aquifer region, also, the land cover type and its composition have been altered over time mostly by urbanization, and the understanding of the relationship between the rate and land cover is necessary to evaluate the regional groundwater recharge. The concept of the analysis was simply designed as the comparison of the rate over the study area under two different conditions: the natural condition (from PCR-GLOBWB natural simulation) and the real-life condition (from PCR-GLOBWB historical simulation). The values were area-averaged for the entire study area in order to minimize local bias as much as possible. As the natural condition is simulated for 1961-1990, and it is shorter than the historical simulation, the time span for the comparison work was set as same as the natural condition: 1961 – 1990.

4.4.4 Non-sustainable groundwater use

Zonal analysis of historical trend of consumptive water use for irrigation

As stated in previous chapters, impacts of water abstraction varies as per geographical features of ecoregions in this study. Thus, it is valuable to be aware of temporal and spatial changes in irrigation practices. Since the irrigated area datasets available on the USDA historical archive were recorded in county level, it needs to be transformed into a raster map in advance to apply to ecoregions. Then the raster data was allocated to each ecoregion and averaged. This work was repeated for each crop as well as for each ecoregion.

Groundwater footprint analysis

The groundwater footprint analysis would be better implemented by a spatial calculation, or more precisely raster calculation, since the acquired datasets are spatial data. In this context, all the requirements such as irrigation efficiency, groundwater irrigation ratio and crop water requirements were rasterized by a GIS program and python scripts (refer to *Figure 5*), and then these data were plugged into *Eq 1*. After the spatial computation in GIS, the zonal groundwater footprint values were assigned into ecoregions.

5. Results

5.1 Validation of model

Validation work is essential for a computer simulation, since it assures the output results of the model represent the real-world phenomena. As explained in Chap. 4.4.1, one input dataset and two output datasets were examined by comparing with the observation values.

5.1.1 Validation for parameterization: Irrigated Area

Historical census records of crop-specific irrigated and harvested area collected from USDA archive were compared to the input data used in PCR-GLOBWB which was originally acquired from FAO archive (FAOSTAT). Among 27 ecoregions, as *Figure 7* shows above, 23 ecoregions show good and reliable KGE values in a range from -0.3 to 0.5. As KGE score stands for anomaly correlation between the observed and the simulated, the parameterization for PCR-GLOBWB is considered good.

5.1.2 Validation for the output: Groundwater recharge and river discharge

For the validation work for the simulated result, groundwater recharge and river discharge were selected as a validation variable for its convenience of ground truth data collection. First, the simulated groundwater recharge datasets from PCR-GLOBWB were examined with USGS estimation. USGS groundwater recharge estimation are the estimated values from the Soil Water Balances (SWB) Model. This validation work was performed with the Residual sum of squares method, and it showed lower values for errors. Its RMSE was 0.046. Second, the validity of the estimated river discharge was checked with GRDC runoff data, Global Runoff Data Centre. As a gauzing station, totally 287 stations over the Mississippi river basin were selected. As *Figure 9 and 10* indicate, the score of KGE and the correlation generally marked “correlated but biased”, which represents high similarity of tendency

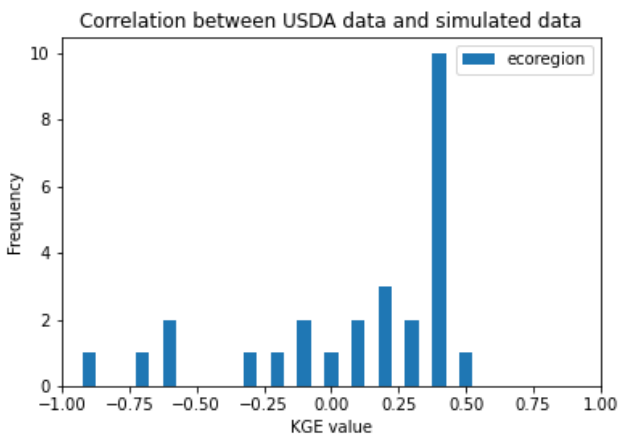

Figure 7 Kling-Gupta values variation. Correlation between USDA data and the simulated data by PCR-GLOBWB

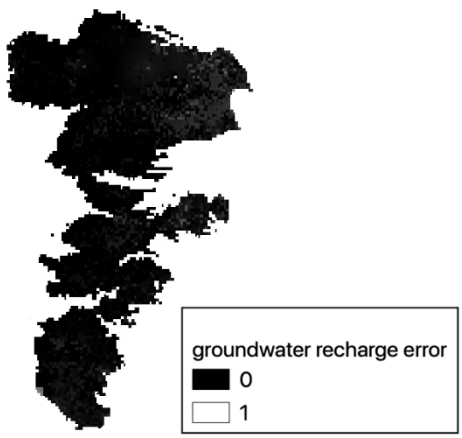

Figure 8 Residual sum of squares of the simulated data and the observations of groundwater recharge

but discrepancy between both datasets. Theoretically, it can be considered from one or the combination of bias and measure of variability. As a result of three validation works, output datasets obtained from the hydrologic model were therefore considered sufficiently reliable.

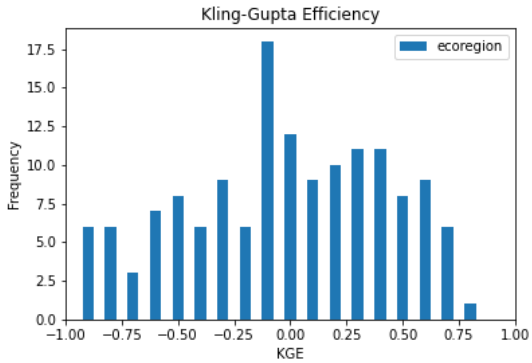

Figure 9 Kling-Gupta Efficiency coefficient of river discharge data between the simulated and the observed

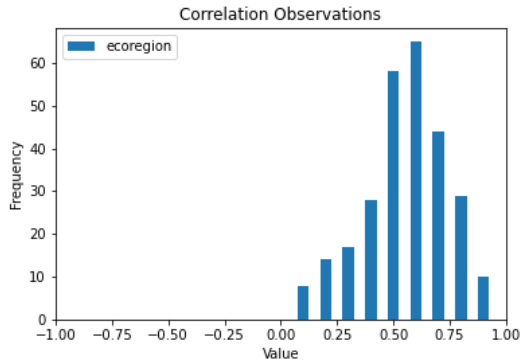

Figure 10 Correlation between the river discharge data of the simulated and the observed

5.2 Impact of irrigation practices to groundwater system and river flows

5.2.1 Groundwater recharge

Annual groundwater recharge and contribution to EFRs

The recharge rate of groundwater is strongly influenced by geological features. From PCR-GLOBWB modeling, its high values were found in the areas where dune sand layers are located (west-central Nebraska, and somewhere in the southern and northern Texas (See *Figure 11*)). Generally, however, the recharge rate was found to be very low over the entire High Plains Aquifer. It indicates that the combination of the regional climate characteristics, e.g. dry and low precipitation, and the relatively impermeable soil formation have limited rainwater percolation.

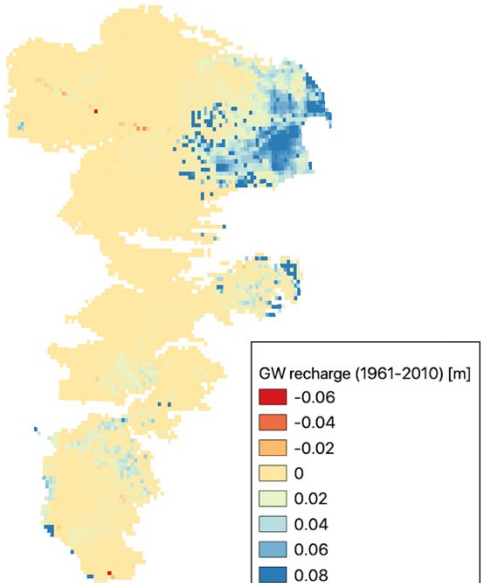

Figure 11 Annual average groundwater recharge rate (1961-2010)

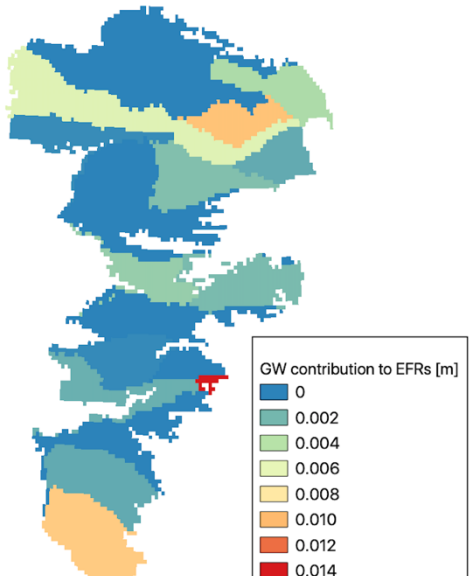

Figure 12 Groundwater contribution to the Environmental flow requirements, baseflow

Groundwater contribution to stream flow was only shown in ecoregions along the river basin as we assumed that the analysis merely takes regional exchanges between groundwater-surface water into account. Despite the values being area-averaged, the results indicate the necessary groundwater flow to stream is considerable, and in some areas, it is even greater than the recharge values. It is obvious that groundwater recharge process takes 10 – 100 years in this region (Sophocleous, 2005) and therefore it does not directly mean that groundwater is naturally depleted. However, groundwater availability securing the environmental flow seems definitely low.

In some regions such as ecoregion 13 and 20, it was found that the groundwater contribution to river and streams has negative value as shown as *Figure A25* and *Figure A39*. It implies that river flow in those areas is not recharged by groundwater but by infiltrating into an aquifer, an adjacent alluvial aquifer, through the riverbed or riverbanks even in the dry season.

Groundwater recharge and land cover (time)

The impact of land cover to the recharge rate of groundwater was briefly analyzed by the comparison of the recharge rate dataset from both simulations, historical condition and natural condition. As *Figure 13* displays below, under the natural condition groundwater is supposed to show a drastic fluctuation shape as the blue solid line in the graph. However, interestingly, the groundwater recharge rate is contained in a range from -0.05 to 0.002 in the real-world, which is relatively more stable variation compared to that of natural condition. It is possibly extrapolated that the land cover in the real-world scenario reduces the amount of recharge by impeding percolation into soil. On the other hand, in dry years, land cover limits evaporation of groundwater so that the actual recharge rate remained greater than the natural rate. Furthermore, even in dry years, irrigation practices are still performed, which recharges the aquifer in a form of return flow. In many cases, the amount of return flow reportedly exceeded precipitation replenishment (Sophocleous, 2005). However, from the graph, the gaps between those two datasets are greater in a humid year than in a dry year. It implies that the loss of groundwater recharge in a humid year is larger than the gain of that in dry year, and therefore land cover, or land use change, aggravates the groundwater recharge as well as groundwater depletion in a long term of time.

5.2.2 Historical trends of groundwater demand for irrigation

From the irrigation area dataset obtained from the USDA archive, it was clarified that irrigation practices for agricultural purposes started to surge in 1950s across the HPA region. Over the High Plains Aquifer region, grain such as corn and wheat have been predominantly cultivated. The proportion of this variable has been kept higher than 50 percent during the entire study time series. Interestingly a feature of this data is an advent of the relatively minor crops, e.g. alfalfa and soybeans, since 1950s. From the beginning of the temporal extent to approximately 1960, irrigation schemes

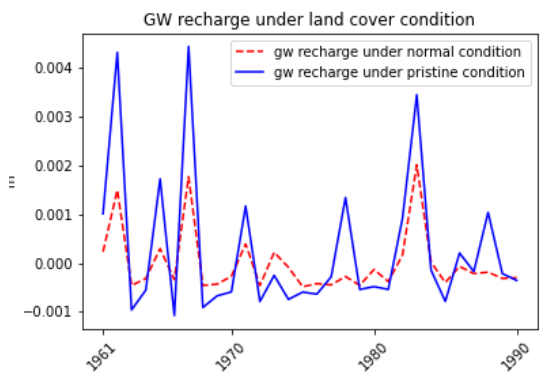

Figure 13 Groundwater recharge rates under real-world condition (red dashed line) and natural condition (blue solid line)

had mainly been applied to the relatively major crops such as corn and wheat (cotton in the SHP). However, since the availability of high capacity pumps had increased since the late 1940s (Alley et al., 1999), it has come to be widely used for various types of crops. One other point of this information is that the irrigation acreage keeps growing over the timeline regardless of the seasonal hydrologic cycles such as seasonality of precipitation and low groundwater recharge, i.e. seasonal drought.

In the NHP, the northern High Plains region, corn is one of the major irrigated crops grown, followed by wheat. Soybeans and alfalfa/hay were first irrigated in the 1950s. The graph, *Figure 15*, indicates that irrigation practices have excessively been occurring even though the northern region is relatively more humid and has easier access to water bodies compared to other two regions. It's most likely due to its seasonal patterns of river discharge dropping drastically in the dry season.

Wheat is the main produce in the CHP, the central High Plains region. Due to its geographical distinction of intermediate connection between the NHP and the SHP, cotton production is shown in the southern CHP.

The most arid area in the HPA, the south High Plains region, traditionally cultivates cotton due to its high temperature. In some farms, other products such as wheat and alfalfa are also produced. Both the CHP and the SHP experienced a dramatic increase in irrigated areas during 1950 – 1980, and these keeps an upwards trend continuously. Considering that the traditional agrarian scheme in the region that is rainfed, it is significantly transforming.

Generally, across the HPA, the area of irrigated land surprisingly has increased since 1950s. It is perhaps from the combination of issues such as spread of high capacity pump availability and rapidly increasing food demands driven by the growing population.

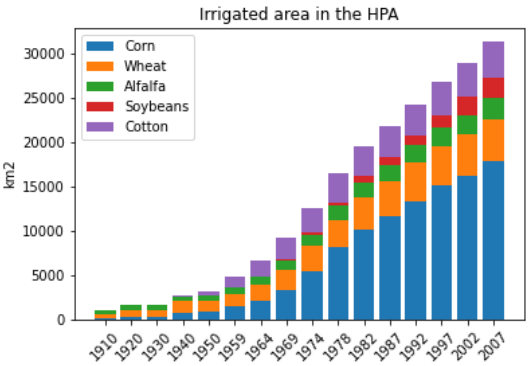

Figure 14 Annual total irrigated area per crop over the High Plains Aquifer

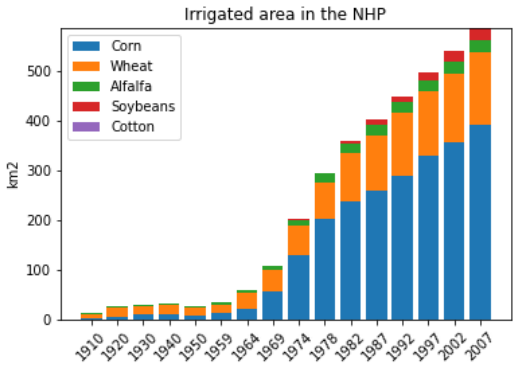

Figure 15 Annual total irrigated area per crop over the NHP

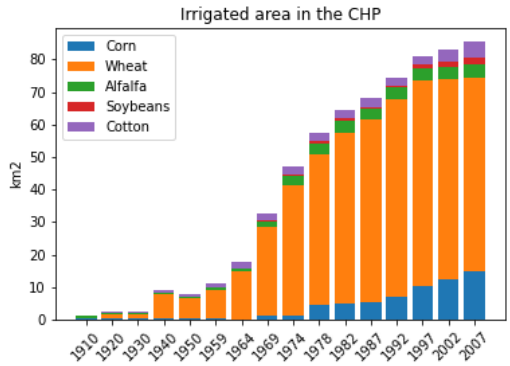

Figure 16 Annual total irrigated area per crop over the CHP

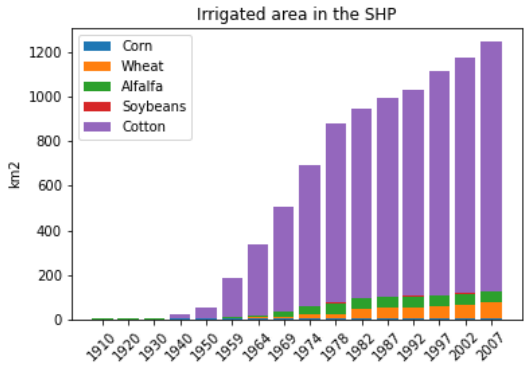

Figure 17 Annual total irrigated area per crop over the SHP

5.2.3 Temporal variation of regional water balance

Mostly in every ecoregion the groundwater abstraction has become excessive. In the regional water balance graphs on the left side, historical estimations of groundwater gain, loss, and the required flow to the EFRs are displayed as blue bar, green dashed line and red dashed line respectively.

Most ecoregions have larger amounts of recharge rates than the EFRs, which indicates that groundwater is naturally and sufficiently able to sustain the regional riparian ecosystem. However, the margin of groundwater is limited to less than 0.02 m in ecoregion 13 – 27 where the CHP and the SHP are situated under. Compared to the total groundwater abstraction showing high values, the margin is helpless. This historical trend resulted in the severe groundwater depletion of the High Plains Aquifer, and it will be presumably aggravated in the future unless appropriate measures are taken at the right moment. The north High Plains Aquifer region, ecoregion 1 to 12 cover, seems to secure more of a groundwater margin in comparison with the CHP and the SHP. However, when the stiff gradient of increasing irrigated area are considered, the NHP groundwater system is anticipated to confront a groundwater depletion phase in the near future.

The regionally analyzed irrigation data graph on the right side shows the temporal tendency of irrigation area. As stated previously, groundwater irrigation schemes have spread across the HPA with high capacity pumps in the late 1940's to mid 1950's. Actually, according to a FAO document (Fraenkel, 1986), mass production of pumps and decreasing fuel prices (until 1973; oil crisis) led to a cheaper price for pumps and inexpensive operation costs, and consequently rapid spreading of groundwater abstraction practices for businesses. Although all the ecoregions have a steadily increasing pattern of irrigation practices, the slope of the upward trend in the SHP (ecoregion 23 – 27) has become more sluggish compared to that of other regions. It implies that water policies such as regulating withdrawal might be applied to the region to better manage the underground resources.

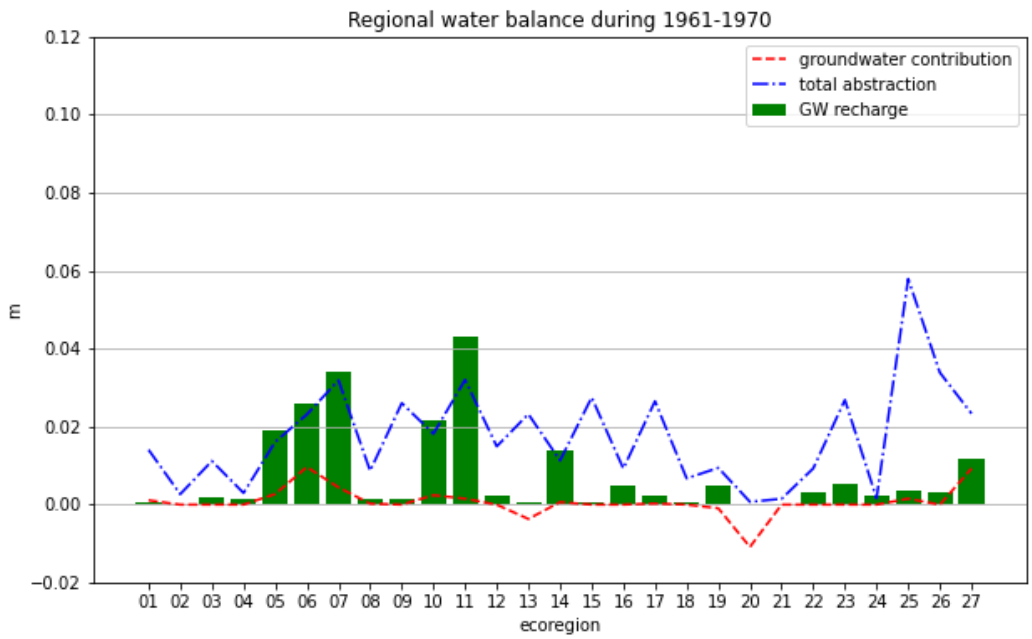

Figure 17 Groundwater recharge, abstraction and environmental contribution in each ecoregion: Averaged features of groundwater during 1961 – 1970

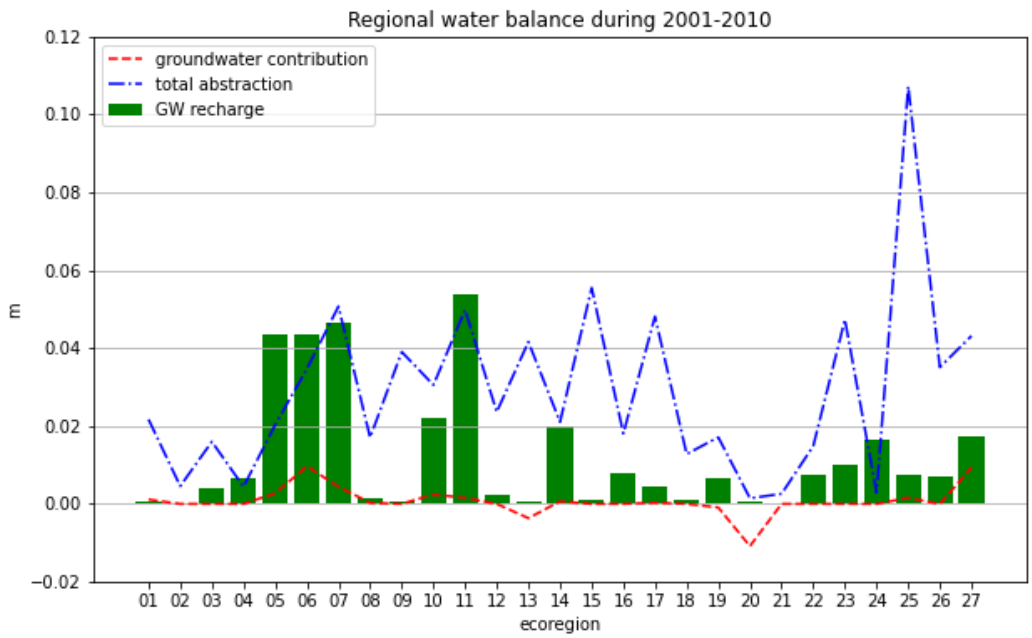

Figure 19 Groundwater recharge, abstraction and environmental contribution in each ecoregion: Averaged features of groundwater during 2001 – 2010

5.2.4 Impact to the groundwater system (Groundwater footprint)

When the HPA is considered to be divided into the NHP, the CHP and the SHP, each region shows distinctive aspects (see *Figure 20*). First in the NHP, this region can also be sorted into two parts, west and east, based on the groundwater footprint index. The west part which covers southern Wyoming, northern Colorado, southern South Dakota and western Nebraska is in the state of excessive groundwater use. Consumptive water use for irrigation in the west part is over three-fold larger than the amount of groundwater resources that the regional aquifer can provide in a sustainable way ("safe yield"). This result was driven by the difference between the groundwater recharge rate in the west part and in the east part. As *Figure 18 and 19* describe above, the recharge rate in the western part stayed under 0.005 mm and it resulted in the state of 'Fossil groundwater extraction'.

The CHP can also be analyzed in parts: the west-central part that covers west Kansas and north-east Oklahoma and the east-south part that covers central Kansas and north Texas. As displayed in *Figure 20*, the GF index in the west-central part, matched to ecoregion 13, 15, 17 and 18, is considerably high. The groundwater contribution in the west-central part is very low, which implies the groundwater replenishment can be used only for irrigation practices. Nevertheless, the groundwater footprint of these ecoregions is extremely high due to the high-level of abstraction. On the other hand, groundwater resources in the east-south part, matched to ecoregion 14, 16, 19, 20 and 22, seems to be well managed. In spite of some areas where river flow recharges the aquifer in part, normally the groundwater abstraction trend has been kept low.

Lastly in the SHP, all areas except ecoregion 27 are under severe pressure from groundwater use as the GF index shows in *Figure 20* below. Traditionally this region has grown cotton extensively and now more than half of the harvested land for cotton is fed by groundwater irrigation schemes (Deines et al., 2019). The increasing rate of irrigated land over the region has become mild since late 1970s. However, groundwater in the area is still being unsustainably extracted.

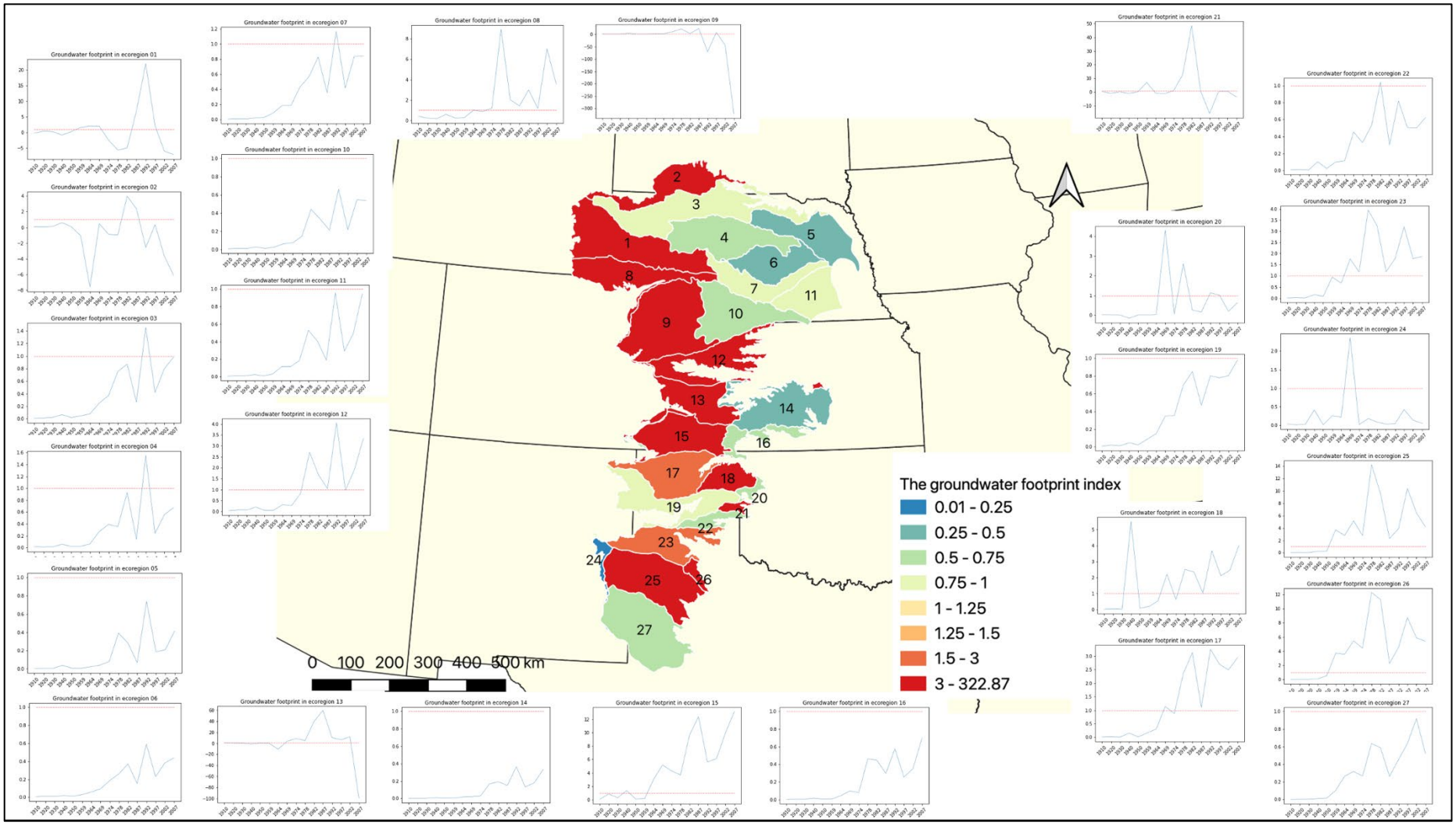

Figure 20 Groundwater footprint index for each ecoregion

6. Conclusion

In conclusion, most ecoregions in the study area have enough amounts of water input to the aquifer to sustain streams and riverine ecosystems. However, the margin, the difference between groundwater recharge and groundwater contribution to the EFRs, differs from 0 to 0.4 m across the HPA and the abstraction history surely has exceeded the sustainable availability. Recently, it has intercepted the amount would have sustained the areas' EFRs. As a lot of graphics have been used to demonstrate, the key factor in the sustainability of groundwater use is the abstraction practices being implemented. Compared to ecoregion 17, for example, ecoregion 19 has a similar level of groundwater recharge as well as the required sustainable availability. However, ecoregion 19 has a lower level of consumptive groundwater use than ecoregion 17. As a result, its GF index is three times lower than the other. Even though the GF index fluctuates depending on climate variation, it is obvious that the historical excessive irrigation practices in the High Plains Aquifer have deteriorated the groundwater availability.

7. Discussion

Based on the results of the thesis, several details can be discussed further, for example unreliability and limitations, implication of the results in regard to state governance towards sustainable development.

7.1 Uncertainties and limitations

First of all, the quality issue of irrigation information available on USDA archive can be discussed. The agrarian information has been collected in a form of census survey since 1840 and irrigation practices was firstly recorded from 1880's census, however, the accurate irrigation data is difficult to acquire due to its recording system until 1940 census: it only shows the total harvested area not the irrigated area (although it gives the state-summed irrigated area). Therefore, the irrigation dataset before 1950 might be compromised with other crop and/or with other counties in the state. The dataset since 1950 also has an aspect that makes uncertainty. The census marked merely for the total irrigated land per crop, hence the actual coverage of groundwater irrigation has not known. However, its data is enough for this study since it gives the trend of irrigation, which enables extrapolation for groundwater use.

In the real-life, groundwater flow is extremely slow compared to the fluctuation of stream level, and it leads to a time-lag between groundwater recharge and groundwater contribution flow. According to Sophocleous (2005), the groundwater replenishment over the High Plains Aquifer normally takes 10 to even 100 years of time. Therefore, even though the low recharge was estimated, its impact would not be seen for several years. However, its indication is critically important. The excessive and less regulated consumptive groundwater use since 1950's may considerably affect regional riparian ecosystems and its services.

7.2 Groundwater management towards the sustainable groundwater pumping

In order to establish management schemes and governance for natural resources including groundwater, the hydrological scientific approach is the only way to be credible as well as reliable (Galloway et al., 2003). The results of this study perhaps offer hints to better manage the underground resources.

As explained in the introductory part, groundwater-related policy is differently adopted in the eight states. Some states, mainly the southern states, apply a 'planned depletion' strategy, while the rest of other states adopt a 'safe yield' strategy (Sophocleous, 2010). Apart from the legislation measures, several innovative approaches have also been undertaken to stop the depletion and enhance the sustainability of the resources use such as use of storage reservoirs, conjunctive use of groundwater and surface water and artificial injection of water to aquifers through wells or surface spreading (Alley et al., 1999). However, the results of this study indicate that those policies and measures have not been successful in many areas, even though the governmental organizations have so far tried to keep the groundwater usage under the groundwater margin level (difference between the recharge and the contribution to stream). As the results show above, each ecoregion has unique geo-features, different hydrologic environments including meteorological factors and therefore different recharge rate. It gives a clue that the strategies and measures may show a better effect applied to a smaller unit of area such as an ecoregion or a county.

Acknowledgements

Prior to everything, I express my gratefulness and praises to almighty God for letting me start the master course and finally finish it with this research.

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Appendix

A. Regional water balance in each ecoregion, groundwater recharge, environmental contribution and abstraction in time series.

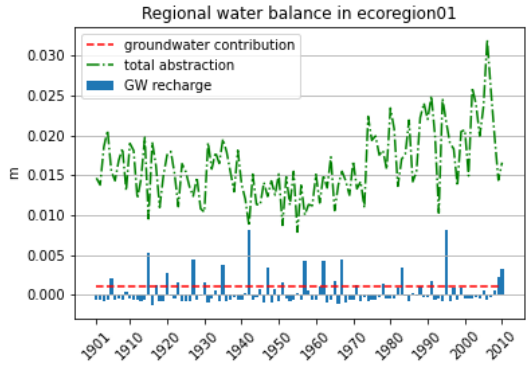

Figure A1 Regional groundwater recharge, baseflow and abstraction (ecoregion 1)

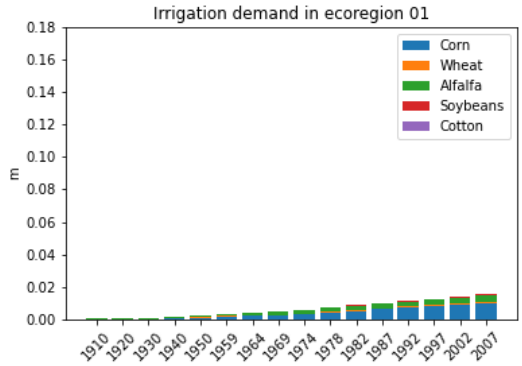

Figure A2 Irrigation demand for the five crops (ecoregion 1)

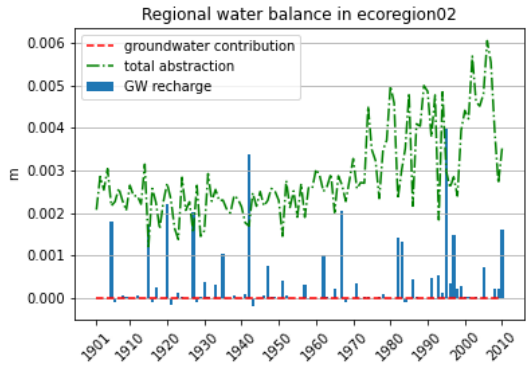

Figure A3 Regional groundwater recharge, baseflow and abstraction (ecoregion 2)

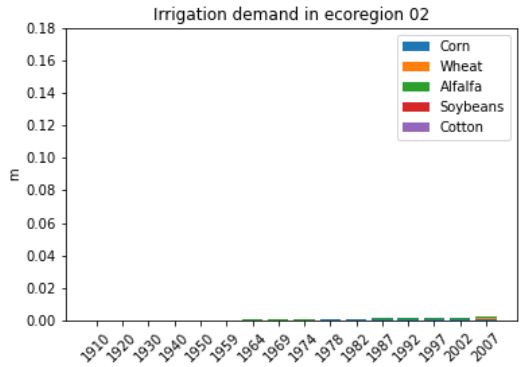

Figure A4 Irrigation demand for the five crops (ecoregion 2)

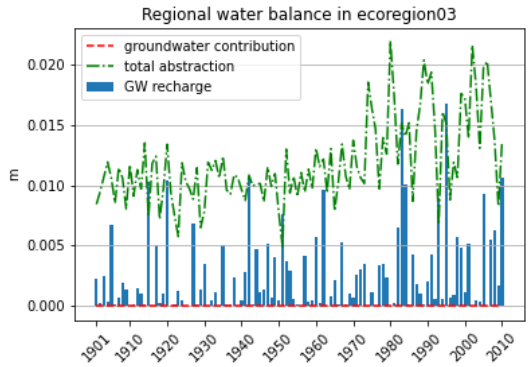

Figure A5 Regional groundwater recharge, baseflow and abstraction (ecoregion 3)

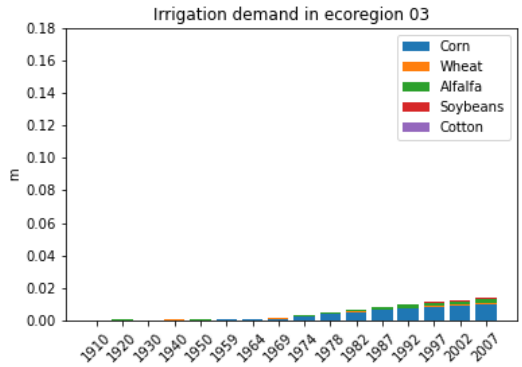

Figure A6 Irrigation demand for the five crops (ecoregion 3)

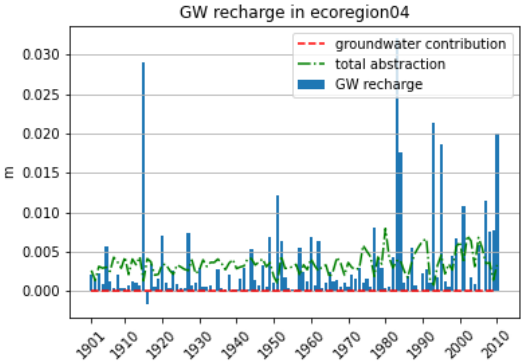

Figure A7 Regional groundwater recharge, baseflow and abstraction (ecoregion 4)

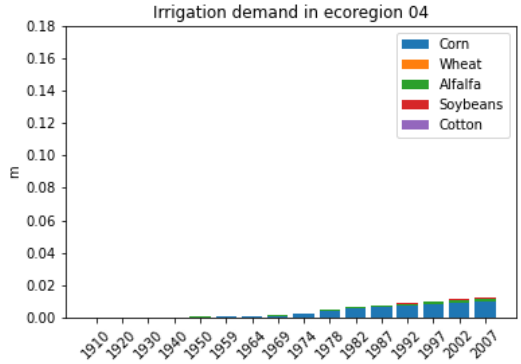

Figure A8 Irrigation demand for the five crops (ecoregion 4)

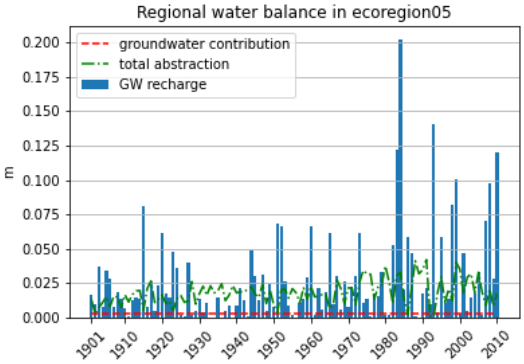

Figure A9 Regional groundwater recharge, baseflow and abstraction (ecoregion 5)

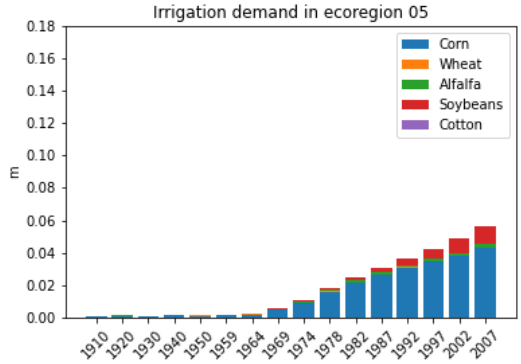

Figure A10 Irrigation demand for the five crops (ecoregion 5)

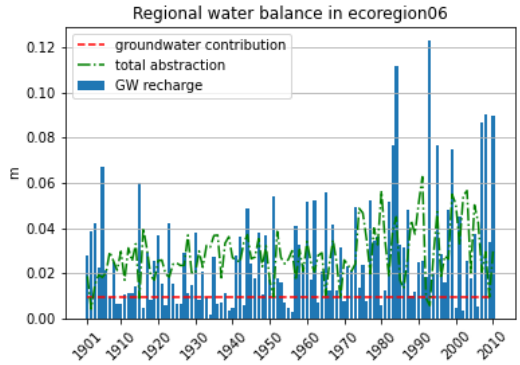

Figure A11 Regional groundwater recharge, baseflow and abstraction (ecoregion 6)

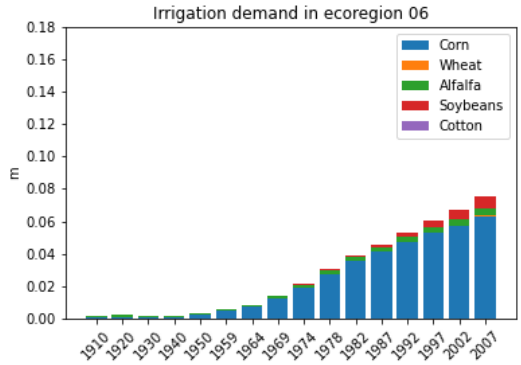

Figure A12 Irrigation demand for the five crops (ecoregion 6)

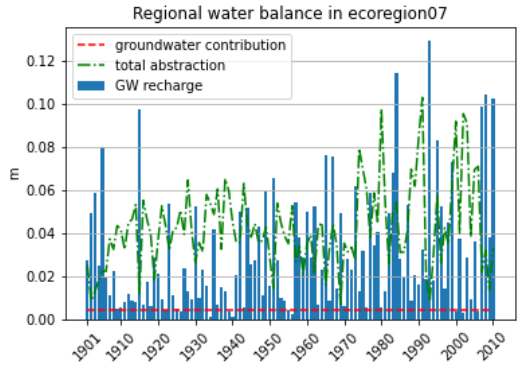

Figure A13 Regional groundwater recharge, baseflow and abstraction (ecoregion 7)

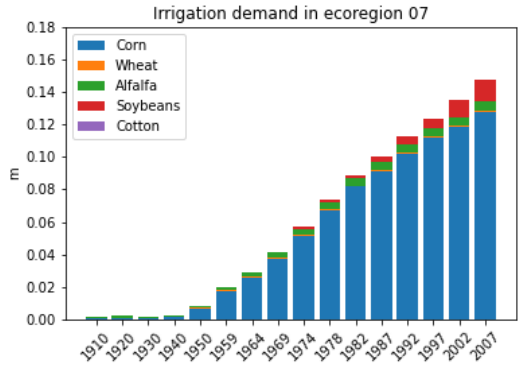

Figure A14 Irrigation demand for the five crops (ecoregion 7)

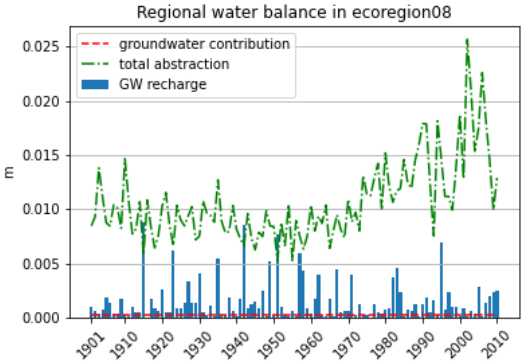

Figure A15 Regional groundwater recharge, baseflow and abstraction (ecoregion 8)

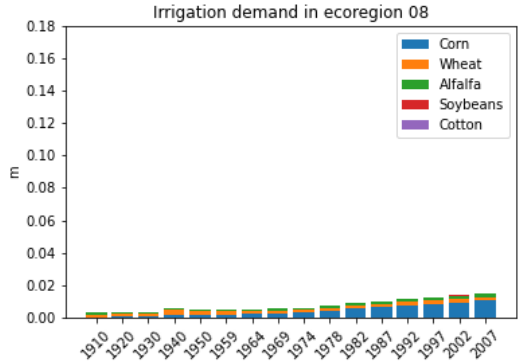

Figure A16 Irrigation demand for the five crops (ecoregion 8)

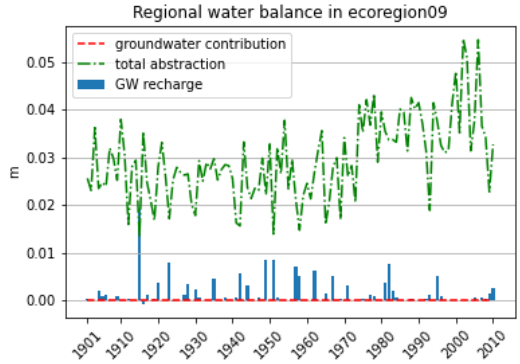

Figure A17 Regional groundwater recharge, baseflow and abstraction (ecoregion 9)

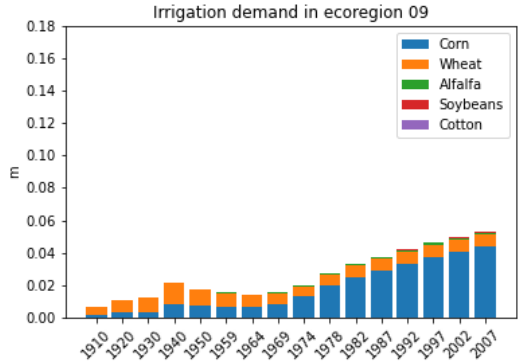

Figure A18 Irrigation demand for the five crops (ecoregion 9)

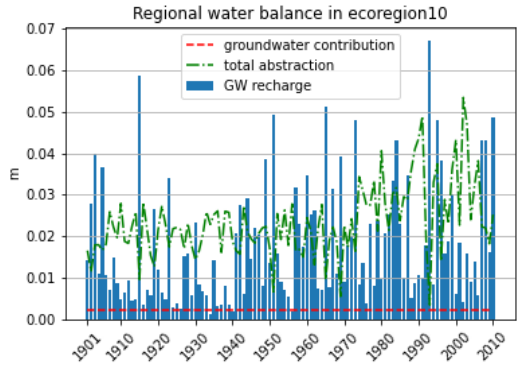

Figure A19 Regional groundwater recharge, baseflow and abstraction (ecoregion 10)

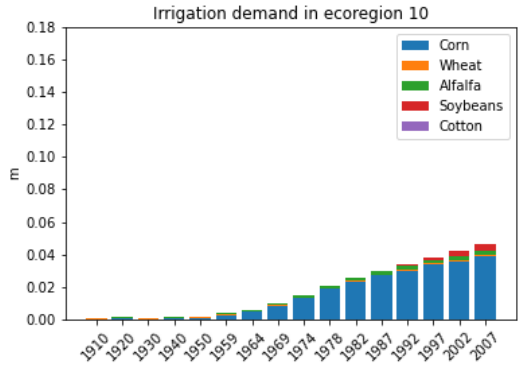

Figure A20 Irrigation demand for the five crops (ecoregion 10)

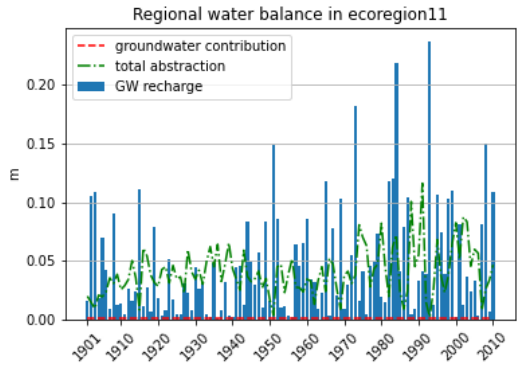

Figure A21 Regional groundwater recharge, baseflow and abstraction (ecoregion 11)

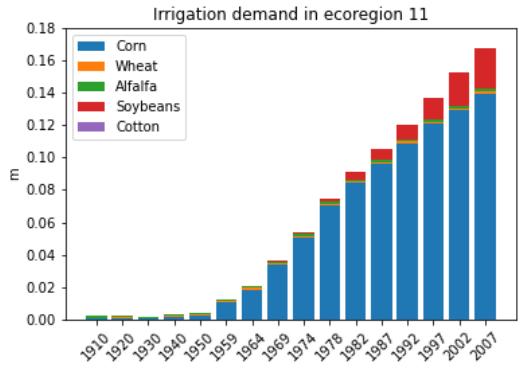

Figure A22 Irrigation demand for the five crops (ecoregion 11)

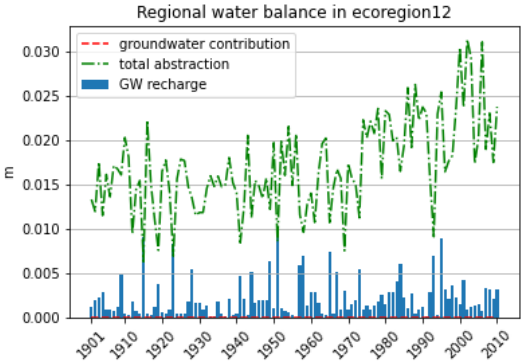

Figure A23 Regional groundwater recharge, baseflow and abstraction (ecoregion 12)

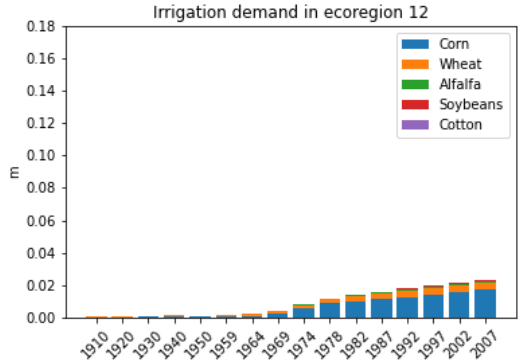

Figure A24 Irrigation demand for the five crops (ecoregion 12)

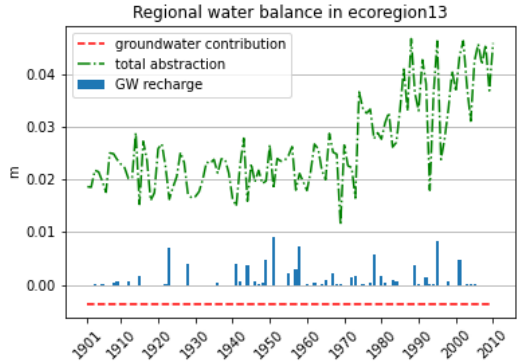

Figure A25 Regional groundwater recharge, baseflow and abstraction (ecoregion 13)

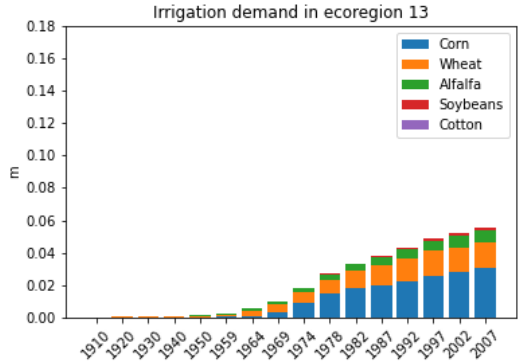

Figure A26 Irrigation demand for the five crops (ecoregion 13)

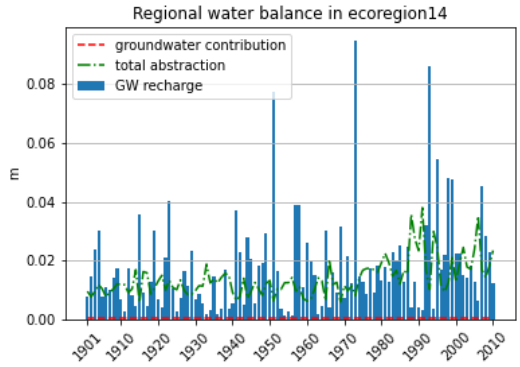

Figure A27 Regional groundwater recharge, baseflow and abstraction (ecoregion 14)

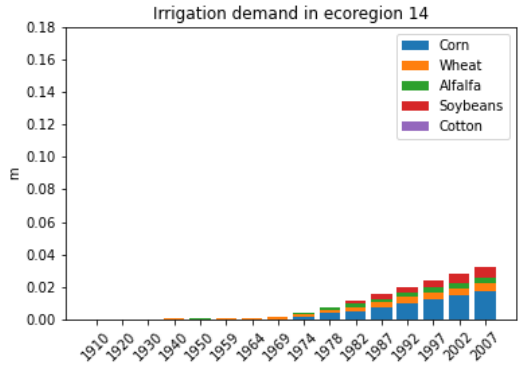

Figure A28 Irrigation demand for the five crops (ecoregion 14)

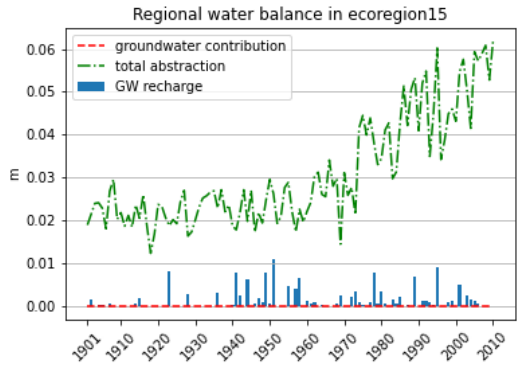

Figure A29 Regional groundwater recharge, baseflow and abstraction (ecoregion 15)

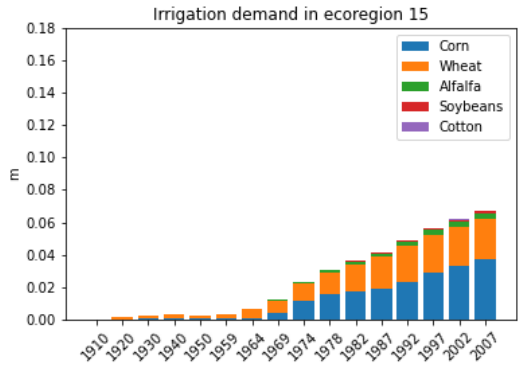

Figure A30 Irrigation demand for the five crops (ecoregion 15)

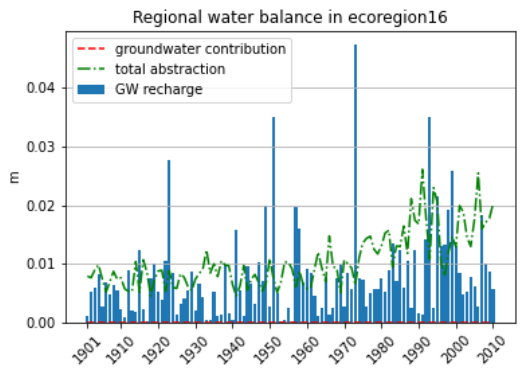

Figure A31 Regional groundwater recharge, baseflow and abstraction (ecoregion 16)

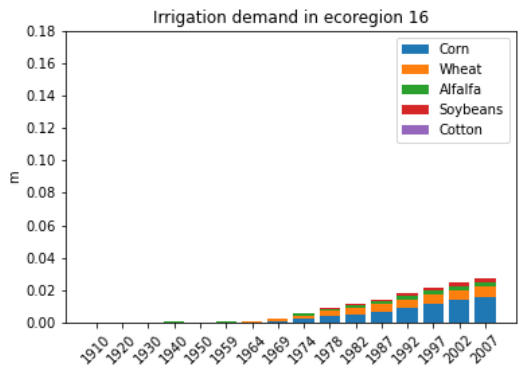

Figure A32 Irrigation demand for the five crops (ecoregion 16)

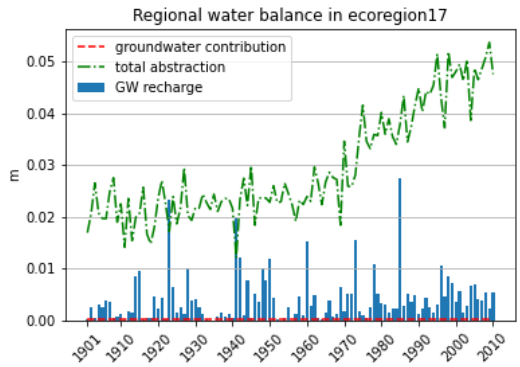

Figure A33 Regional groundwater recharge, baseflow and abstraction (ecoregion 17)

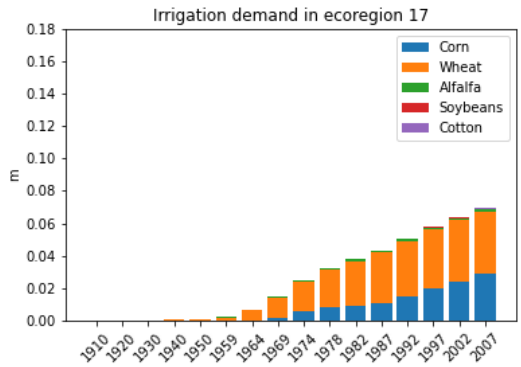

Figure A34 Irrigation demand for the five crops (ecoregion 17)

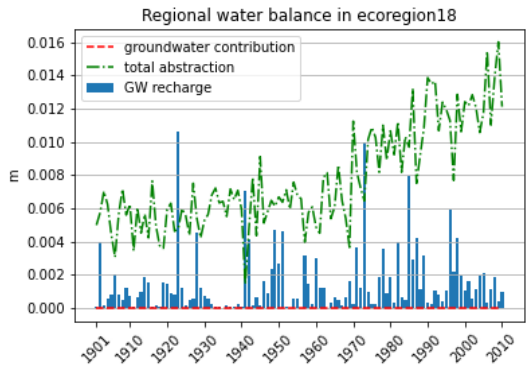

Figure A35 Regional groundwater recharge, baseflow and abstraction (ecoregion 18)

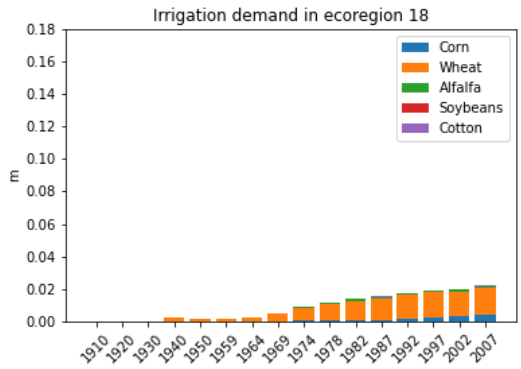

Figure A36 Irrigation demand for the five crops (ecoregion 18)

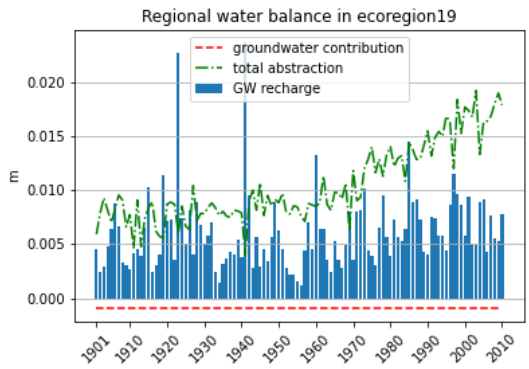

Figure A37 Regional groundwater recharge, baseflow and abstraction (ecoregion 19)

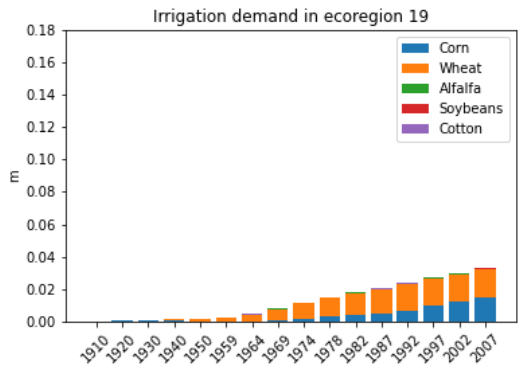

Figure A38 Irrigation demand for the five crops (ecoregion 19)

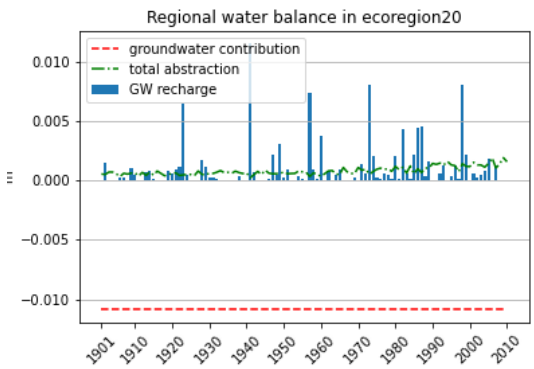

Figure A39 Regional groundwater recharge, baseflow and abstraction (ecoregion 20)

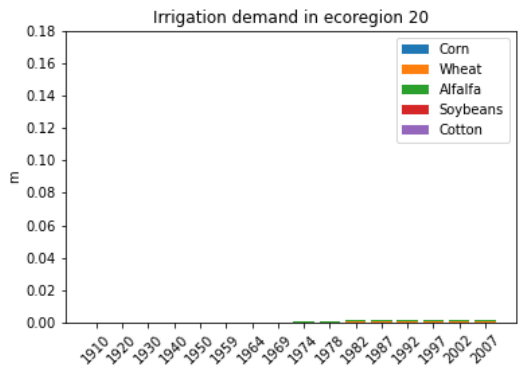

Figure A40 Irrigation demand for the five crops (ecoregion 20)

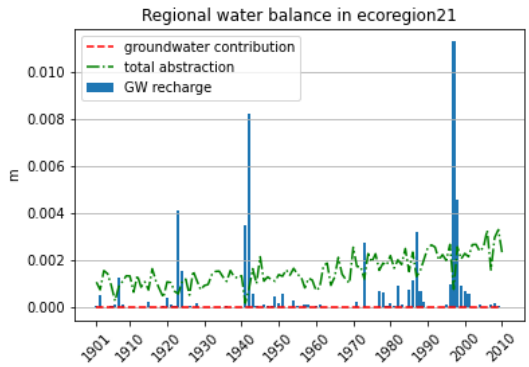

Figure A41 Regional groundwater recharge, baseflow and abstraction (ecoregion 21)

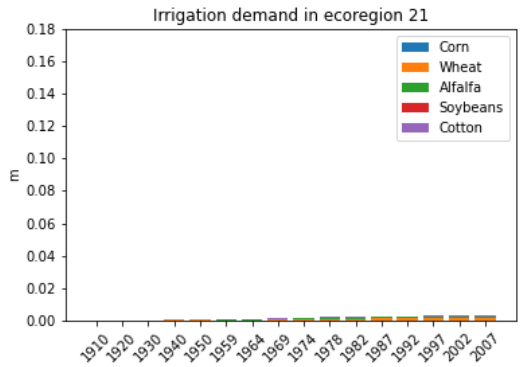

Figure A42 Irrigation demand for the five crops (ecoregion 21)

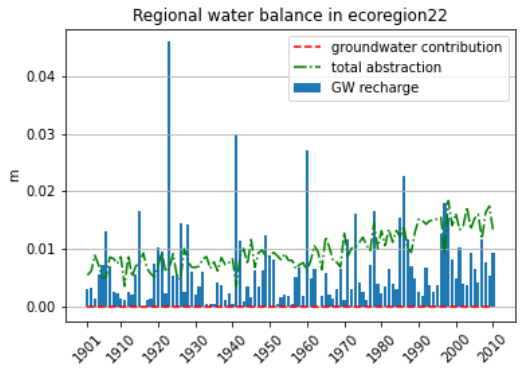

Figure A43 Regional groundwater recharge, baseflow and abstraction (ecoregion 22)

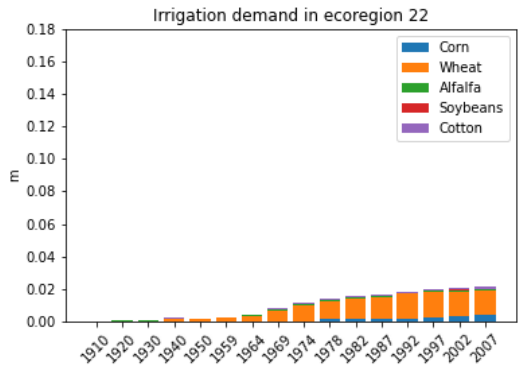

Figure A44 Irrigation demand for the five crops (ecoregion 22)

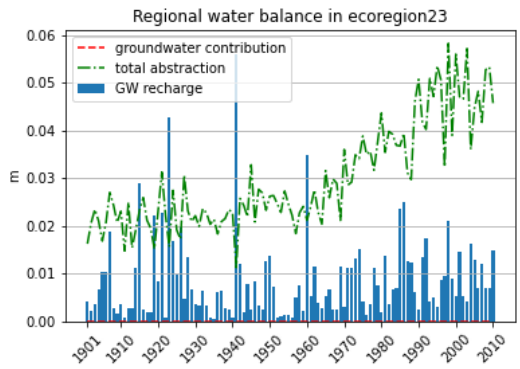

Figure A45 Regional groundwater recharge, baseflow and abstraction (ecoregion 23)

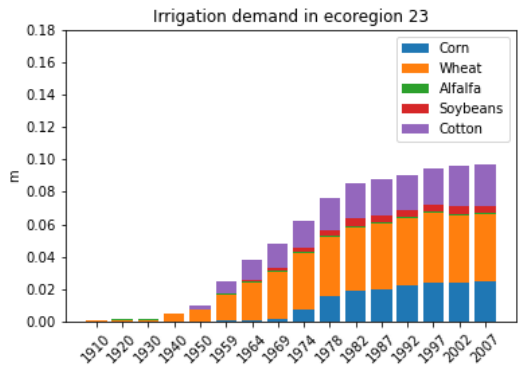

Figure A46 Irrigation demand for the five crops (ecoregion 23)

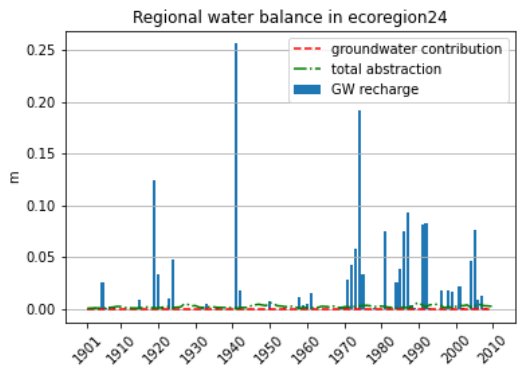

Figure A47 Regional groundwater recharge, baseflow and abstraction (ecoregion 24)

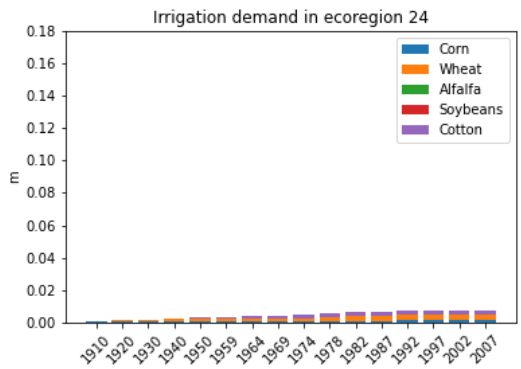

Figure A48 Irrigation demand for the five crops (ecoregion 24)

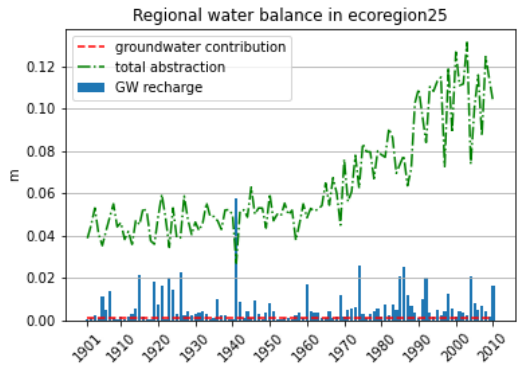

Figure A49 Regional groundwater recharge, baseflow and abstraction (ecoregion 25)

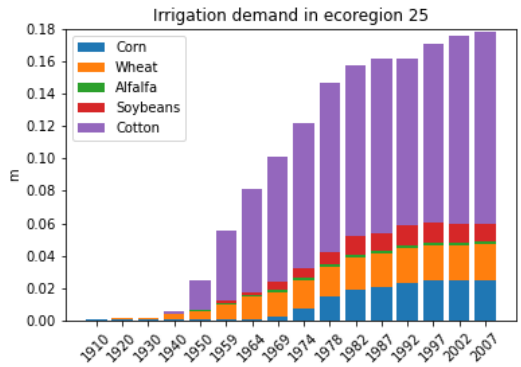

Figure A50 Irrigation demand for the five crops (ecoregion 25)

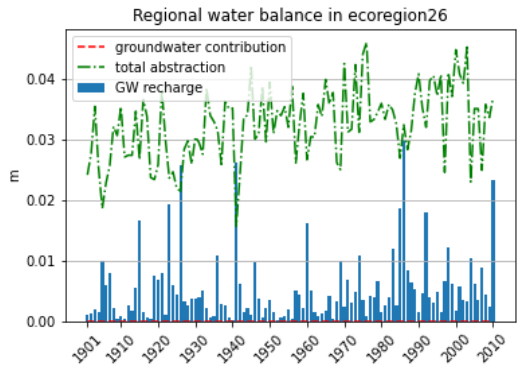

Figure A51 Regional groundwater recharge, baseflow and abstraction (ecoregion 26)

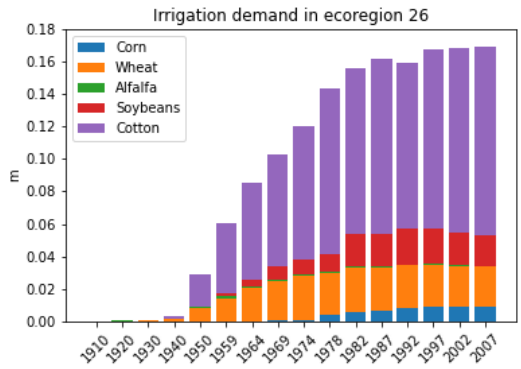

Figure A52 Irrigation demand for the five crops (ecoregion 26)

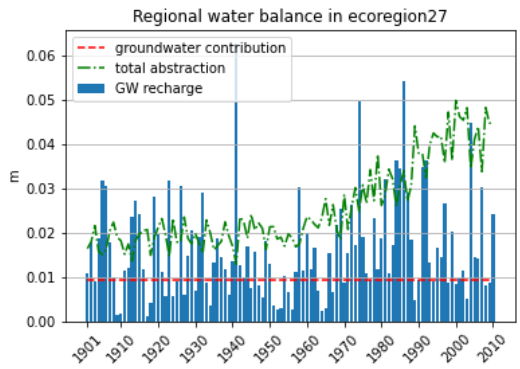

Figure A53 Regional groundwater recharge, baseflow and abstraction (ecoregion 27)

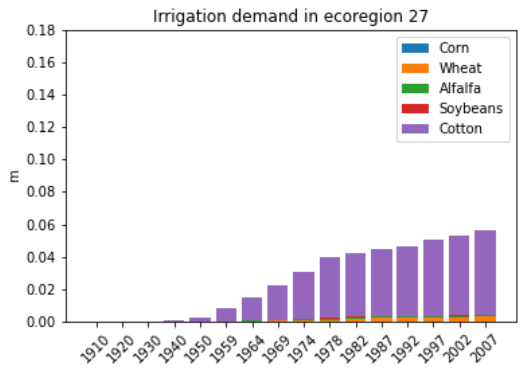

Figure A54 Irrigation demand for the five crops (ecoregion 27)