sustainability

MDPI

Review

High Plains Aquifer–State of Affairs of Irrigated Agriculture and Role of Irrigation in the Sustainability Paradigm

Ali Ajaz [1,*], Sumon Datta [1] and Scott Stoodley [2]

1 Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK 74078, USA; sdatta@okstate.edu
2 Environmental Science Graduate Program, Oklahoma State University, Stillwater, OK 74078, USA; scott.stoodley@okstate.edu
* Correspondence: ali.ajaz@okstate.edu

Received: 7 April 2020; Accepted: 24 April 2020; Published: 5 May 2020

check for updates

Abstract: Groundwater depletion is a serious issue in the southern and central parts of the High Plains Aquifer (HPA), USA. A considerable imbalance exists between the recharge process and groundwater extractions in these areas, which threatens the long-term sustainability of the aquifer. Irrigated agriculture has a major share in the economy, and it requires high pumping rates in regions vulnerable to large groundwater level declines. A literature review has been conducted to understand the state of affairs of irrigated agriculture in the HPA, along with the dynamics of groundwater decline and recharge using statistical and remote-sensing based datasets. Also, three irrigation management and technology-based approaches have been discussed from the perspective of sustainability. The southern and central parts of the HPA consist mostly of non-renewable groundwater formations, and the natural water storage is prone to exhaustion. Moreover, the aforementioned regions have comparatively higher crop water requirement due to the climate, and irrigating crops in these regions puts stringent pressure on the aquifer. The upper threshold of irrigation application efficiency (IAE) is high in the HPA, and could reach up to 95%; however, considerable room for improvement in irrigation water management exists. In general, the practices of irrigation scheduling used in the HPA are conventional and a small proportion of growers use modern methods to decide about irrigation timing. Among numerous ways to promote sustainable groundwater use in the HPA, deficit irrigation, use of soil moisture sensors, and subsurface drip irrigation can be considered as potential ways to attain higher lifespans in susceptible parts of the aquifer.

Keywords: water resources; irrigation scheduling; groundwater depletion; water management; sustainability; remote sensing; Ogallala aquifer

1. Introduction

The High Plains Aquifer (HPA) in the United States (US), also known as Ogallala Aquifer, is spread over an area of 450,658 km^2. Being one of the world's largest aquifers, it serves as the primary source of water for millions of people living in Texas, Oklahoma, Kansas, New Mexico, Nebraska, Colorado, Wyoming, and South Dakota [1]. The economy of the aforementioned states relies heavily on agriculture, and almost 60% of their agriculture-related sales rely on the water supplies from the HPA [2]. Irrigated agriculture consists almost 23% of the total area situated above this colossal groundwater formation, which makes agriculture the largest consumer among the sectors benefiting from the aquifer [3,4] (Figure 1). Almost a quarter of net agricultural water supplies in the US are dependent on the HPA, and in terms of irrigated crop production, 20 percent of the national corn, wheat, and cotton harvest originates from this aquifer [5,6].

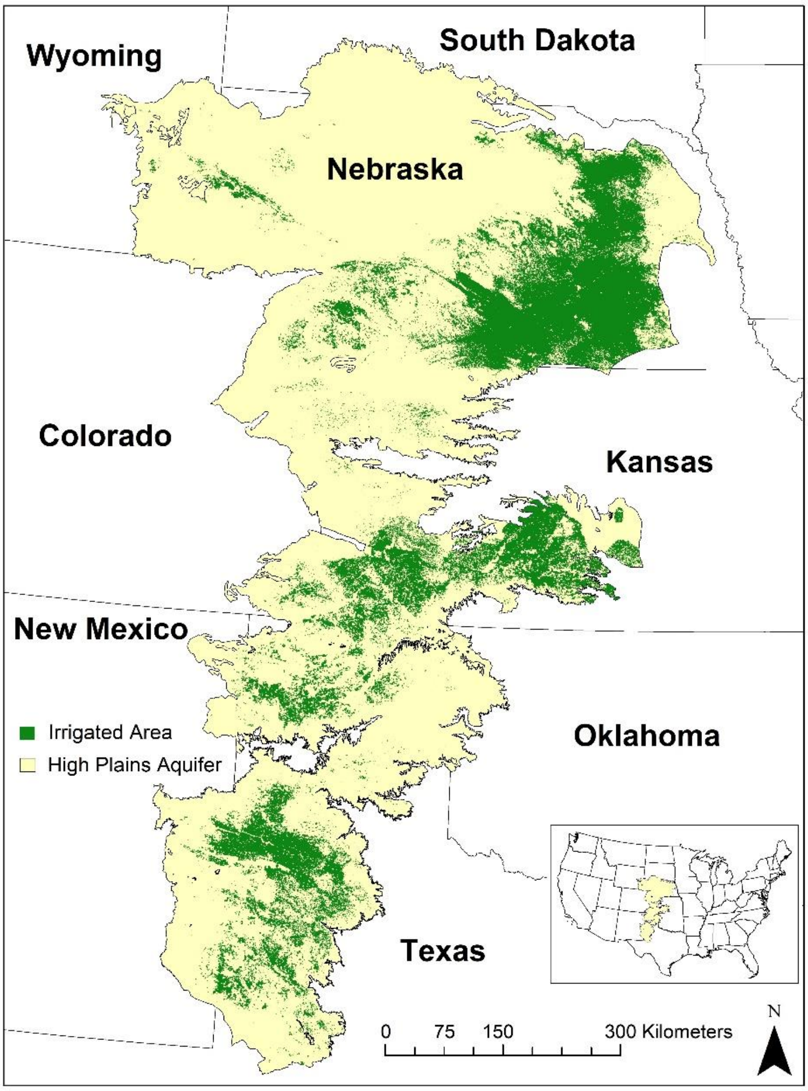

Figure 1. The spread of irrigated areas over the High Plains Aquifer (HPA) in the United States (Source: irrigated area raster data by Salmon et al. [3]; Pixel size 500 m).

Large-scale groundwater extraction in the HPA was made possible due to the availability of improved and low-cost pumping technology following World War II, when, in order to mitigate the impacts of recurring droughts (between the 1930s and 1950s), the farmers increased their reliance on aquifer water [7,8]. In addition, the introduction of a relatively less labor-intensive and high-area coverage irrigation application method (center-pivot irrigation) in 1952 triggered a rapid growth of irrigated agriculture in the region, boosting the groundwater use. According to the Irrigation and Water Management Survey [9], the net groundwater extractions for irrigation in eight beneficiary states of the HPA were 17 km^3 during 2017 with pumping capacity ranging from 48 m^3 h^{-1} to 160 m^3 h^{-1}. It is important to note here that average recharge rate of the HPA, which is as low as <5 mm year^{-1} in the most vulnerable areas of the aquifer [10], is not adequate to cope with the existing pumping rates [6]. This scenario has caused continuous declines in the depth to water in most of the areas where growers are required to practice intensive irrigated farming [11]. The overall decrease in depth to water is approximately 71 m, and it translates into a reduction in saturated thickness ranging between 10% and 50% on a spatial basis, which occurred from 1950 to 2015 [12]. Based on these facts, a decline of 24% in the irrigated land in the HPA has been projected by the year 2100 [13], which can be alarming for the region's economy.

Over-drafting is the most crucial issue challenging the sustainability of the HPA [14]. Alley et al. [15] described the sustainability of the groundwater resources as a well-planned utilization and development of the aquifer, ensuring the indefinite or long-term availability of water. Irrigation holds a pivotal position in the sustainability debate of the HPA since it is the largest consumer of water in the region. However, a comprehensive and integrated groundwater management encompassing the irrigation water use by and large lacks, which undermines the sustainability of the HPA [16]. The economic needs of the region play an important role in the overexploitation of the HPA. To meet the market demand, the farmers are required to grow water-intensive crops [17,18]. Furthermore, the continuous production of irrigated energy-crops to feed the biofuel sector brings additional challenges for effectively managing water resources in the long term [19,20].

Undoubtedly, irrigation acts as a lifeline for the farming sector in the HPA, ensuring livelihoods by protecting against recurrent droughts, and providing better yields than dryland farming. Therefore, understanding the bigger picture of irrigated agriculture in the context of sustainability and the potential role of technology and management interventions to extend the life of the exhaustible parts of the aquifer is imperative. The main objective of this paper was to look into the sustainability paradigm of the HPA with respect to the irrigation sector. The sub-objectives were (i) to review and describe the current state of affairs of irrigated agriculture in the HPA; (ii) to analyze the spatial variation in groundwater recharge, decline, and soil moisture in the HPA (iii) to discuss three pragmatic solutions based on irrigation management for promoting the long-term sustainability of the aquifer. This study would contribute to the development of future policies related to irrigated agriculture and ground water management in the HPA region. Also, the discussion related to irrigation management and technology would help extension workers assimilate the water conservation strategies in the context of sustainability.

The present work is organized as follows: Section 2 explains the general attributes of the HPA, which are followed by the state of affairs of irrigated agriculture in the HPA with focus on crop production and water use, irrigation application efficiency, and irrigation scheduling. In Section 3, overall sustainability paradigm of the HPA has been discussed with respect to groundwater recharge and decline, and remote sensing-based soil moisture variability. Section 4 focuses on the irrigation management and use of modern technology to promote sustainability as well as it provides discussion on some of the adaptation challenges. Section 5 carries the conclusion, and it highlights the importance of water conservation strategies to increase the life of the HPA's regions that are vulnerable to rapid groundwater decline.

2. High Plains Aquifer: The Attributes

It is important to understand the topography, landscape, climate, and surface water availability in the regions lying above the aquifer in order to gain insight into the sustainability of the groundwater resources. Based on its hydrogeological boundaries, the HPA has been divided into three regions, namely the northern, central, and southern regions [17] (Figure 2). The highest elevation in the landscape is approximately 2255 m in the northwestern regions, whereas the low-lying areas in the east have an elevation of around 304 m. The topography of the region is either gentle slopes or flat plains. There are sand dunes sited within the aquifer boundaries and the largest ones are located in Nebraska. These sand dunes are covered with grass and they significantly contribute to the aquifer recharge process [21]. In addition, the short-lived shallow natural lakes, known as playas, are also part of the aquifer landscape. They collect the runoff in the natural land depressions and play their role in the recharge of Ogallala Aquifer [22].

Figure 2. Regions in the High Plains Aquifer.

The climate of the HPA region is continental, with hot summers in the south and extreme winters in the north [23]. The average temperature between the year 1988 and 2017 ranged from 5 °C to 18.4 °C (Figure 3a). Moreover, the precipitation gradient is higher in the east in comparison to the western parts, and the annual average precipitation ranges between 254 and 730 mm (Figure 3b). The northern regions of the HPA have a higher number of streams than the southern parts. Two major rivers, Canadian and Arkansas, flow through the central regions. Most of the streams and rivers that drain the High Plains region have control structures and are channelized in order to utilize water for domestic and agriculture purposes [24].

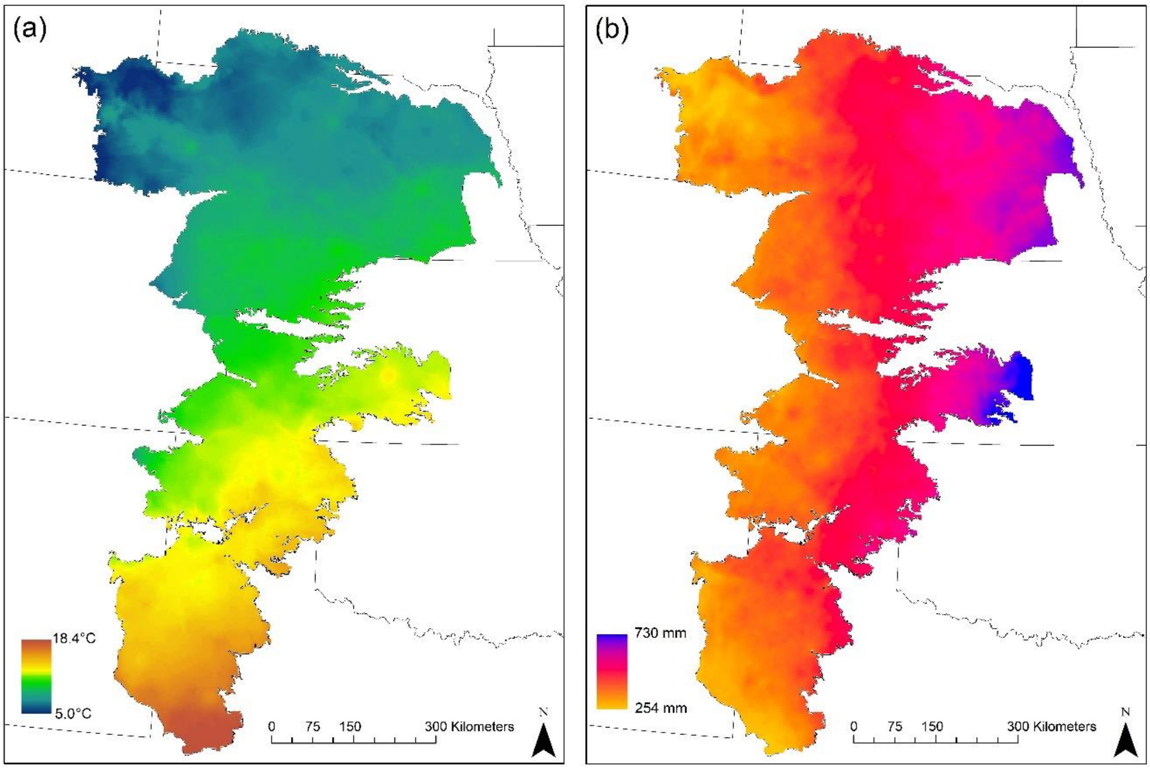

Figure 3. (**a**) Long-term average temperature 1988–2017 (**b**) Long-term average precipitation 1988–2017 (PRISM Climate Group [25]).

2.1. Agriculture and Irrigation in the High Plains Aquifer

2.1.1. Crop Production and Water Use

The main crops grown in the Ogallala Aquifer region are alfalfa (Medicago sativa), corn (Zea mays), cotton (Gossypium hirsutum), soybean (Glycine max), winter wheat (Triticum aestivum), and sorghum (Sorghum bicolor) (Figure 4a). Altogether, irrigation practices to fulfill the crop water needs have an almost 88% share in the total withdrawals from the HPA [26]. The overall irrigation water requirement varies with respect to crop types and regional climate (Figure 5). Water demand for these crops could even go higher in case of extremely dry weather cycles such as droughts [27]. Following Nebraska with the largest cropped area and ample groundwater availability in the northern HPA, significant area is irrigated in the southern and central regions i.e., Texas, Oklahoma, and Kansas. These regions have a long history of recurring droughts, and the potential evapotranspiration (PET) could go considerably higher during dry years such as 2013 (Figure 4b). Irrigating crops in these regions put stringent pressure on the aquifer, and repercussions could occur in the form of considerably large annual depletions, which could go as high as 8.25 km^3 with about more than 70% contribution from the aforementioned states in southern and central regions [28].

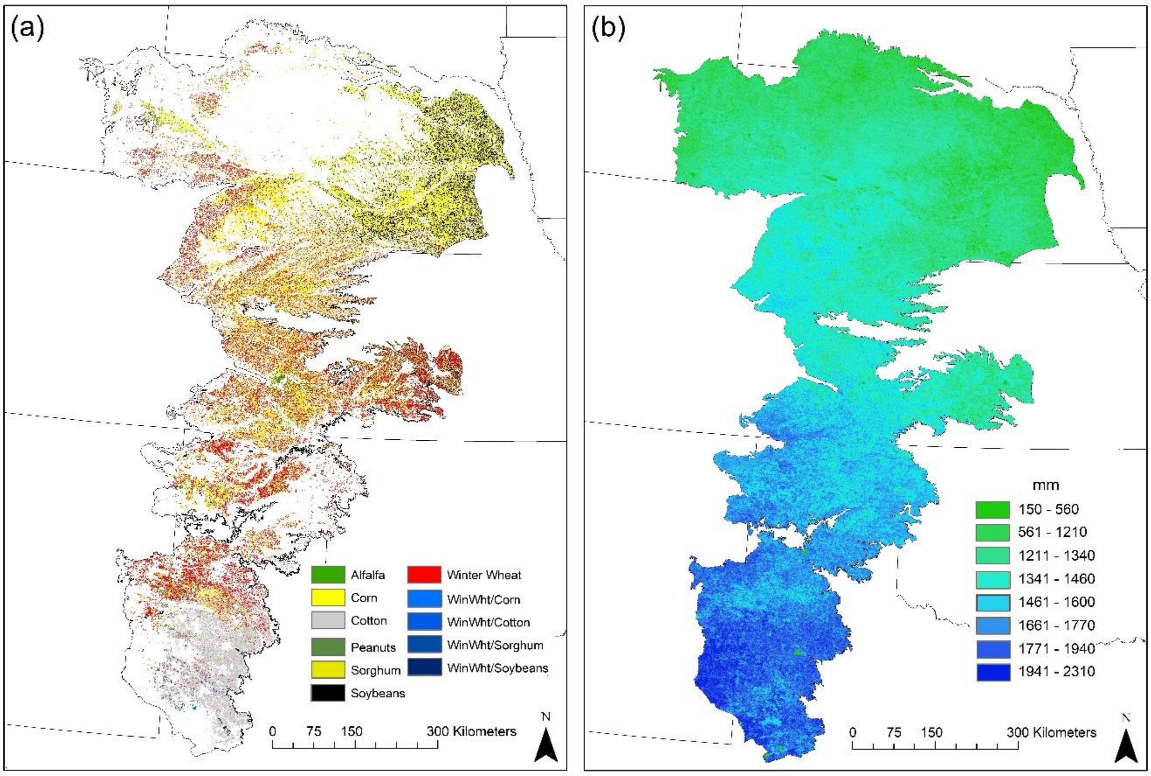

Figure 4. (**a**) Croplands in the High Plains Aquifer (HPA) during the year 2013, 30 m; Source: Cropland Data Layer, National Agricultural Statistical Service, US Department of Agriculture (USDA) (**b**) Cumulative potential evapotranspiration (PET) map for the year 2013; Source: MOD16A2.006, spatial resolution: 500 m, temporal resolution: eight days.

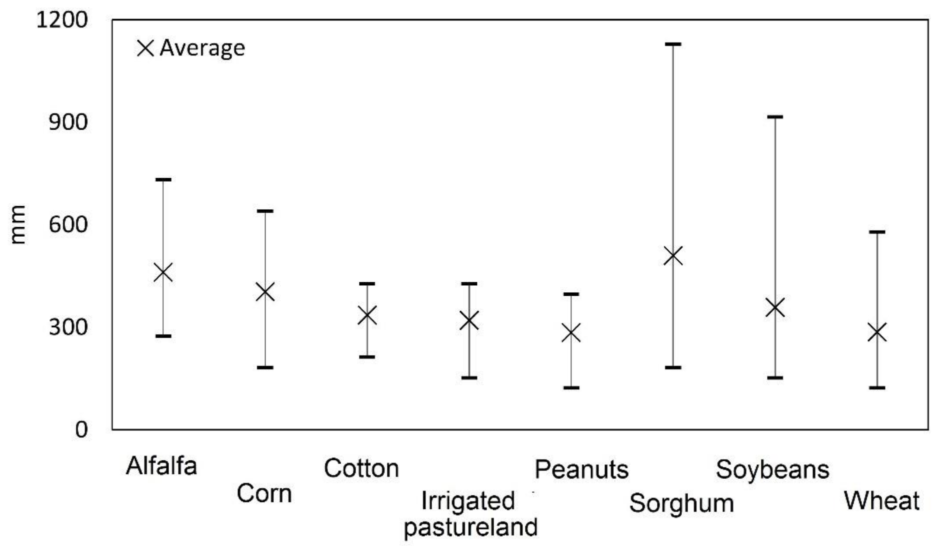

Figure 5. Maximum, minimum, and average irrigation water applied (mm) in the High Plains Aquifer region's states; Source: Irrigation and Water Management Survey [9].

2.1.2. Irrigation Application Efficiency

Irrigation application efficiency (IAE) can be defined as a function of quantity of water emitted from a system that is being stored in the root zone for crop water uptake [29]. The conventional gravity-based irrigation techniques usually have lower efficiencies that range from 30 to 62% [30]. Sprinkler irrigation systems, which include center-pivot, linear, and solid set systems, have comparatively higher application efficiencies at farm level ranging between 70 and 90% [31]. Drip irrigation and micro sprinklers' efficiencies go up to 85%. In the case of the Ogallala Aquifer region, low-energy precision application (LEPA) and sub-surface drip irrigation (SDI) have pushed the upper threshold of IAE up to 95% [32]. The magnitude of the irrigation-related water withdrawals can be associated with the efficiency of the irrigation systems. Ideally, the net water withdrawals would decrease as irrigation systems become more efficient [33]. However, the increase in efficiency may also result in the growth of irrigated area as more water is available to irrigate extra land [34]. For example, 20 to 25% additional land can be irrigated using center-pivot sprinklers in comparison with gravity-based furrow irrigation [32]. Aistrup et al. [14] and Upendram and Peterson [35] discussed the increase of irrigated area in the HPA region resulting from surplus water availability due to water conservation practices, and found that climatic and economic factors (droughts, net returns on irrigated land) mainly govern the expansion.

2.1.3. Irrigation Scheduling

Though improving the IAE can save a significant amount of water in irrigated agriculture, precise irrigation scheduling further complements the efforts to develop a path towards the sustainable use of water resources. Irrigation scheduling can be defined as the optimization of the crop water supply schedule in order to maintain the root zone at a non-stress water content [36]. Irrigation scheduling is feasible when there is an adequate or nearly adequate water supply available throughout the cropping period. Nevertheless, for limited water supply, the irrigation scheduling is further optimized for saving the plants from water stress during highly sensitive periods of crop growth. There are a number of methods to make irrigation-related decisions. According to USDA [9], among all the farms participating in the Irrigation and Water Management Survey from the eight states harnessing the water from the HPA, about 75% and 40% used traditional irrigation scheduling methods such as the condition of crop and feel of soil, respectively. Approximately 10% of farms used irrigation scheduling services and daily crop-evapotranspiration reports, whereas 11.5% relied on modern soil moisture sensors to estimate the root-zone water availability. Furthermore, almost 7% of farms followed their neighbors to decide whether they should irrigate or not.

The trend among farmers to decide about irrigation timing shows that conventional methods dominate the domain of irrigation scheduling in the HPA, which eventually leads towards the excessive application of water [37]. This also points towards the potential for water savings in the region by updating the traditional ways for scheduling the irrigation; however, such initiative needs to be backed with firm support from the public sector. One example of such initiative is Ogallala Aquifer Program (OAP), which is a 'research-education consortium' working for improved water management for helping the farmers and growers in Kansas and Texas regions of the HPA to save water. Brauer et al. [38] found that under the OAP's water conservation programs, a 15% reduction in irrigation water application was noted in a decade's time for those farmers who scheduled their irrigation using evapotranspiration (ET); saving almost $200 million in terms of production cost. Water Technology Farms in Kansas are another example of partnership between the public and private sector to encourage water conservation in the HPA, where farmers extend their help demonstrating the modern agricultural water management practices (e.g., ET-based irrigation scheduling tools, etc.) [39]. Such programs also highlight the importance of a collaborative approach needed to promote sustainable water use in the HPA.

Moving forward, it is important to understand the hydrological regime of the aquifer to point out the regions facing severe challenges in term of sustainability [15], since this could help the stakeholders and policy makers to strategize at regional scale.

3. Sustainability in High Plains Aquifer–Northern, Central and Southern Regions

3.1. Groundwater Recharge and Decline

Significant variability exists in the type of groundwater storage in different regions of the HPA. On one hand, the northern regions of the aquifer consist of renewable groundwater formations, which virtually cannot be fully depleted [18] as they receive continuous recharge through the hydrological cycle (Figure 6a). On the other hand, the central and southern parts of the aquifer are the huge reservoirs of the fossil groundwater that are limited by the shortfall of recharge in relation to extraction by pumping, and are thus exhaustible (Figure 6b). In addition, the net storage of the groundwater also varies spatially, which was 2882, 735, and 296 km^3, according to the 2007 estimates, in northern, central and southern regions of the aquifer, respectively [40]. Furthermore, the annual average modeled recharge and depletion in the aforementioned regions was 9.96; 1.07, 1.28; 2.48, and 0.77; 2.12 km^3, respectively. Subsequently, the lifespans of the central and southern region are estimated as 238 and 81 years, respectively, counted from the year 2007, whereas the northern regions of the aquifers are renewable and have a theoretically infinite lifespan.

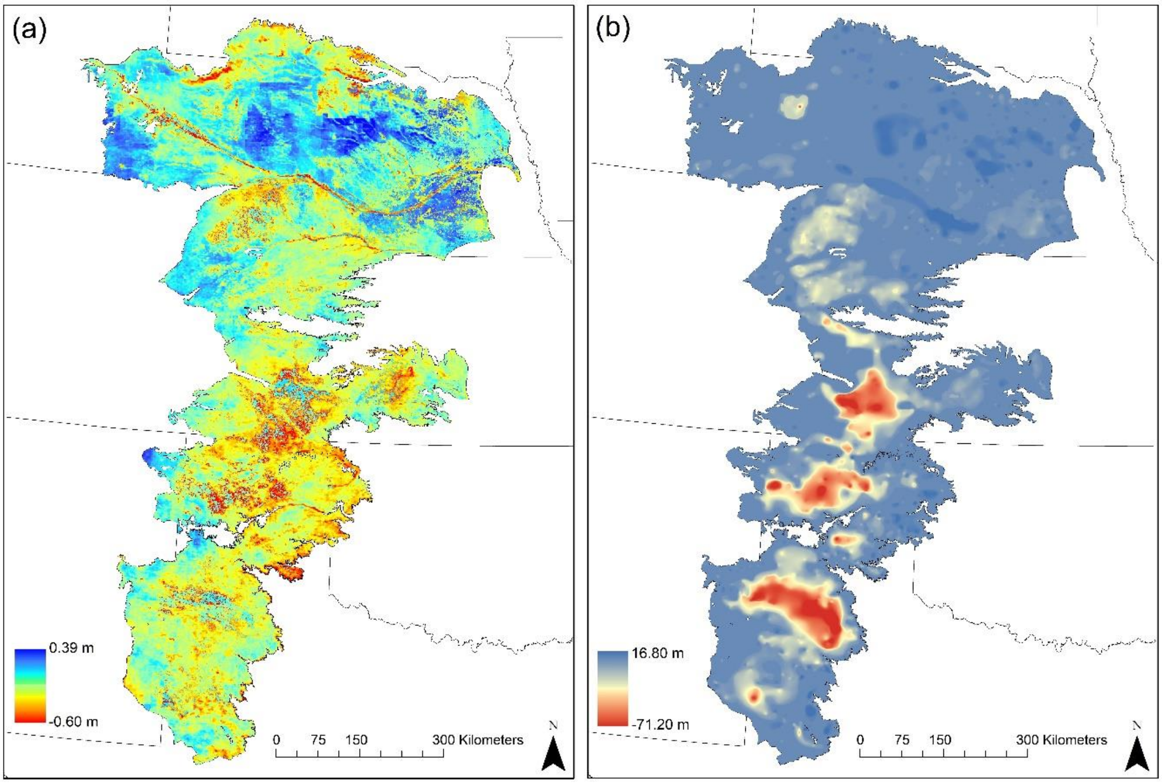

Figure 6. (**a**) Recharge across the HPA from 2000–2009; (**b**) decline in depth to water across the High Plains Aquifer (HPA) from 1950–2015 (Raster Data Source: Houston et al. [5]).

The spatial variation in the extractions and recharge clearly shows that southern parts of the HPA are the ones that face imminent sustainability-related challenges, and they are followed by the central parts. In both of these regions, the depletion in the depth to water has been rapid since 1950, where decline trends are virtually linear in the case of central High Plains, and the southern parts of the aquifer have faced almost exponential declines [41]. This situation also puts a question mark on the sustainability of groundwater-fed agriculture in these regions.

From the sustainability perspective, these groundwater depletions are occurring because the water extractions are comparatively larger than the recharge. In natural conditions, the groundwater system maintains its storage by balancing between the recharge and the discharge towards the streams and base flow of the rivers. However, when intensive pumping operations are performed, the water is not only harnessed from the storage in the system but also from the components that contribute to natural discharge. Ironically, in large irrigated areas, the recharge is usually increased because of the deep infiltration of irrigation applications; however, for net recharge calculations, only the percolation of irrigation water extracted from surface water resources can be counted as recharge contributing to the storage [18], as the recharge that comes from the percolation of the same-source groundwater can simply be considered as a part of the continuous cycle. Moreover, the scale of water extraction also varies spatially with respect to crop type and evaporative demand (Figure 4b). For example, a study comparing the annual irrigation water pumped in Nebraska and Texas substantiated almost 30% more water extractions in the latter state [18].

3.2. Soil Moisture Variability

Soil moisture estimates can provide additional insight into the regional comparison of the HPA in terms of groundwater use and sustainability. Satellite imagery offers datasets of soil moisture with high temporal resolution (TR) and coarse spatial resolution (SR), which is suitable for large-scale spatial studies. For this purpose, monthly normalized soil moisture (NSM) was estimated using the approach followed by Dutra et al. [42]. Subsurface soil moisture data was downloaded for northern, central, and southern regions of the HPA from the National Aeronautics and Space Administration (NASA)–USDA Global Soil Moisture database [43] using Google Earth Engine from 2010 and 2019. This dataset is produced by integrating the remote sensing-based Soil Moisture Ocean Salinity (SMOS) level 2 soil moisture observations (SR $0.25° \times 0.25°$, TR 3-days) and a modified two-layer Palmer model. Since the top layer of soil is likely to have higher fluctuations in soil water content mainly due to evaporation, the surface soil moisture was not included in the estimations. Additionally, groundwater storage percentiles that are estimated by Beaudoing et al. [44] based on GRACE Data Assimilation L4 (SR 0.125°, TR 7-days) V2.0 were downloaded from 2010 to 2019 using Giovanni V4.33.

The monthly timeline of NSM showed that all three regions of the HPA experienced long- and short-term droughts during the 10-year period, with variations in magnitude and occurrence (Figure 7a–c). Almost year-long drought episodes occurring in northern and southern regions of the HPA during 2012–2013 and 2010–2011, respectively, point towards the additional requirement of irrigation to offset drought induced crop water stress. The implications of high groundwater use, however, can be spatially different. The groundwater storage percentile timeline showed that southern parts of the HPA had the highest impact from extended drought events, followed by central regions, whereas northern regions evinced lesser impact (Figure 7d). Provided that the groundwater of southern high plains is exhaustible, such drought events could accelerate the depth to water declines, and the same applies to central regions. Whereas, for northern regions, the amount of water consumed during the dry growing seasons can be easily recovered in wet years due to higher recharge rates. Besides this, the drought timing can be also viewed as a factor challenging the aquifer's vulnerability in central and southern regions of the HPA. For example, a severe drought event that started in late 2017 in the aforementioned regions prevailed till July 2018. The drought coincided with the corn-growing season in the HPA (spring to fall), and the higher consumption of groundwater for irrigating the crops, in comparison to non-drought periods, was evident, with considerable drops in groundwater storage percentiles (Figure 7d).

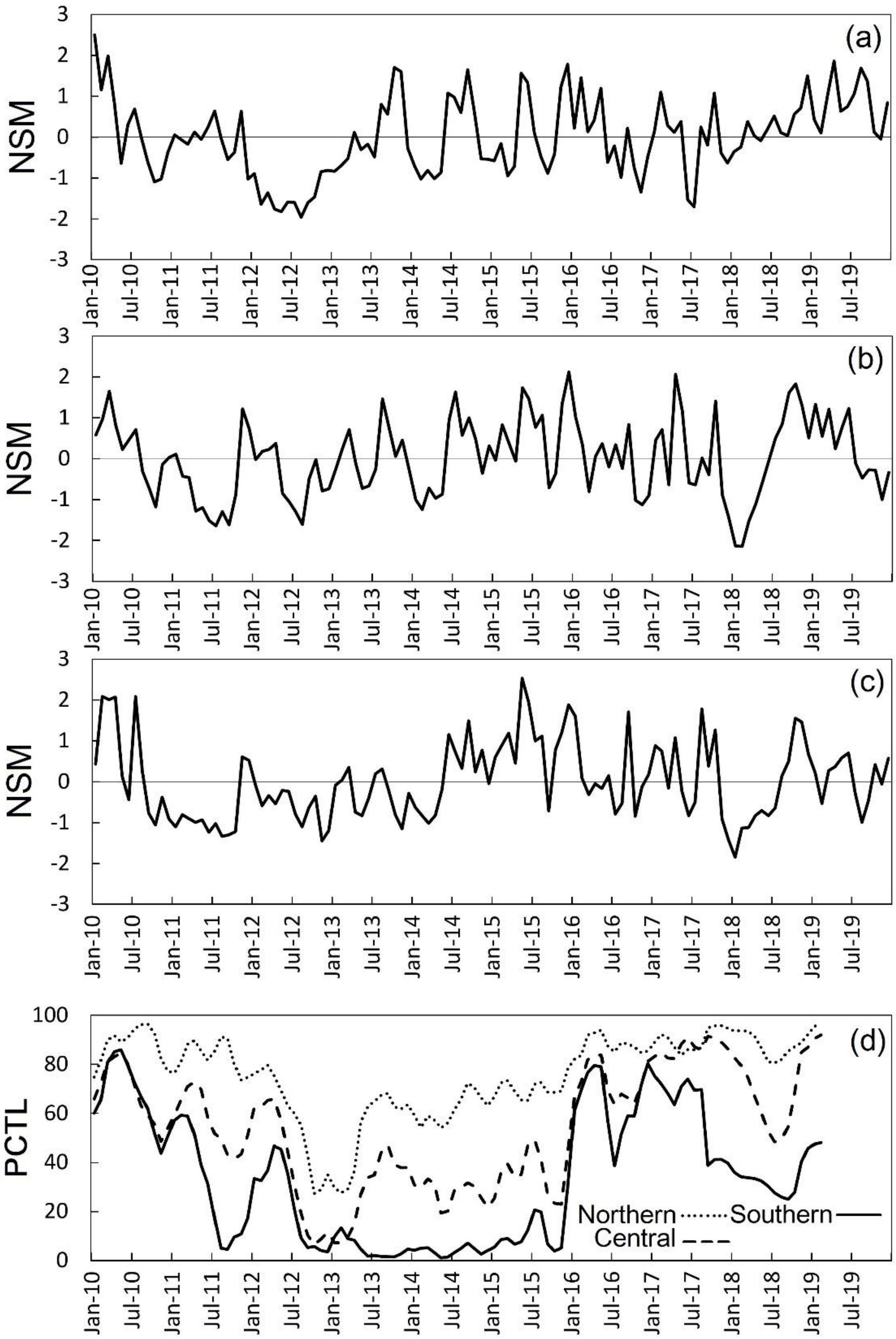

Figure 7. Monthly normalized soil moisture timeline of (**a**) northern high plains (**b**) central high plains (**c**) southern high plains. (**d**) Monthly groundwater storage percentile (PCTL).

4. How Can Irrigation Contribute towards Achieving Sustainability?

Multiple domains overlap each other in the sustainability debate of the HPA including technology, environment, economics, legislation, social awareness, etc. Among these, improved water management and advanced water application technologies could have a significant role in promoting sustainable irrigation practices in the region. In this regard, deficit irrigation, soil moisture sensors, and sub-surface drip irrigation are some of the potential ways to reduce the load of anthropogenic activities.

4.1. Deficit Irrigation

Deficit irrigation is the method of applying a certain amount of water to crop's root zone, which is marginally below its actual water requirement for improving the water productivity with a nominal impact on the yield [45]. The concept of deficit irrigation is quite straightforward, as the crop is not allowed to achieve its potential evapotranspiration with planned cut-offs in the water delivery schedules and in turn, the water is saved [46]. This unused water can be either used for some other purposes or could be left in the reservoir for future use. Deficit irrigation is considered as one of the significant management practices to reduce water withdrawals from finite water resources such as fossil water aquifers. It can also help in sustaining the irrigated agriculture in regions with declined pumping capacities [47]. In addition, during the drought periods when the pumping limits are enforced, deficit irrigation can be adopted as a practical solution to continue the farming operations.

English and Raja [48] described three main benefits of the deficit irrigation that include improved irrigation efficiency, reduced cost of irrigation, and the opportunity cost of the water. Undoubtedly, all of these three advantages can directly serve the sustainability of the HPA. Several studies have been conducted in the High Plains regions to validate the feasibility of deficit irrigation and potential water savings. Rudnick et al. [49] reviewed numerous research projects on the deficit irrigation for corn in the HPA beneficiary states. The studies showed that corn's yield was most sensitive to water shortages during the milking and dough stages of the growth. Therefore, the provision of required evapotranspiration at sensitive growth stages while saving water in other growth periods may result a minimum reduction in the desired yields, and such practices can lead towards a saving of up to 20% of irrigation water [49].

Likewise, there is a significant prospective of water saving by using the deficit irrigation approach in cotton farming [46]. Cotton is mostly grown in the southern parts of the aquifer (Texas and Oklahoma), which are already under stress due to extensive water extractions and limited recharge. Howell et al. [50] studied the response of irrigated cotton to limited water supply in Texas High Plains and found that there was 10% decline in the yields by providing 80% of crop water requirement. Bell et al. [51] managed the deficit irrigation for sorghum around critical growth stages in Texas, and found an average reduction of 41% in irrigation water with 33% decline in the yield. Variable plant available water based irrigation thresholds were explored for simulating the impact of deficit irrigation on soybean in Texas High Plains by Sharda et al. [52], and thresholds of 50% and 65% provided reasonable yields in comparison to higher thresholds for initiating irrigation.

Apparently, deficit irrigation challenges the rationale of 'use it or lose it' by considering the unused water as a saved resource for future use [53]; a much-required rumination for the region. However, the adaptation process requires several adjustments in the multiple domains of farming sector, e.g., agronomic practices, crop genetics, growers' capacity, incentives, water-use policies, subsidies, crop insurance, etc. In addition to this, information on root zone water availability is crucial to growers for making educated decisions related to deficit irrigation, which leads to soil moisture sensing.

4.2. Soil Moisture Sensing

Soil moisture sensors measure the amount of water present in soil at single or multiple depths. These sensors provide a unique opportunity for farmers to have real-time information about the presence of moisture in their fields without disturbing the soil [54]. In general, soil moisture sensing devices require minimum maintenance compared to traditional soil moisture measurement and monitoring techniques, and procuring them does not cost a fortune because of a considerable decline in prices in the past few years. From the water-saving viewpoint, a soil moisture sensor brings a great opportunity for the growers to implement precise irrigation and avoid unnecessary application of water to their fields [55]. One of the significant potential advantages of using soil moisture sensors in irrigated agriculture is the optimum scheduling of irrigation activities for fulfilling crop water requirements [56]. As mentioned earlier, only a small proportion of farms in the beneficiary states of the HPA use efficient methods (e.g., crop evapotranspiration reports, sensors) to make informed decisions regarding the irrigation scheduling. This implies that there are considerable prospects for water conservation in the HPA farming sector by improving irrigation scheduling practices using soil moisture sensors [57]. Furthermore, the farmers who are already experiencing decreased well capacities in the HPA [58] can better strategize their irrigation management by using soil moisture sensors [59].

The approach of using sensors to save irrigation water is simply based on the idea of knowing the root zone water availability and optimization of crop water supply according to plants' needs, by restricting the unnecessary deep percolation [60]. Since conventional irrigation scheduling approaches do not incorporate the moisture availability in the soil layers, there is a high chance of overwatering the fields. This application of extra water results in the infiltration into deeper layers of the soil that are not contributing to the root-water uptake.

The soil moisture sensor technology fits as one of the keys which are required for a pragmatic solution to the HPA's sustainability issues. Considerable reduction in water use for irrigation during the growing season has been evidenced in the ground-water management districts in Kansas that use soil moisture sensors for scheduling their crop water supplies [61]. Similarly, higher crop water productivity has been anticipated for irrigated agriculture in Texas by using soil water sensors. Also, a monetary benefit of almost $10 million in terms of cost saving has been predicted in the result of a complete implementation of sensing technologies for irrigation scheduling all over Texas [62]. Moreover, considering the information from soil moisture sensors for irrigation scheduling plans has been recommended for irrigated agriculture in Colorado [63]. Clearly, by knowing about the moisture content in the root zone, the irrigators would have a better understanding of the crop water use trends and soil water storage, and they would be able to project the number of future water applications with higher accuracy. According to Nebraska Corn Board [64], growers who have installed the soil moisture sensors at multiple depths in their farms, are confident regarding their irrigation timing decisions, thus they save water by making necessary adjustments to their irrigation schedules. Similarly, the extractions from the vulnerable regions of the HPA could be reduced following this approach, hence extending the aquifer's life. Additionally, the availability of sensors to accurately manage the root zone water also provides confidence to farmers for adopting precise water application technologies such as SDI.

4.3. Sub-Surface Drip Irrigation

SDI is the method of applying water to the crops by using drip tubes or tapes, which are usually buried at a depth ranging from 0.2 to 0.7 m in the root zone depending on multiple factors, e.g., soil type, crop, climate [65]. The SDI systems operate at a pressure range approximately equal to low-pressure center-pivot irrigation systems (<25 m of head) [66]. Since the water is applied directly at the root zone, the chances of water loss due to evaporation and low application uniformity because of wind are negligible. Subsequently, the SDI promotes higher water use efficiency for the crops as relatively less water is required for the irrigation operations, which can reduce the water usage up to 45% on average, with an application efficiency up to 97% [67–69]. Besides the water saving benefits, an additional advantage of the SDI systems is their capability to operate under low flow rates that are often caused due to declining well capacities in the HPA [70,71].

Keeping in view the potential benefits of the SDI, this technology can definitely be seen as the future of the irrigation for the regions of the HPA that are vulnerable to higher declines in depth to water and low pumping capacities [32]. Several studies have been conducted with the purpose of assessing the prospects of shifting some of the cash crops of the region (i.e., corn and cotton) to SDI system. The efficacy of SDI was tested for corn in Nebraska and the results showed that yield-based irrigation water use efficiency was almost three times greater in comparison to treatments with 10% higher irrigation application [72]. A Texas-based study for comparing SDI and mid-elevation spray application (MESA) technique for corn crop demonstrated that SDI was able to decrease the irrigation water application by 147 mm along with a 20% increase in yield [73]. Field experiments conducted for cotton under different irrigation systems in North Texas high plains evidenced the effectiveness of SDI for low capacity irrigation systems [67].

Though the SDI is not a new technology for the farming community of the HPA [68], shifting from the conventional irrigation systems (furrow, center-pivot) to the relatively expensive SDI would require an incentivized transition framework such as cost-sharing arrangements [74] along with a comprehensive capacity development and technological support from the government agencies, e.g., the Ogallala Aquifer Initiative [75] and the Regional Conservation Partnership Program [76]. Another factor that slows down the adoption of SDI is that more than half of farmland in the US is rented [77], and the landlords (80% not actively involved in farming) are to make this decision. Also, the need of global positioning system-guided tractors for planting the crop precisely according to the driplines' positions could add additional input cost [78].

It is important to note here that the combination of management and technological approaches (i.e., deficit irrigation and SDI, respectively) can bring supplementary benefits in terms of water savings and long-term use of the exhaustible parts of the aquifer. Therefore, it is vital from the sustainability perspective that continuous and thorough research is carried out for finding the feasible options of reduced agricultural water usage coupled with SDI; aiming to serve the future needs of the groundwater management.

5. Conclusions

Groundwater depletion is a critical issue in the High Plains Aquifer, especially in the southern and central regions that lie on non-renewable groundwater formations with approximate life spans of 81 and 238 years, respectively. A significant imbalance exists between the recharge and irrigation-dominated groundwater extractions in the southern and central HPA, which restricts the long-term sustainability/availability of the aquifer. This study focused on the irrigation sector in the HPA to review its state of affairs and discuss some of the potential strategies to improve the long-term use of the aquifer. Irrigated agriculture is the largest consumer of water in the HPA, and with a considerable share in the economy it requires higher pumping rates that augment the declines in depth to water. Crop production-related water use is high in the vulnerable parts of the HPA mostly because of higher evaporative demand. Almost 75% of the farms, in the beneficiary states of the HPA, lack the modern sensing equipment to decide when to irrigate their crops; instead, conventional methods are used for irrigation scheduling (e.g., condition of crop, feel of soil)–subsequently leading to excess application of irrigation water causing over-pumping from irrigation wells. For interlinking the debate of sustainability and potential water saving in the irrigation sector, three approaches based on water management and technological advancement were discussed. These approaches comprise (a) implementation of deficit irrigation approach to reduce the overall volume of water that is applied to the crops, (b) use of soil moisture sensors for optimizing the decisions pertaining to irrigation scheduling, and (c) shifting to sub-surface drip irrigation for minimizing the evaporation losses, and to enhance the viability of low-discharge wells. Though the southern and central parts of the HPA cannot be considered as an everlasting source of water to feed the irrigated agriculture of the region, the abovementioned approaches still could help increase the useful life of the aquifer–keeping it beneficial for more upcoming generations of growers. Policymakers could refer to this study while devising future policies related to irrigated agriculture and groundwater use in the HPA region. Also, the extension workers could assimilate the water-saving strategies in the context of sustainability by looking at the bigger picture. Future studies may focus on the integrated water-saving approaches by combining management and technological advancements to assist growers in harnessing the aquifer for prolonged periods.

Author Contributions: Conceptualization, A.A. and S.S.; methodology, A.A. and S.D.; software, A.A.; formal analysis, A.A.; investigation, A.A.; resources, S.S.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A., S.D.; visualization, A.A.; supervision, S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This publication is based on the term project of Issues in Environmental Sustainability class offered by the Environmental Science Graduate Program, Oklahoma State University.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. McGuire, V. *Changes in Water Levels and Storage in the High Plains Aquifer, Predevelopment to 2005*; USA Geological Survey: Reston, VA, USA, 2007; pp. 1–2. Available online: https://pubs.er.usgs.gov/publication/fs20073029 (accessed on 12 December 2019).
2. Perrin, R.K.; Fulginiti, L.E.; Garcia, F. Agricultural production from the high plains aquifer is worth over $3 billion per year. In *Cornhusker Economics*; University of Nebraska-Lincoln Extension: Lincoln, NE, USA, 2018; pp. 1–2. Available online: https://agecon.unl.edu/cornhusker-economics/2018/agricultural-production-from-high-plains-aquifer.pdf (accessed on 12 December 2019).
3. Salmon, J.M.; Friedl, M.A.; Frolking, S.; Wisser, D.; Douglas, E.M. Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data. *Int. J. Appl. Earth Obs. Geoinf.* **2015**, *38*, 321–334. [CrossRef]
4. Gollehon, N.; Winston, B. *Groundwater Irrigation and Water Withdrawals: The Ogallala Aquifer Initiative*; USA Department of Agriculture: Washington, DC, USA, 2013; p. 15.
5. Houston, N.A.; Gonzales-Bradford, S.L.; Flynn, A.; Qi, S.; Peterson, S.M.; Stanton, J.; Ryter, D.W.; Sohl, T.L.; Senay, G.B. *Geodatabase Compilation of Hydrogeologic, Remote Sensing, and Water-Budget-Component Data for the High Plains Aquifer, 2011*; USA Geological Survey: Reston, VA, USA, 2013; p. 12.
6. Winter, M.; Foster, C. *Ogallala Aquifer—Lifeblood of the High Plains Part 1: Withdrawals Exceed Recharge*; CoBank Knowledge Exchange: Denver, CO, USA, 2014; Available online: https://aquadoc.typepad.com/files/ke_ogallalaaquifer_reportpt1-oct2014.pdf (accessed on 7 December 2019).
7. Hornbeck, R.; Keskin, P. The historically evolving impact of the Ogallala aquifer: Agricultural adaptation to groundwater and drought. *Am. Econ. J. Appl. Econ.* **2014**, *6*, 190–219. [CrossRef]
8. Baumhardt, R.L. *Dust Bowl Era*; Stewart, B.A., Howell, T.A., Eds.; Marcel-Dekker, Inc.: New York, NY, USA, 2003; pp. 187–191.
9. USDA—U.S. Department of Agriculture. National Agricultural Statistics Service. Irrigation and Water Management Survey. 2018. (a) Table 4. Estimated Quantity of Water Applied By Source (Ground water from wells); Table 9. Characteristics of Irrigation Wells Used on Farms. (b) Table 36. Field Water Distribution for Selected Crops Harvested in the Open and Irrigated Pastureland (c) Table 23. Methods Used in Deciding When to Irrigate. Available online: https://www.nass.usda.gov/ (accessed on 10 March 2020).
10. Crosbie, R.S.; Scanlon, B.R.; Mpelasoka, F.S.; Reedy, R.C.; Gates, J.B.; Zhang, L. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resour. Res.* **2013**, *49*, 3936–3951. [CrossRef]
11. Kastner, W.; Schild, D.; Spahr, D. *Water-Level Changes in the High Plains Aquifer Underlying Parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas; Predevelopment through Nonirrigation Season 1987–1988*; USA Geological Survey: Reston, VA, USA, 1989; pp. 89–4073.
12. McGuire, V. *Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2015 and 2013–2015*; USA Geological Survey: Reston, VA, USA, 2017; p. 14. [CrossRef]
13. Deines, J.M.; Kendall, A.D.; Crowley, M.A.; Rapp, J.; Cardille, J.A.; Hyndman, D.W. Mapping three decades of annual irrigation across the US High Plains Aquifer using Landsat and Google Earth Engine. *Remote. Sens. Environ.* **2019**, *233*, 111400. [CrossRef]
14. Aistrup, J.A.; Bulatewicz, T.; Kulcsar, L.; Peterson, J.M.; Welch, S.M.; Steward, D.R. Conserving the Ogallala Aquifer in southwestern Kansas: From the wells to people, a holistic coupled natural–human model. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 6167–6183. [CrossRef]
15. Alley, W.M.; Reilly, T.; Franke, O.L. *Sustainability of Ground-Water Resources*; USA Geological Survey: Reston, VA, USA, 1999; Volume 1186, p. 86. Available online: https://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf (accessed on 26 December 2019).

16. Schoengold, K.; Brozović, N. The future of groundwater management in the high plains: Evolving institutions, aquifers and regulations. *Environ. Econ. Policy* **2018**, *16*, 47–53. Available online: https://ageconsearch.umn.edu/record/273678/files/7.pdf (accessed on 26 December 2019).
17. Dennehy, K.F.; Litke, D.W.; McMahon, P.B. The High Plains Aquifer, USA: Groundwater development and sustainability. *Geol. Soc. Lond. Spéc. Publ.* **2002**, *193*, 99–119. [CrossRef]
18. Scanlon, B.R.; Faunt, C.C.; Longuevergne, L.; Reedy, R.C.; Alley, W.M.; McGuire, V.L.; McMahon, P.B. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 9320–9325. [CrossRef]
19. Pingali, P.; Raney, T.; Wiebe, K. Biofuels and food security: Missing the point. *Rev. Agric. Econ.* **2008**, *30*, 506–516. [CrossRef]
20. Imhoff, D.; Badaracoo, C. Ethanol. In *The Farm Bill*; Island Press: Washington, DC, USA, 2019; pp. 137–146.
21. Adane, Z.; Zlotnik, V.A.; Rossman, N.R.; Wang, T.; Nasta, P. Sensitivity of potential groundwater recharge to projected climate change scenarios: A site-specific study in the Nebraska sand Hills, USA. *Water* **2019**, *11*, 950. [CrossRef]
22. Gurdak, J.J.; Roe, C.D. *Recharge Rates and Chemistry Beneath Playas of the High Plains Aquifer—A Literature Review and Synthesis*; United States Geological Survey: Denver, CO, USA, 2009. [CrossRef]
23. Stanton, J.; Qi, S.; Ryter, D.W.; Falk, S.E.; Houston, N.A.; Peterson, S.M.; Westenbroek, S.M.; Christenson, S.C. *Selected Approaches to Estimate Water-Budget Components of the High Plains, 1940 through 1949 and 2000 through 2009*; US Geological Survey: Reston, VA, USA, 2011.
24. BoR-Bureau of Reclamation. *Great Plains Region: Billings, Mont., Bureau of Reclamation*; BoR-Bureau of Reclamation: Denver, CO, USA, 2011.
25. *PRISM Climate Group*; Oregon State University: Corvallis, OR, USA, 2017; Available online: http://prism.oregonstate.edu (accessed on 1 January 2020).
26. Hornbeck, R.; Keskin, P. The evolving impact of the Ogallala aquifer: Agricultural adaptation to groundwater and climate. *Science* **2011**, *6*, 190–219. [CrossRef]
27. White, K.D.; Vaddey, S.V.; Hamlet, A.F.; Cohen, S.; Neilsen, D.; Taylor, W. Integrating climate impacts in water resource planning and management. In Proceedings of the 13th International Conference on Cold Regions Engineering, Orono, ME, USA, 23–26 July 2006; pp. 1–11.
28. Steward, D.R.; Allen, A.J. Peak groundwater depletion in the High Plains Aquifer, projections from 1930 to 2110. *Agric. Water Manag.* **2016**, *170*, 36–48. [CrossRef]
29. Rajan, N.; Maas, S.; Kellison, R.; Dollar, M.; Cui, S.; Sharma, S.; Attia, A. Emitter uniformity and application efficiency for centre-pivot irrigation systems. *Irrig. Drain.* **2015**, *64*, 353–361. [CrossRef]
30. Harms, T. *Irrigation System Application Efficiency Values*; Alberta Agriculture: Red Deer, AB, Canada, 2011; Available online: https://open.alberta.ca/ (accessed on 1 January 2020).
31. Howell, T.A. Irrigation efficiency. In *Encyclopedia of Water Science*; Marcel Dekker: New York, NY, USA, 2003; pp. 467–472.
32. Evett, S.R.; Trout, T.J.; Lamm, F.R.; Colaizzi, P.D.; Kranz, W.K.; O'Shaughnessy, S.A. The future of irrigation on the U.S. Great Plains. In Proceedings of the Central Plains Irrigation Conference, Burlington, CO, USA, 25–26 February 2014; Volume 970, p. 565.
33. Cai, X.; Rosegrant, M.W.; Ringler, C. Physical and economic efficiency of water use in the river basin: Implications for efficient water management. *Water Resour. Res.* **2003**, *39*. [CrossRef]
34. Lankford, B. Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. *Agric. Water Manag.* **2012**, *108*, 27–38. [CrossRef]
35. Upendram, S.; Peterson, J.M. Irrigation technology and water conservation in the high plains aquifer region. *J. Contemp. Water Res. Educ.* **2009**, *137*, 40–46. [CrossRef]
36. Jones, H. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Exp. Bot.* **2004**, *55*, 2427–2436. [CrossRef]
37. Dugan, J.T.; McGrath, T.; Zelt, R.B. *Water-Level Changes in the High Plains Aquifer—Predevelopment to 1993*; USA Geological Survey: Reston, VA, USA, 1994; Volume 56, pp. 94–4027.
38. Brauer, D.; Devlin, D.; Wagner, K.; Ballou, M.; Hawkins, D.; Lascano, R. Ogallala aquifer program: A catalyst for research and education to sustain the ogallala aquifer on the southern high plains (2003–2017). *J. Contemp. Water Res. Educ.* **2017**, *162*, 4–17. [CrossRef]

39. KCARE—Kansas Center for Agricultural Resources and the Environment, K.S.U. Letting It All Soak in: Water Technology Farms Lead the Way in Water Conservation. KCARE Research Today. 2017. Available online: http://enewsletters.k-state.edu/kcare/2017/08/31/letting-it-all-soak-in-water-technology-farms-lead-the-way-in-water-conservation/ (accessed on 9 January 2020).
40. Scanlon, B.R.; Reedy, R.; Gates, J.; Gowda, P. Impact of agroecosystems on groundwater resources in the Central High Plains, USA. *Agric. Ecosyst. Environ.* **2010**, *139*, 700–713. [CrossRef]
41. Haacker, E.M.K.; Kendall, A.D.; Hyndman, D.W. Water level declines in the high plains aquifer: Predevelopment to resource senescence. *Ground Water* **2015**, *54*, 231–242. [CrossRef]
42. Dutra, E.; Viterbo, P.; Miranda, P. ERA-40 reanalysis hydrological applications in the characterization of regional drought. *Geophys. Res. Lett.* **2008**, *35*. [CrossRef]
43. Mladenova, I.E.; Bolten, J.; Crow, W.T.; Anderson, M.C.; Hain, C.R.; Johnson, D.M.; Mueller, R. Intercomparison of soil moisture, evaporative stress, and vegetation indices for estimating corn and soybean yields over the U.S. *IEEE J. Sel. Top. Appl. Earth Obs. Remote. Sens.* **2017**, *10*, 1328–1343. [CrossRef]
44. Hiroko, B.; Rodell, M.; Getirana, A.; Li, B. *Groundwater and Soil Moisture Conditions from GRACE Data Assimilation L4 7-Days 0.125 × 0.125 Degree V2.0*; Goddard Earth Sciences Data and Information Services Center (GES DISC): Greenbelt, MD, USA, 2017.
45. FAO—Food and Agriculture Organization of the UN. *Deficit Irrigation Practices*; FAO: Roma, Italy, 2002; Available online: http://www.fao.org/tempref/agl/AGLW/ESPIM/CD-ROM/documents/5K_e.pdf (accessed on 11 January 2020).
46. Fereres, E.; Soriano, M.A. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **2006**, *58*, 147–159. [CrossRef] [PubMed]
47. Rudnick, D.R.; Irmak, S.; West, C.; Chávez, J.; Kisekka, I.; Marek, T.; Schneekloth, J.; McCallister, D.M.; Sharma, V.; Djaman, K.; et al. Deficit irrigation management of maize in the high plains aquifer region: A review. *JAWRA J. Am. Water Resour. Assoc.* **2019**, *55*, 38–55. [CrossRef]
48. English, M.; Raja, S.N. Perspectives on deficit irrigation. *Agric. Water Manag.* **1996**, *32*, 1–14. [CrossRef]
49. Rudnick, D.; Irmak, S.; Schneekloth, J.P.; Schipanski, M.; Kisekka, I.; Schlegel, A.J.; Porter, D.; Ray, C.; Aguilar, J.; Rogers, D.; et al. Deficit irrigation management of corn in the high plains: A review. In Proceedings of the 29th Annual Central Plains Irrigation Conference, Burlington, CO, USA, 21–22 February 2017.
50. Howell, T.A.; Evett, S.R.; Tolk, J.A.; Schneider, A.D. Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains. *J. Irrig. Drain. Eng.* **2004**, *130*, 277–285. [CrossRef]
51. Bell, J.M.; Schwartz, R.C.; McInnes, K.J.; Howell, T.A.; Morgan, C.L. Effects of irrigation level and timing on profile soil water use by grain sorghum. *Agric. Water Manag.* **2020**, *232*, 106030. [CrossRef]
52. Sharda, V.; Gowda, P.H.; Marek, G.; Kisekka, I.; Ray, C.; Adhikari, P. Simulating the impacts of irrigation levels on soybean production in texas high plains to manage diminishing groundwater levels. *JAWRA J. Am. Water Resour. Assoc.* **2019**, *55*, 56–69. [CrossRef]
53. Deines, J.M.; Kendall, A.D.; Butler, J.J.; Hyndman, D.W. Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US High Plains Aquifer. *Environ. Res. Lett.* **2019**, *14*, 044014. [CrossRef]
54. Cardenas-Lailhacar, B.; Dukes, M. Precision of soil moisture sensor irrigation controllers under field conditions. *Agric. Water Manag.* **2010**, *97*, 666–672. [CrossRef]
55. Blonquist, J.M., Jr.; Jones, S.; Robinson, D.A. Precise irrigation scheduling for turfgrass using a subsurface electromagnetic soil moisture sensor. *Agric. Water Manag.* **2006**, *84*, 153–165. [CrossRef]
56. Leib, B.G.; Jabro, J.D.; Matthews, G.R. Field evaluation and performance comparison of soil moisture sensors. *Soil Sci.* **2003**, *168*, 396–408. [CrossRef]
57. Madramootoo, C.A. Sustainable groundwater use in agriculture. *Irrig. Drain.* **2012**, *61*, 26–33. [CrossRef]
58. Marek, G.W.; Chen, Y.; Marek, T.H.; Heflin, K.R.; O'Shaughnessy, S.A.; Gowda, P.H.; Brauer, D.K. Assessing planting date effects on seasonal water use of full- and short-season maize using SWAT in the southern Ogallala Aquifer region. *Irrig. Sci.* **2019**, *38*, 77–87. [CrossRef]
59. Vellidis, G.; Tucker, M.; Perry, C.; Reckford, D.; Butts, C.; Henry, H.; Edwards, W. A soil moisture sensor-based variable rate irrigation scheduling system. In *Precision Agriculture*; Wageningen Academic Publishers: Wageningen, The Netherlands, 2013; pp. 713–720.
60. Rudnick, D.R.; Specialist, I.M. *Soil Water Sensors for Irrigation Management*; University of Nebraska-Lincoln: Lincoln, NE, USA, 2016; pp. 1–9.

61. Butler, J.J.; Whittemore, D.O.; Wilson, B.B.; Bohling, G.C. Sustainability of aquifers supporting irrigated agriculture: A case study of the High Plains aquifer in Kansas. *Water Int.* **2018**, *43*, 815–828. [CrossRef]
62. Ogallala Aquifer Program. Ogallala Aquifer Program: Sustaining Rural Communities through New Water Management Technologies. 2015. Available online: https://ogallala.tamu.edu/media/1115/ogallala-aquifer-program-2015-annual-accomplishmensts-report.pdf (accessed on 15 January 2020).
63. CAWQ—Colrado Ag Water Quality. Irrigation Management. 2018. Available online: https://coagnutrients.colostate.edu/ag-best-management-practices/irrigation-management/ (accessed on 15 January 2020).
64. Nebraska Corn Board. 'Water' We Know About Water? 2010. Available online: http://www.nebraskacorn.org/wp-content/uploads/2010/07/cornstalk_may_2010.pdf (accessed on 15 January 2020).
65. Lamm, F.R.; Ayars, J.E.; Nakayama, F.S. *Microirrigation for Crop Production: Design, Operation, and Management*; Elsevier: Amsterdam, The Netherlands, 2006.
66. Rogers, D.H.; Lamm, F.R.; Alam, M. *Subsurface Drip Irrigation (SDI) Components: Minimum Requirements*; K-State Research and Extension: Manhattan, KS, USA, 2003; pp. 550–554.
67. Colaizzi, P.D.; Schneider, A.D.; Evett, S.R.; Howell, T.A. Comparison of Sdi, Lepa, and spray irrigation performance for grain sorghum. *Trans. ASAE* **2004**, *47*, 1477–1492. [CrossRef]
68. Lamm, F.R.; Trooien, T.P. Subsurface drip irrigation for corn production: A review of 10 years of research in Kansas. *Irrig. Sci.* **2003**, *22*, 195–200. [CrossRef]
69. Amosson, S.; Almas, L.; Kenny, N.; Guerrero, B.; Vimlesh, K.; Marek, T. Economics of Irrigation Systems. 2011. Available online: http://amarillo.tamu.edu/files/2011/10/Irrigation-Bulletin-FINAL-B6113.pdf (accessed on 7 February 2020).
70. Payero, J.O.; Yonts, C.D.; Irmak, S.; Tarkalson, D. Advantages and Disadvantages of Drip Irrigation. 2005. Volume EC776. Available online: http://extensionpublications.unl.edu/assets/pdf/ec776.pdf (accessed on 7 February 2020).
71. Araya, A.; Prasad, P.; Gowda, P.; Kisekka, I.; Foster, A. Yield and water productivity of winter wheat under various irrigation capacities. *JAWRA J. Am. Water Resour. Assoc.* **2019**, *55*, 24–37. [CrossRef]
72. Payero, J.O.; Tarkalson, D.D.; Irmak, S.; Davison, D.; Petersen, J.L. Effect of irrigation amounts applied with drip irrigation on maize evapotranspiration, yield, water use efficiency, and net return in a sub-humid climate. *Turk. J. Field Crop.* **2013**, *18*, 13–19.
73. Steven, E.; David, B.; Judy, T.; Paul, C.; O'Shaughhnessy, S. Corn and Sorghum Performance are Affected by Irrigation Application Method: SDI Versus Mid-Elevation Spray Irrigation. 2015. Available online: https://www.ars.usda.gov/research/publications/ (accessed on 9 February 2020).
74. Pate, J.; Yates, J.; Young, M.; Klose, S.; Kaase, G. *Pivot vs. SDI Irrigation Illustration for Side Oats Grama in the Southern High Plains*; Texas A&M University: College Station, TX, USA, 2009; Available online: http://farmassistance.tamu.edu/files/2013/08/2009-2.pdf (accessed on 12 February 2020).
75. Ogallala Aquifer Initiative. *Ogallala Aquifer Initiative 2011 Report*; United States Department of Agriculture: Washington, DC, USA, 2012. Available online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1048827.pdf (accessed on 9 February 2020).
76. Lichtenberg, E. Conservation and the environment in US farm legislation. *EuroChoices* **2019**, *18*, 49–55. [CrossRef]
77. Bigelow, D.; Borchers, A.; Hubbs, T. *US Farmland Ownership, Tenure, and Transfer*; EIB-161; USA Department of Agriculture: Washington, DC, USA, 2016.
78. Bordovsky, J.P.; Mustian, J.T. Cotton production response to crop row offset and orientation to SDI laterals in the texas high plains. In Proceedings of the 5th National Decennial Irrigation Conference Proceedings, Phoenix Convention Center, Phoenix, AZ, USA, 5–8 December 2010; p. 1.