Irrigation Efficiency in the High Plains Aquifer

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Objectives

In the face of anthropogenic climate change and dwindling water resources, managing our remaining water resources in a sustainable way is increasingly important to human development. Due to a growing population, demand for agricultural products is constantly increasing. This surge in demand ranges from crops for both human and livestock consumption to biofuel, and gives farmers economic incentive to grow more water intensive crops and increase the strain on our water resources (Hornbeck & Keskin, 2014). Given the importance of the crops grown and the water resources used to grow them, we are interested in exploring efficiencies revolving around the extraction of water resources for irrigation use. Studies have indicated that the water levels in the High Plains Aquifer are currently being depleted at a rate of about 10 % per decade (Haacker et al., 2016). Since the irrigation of agriculture uses a large portion of the water extracted from the High Plains Aquifer we are interested in the following question: Is the amount of water extracted for irrigation within the High Plains Aquifer necessary to meet water requirements for crops in the region?

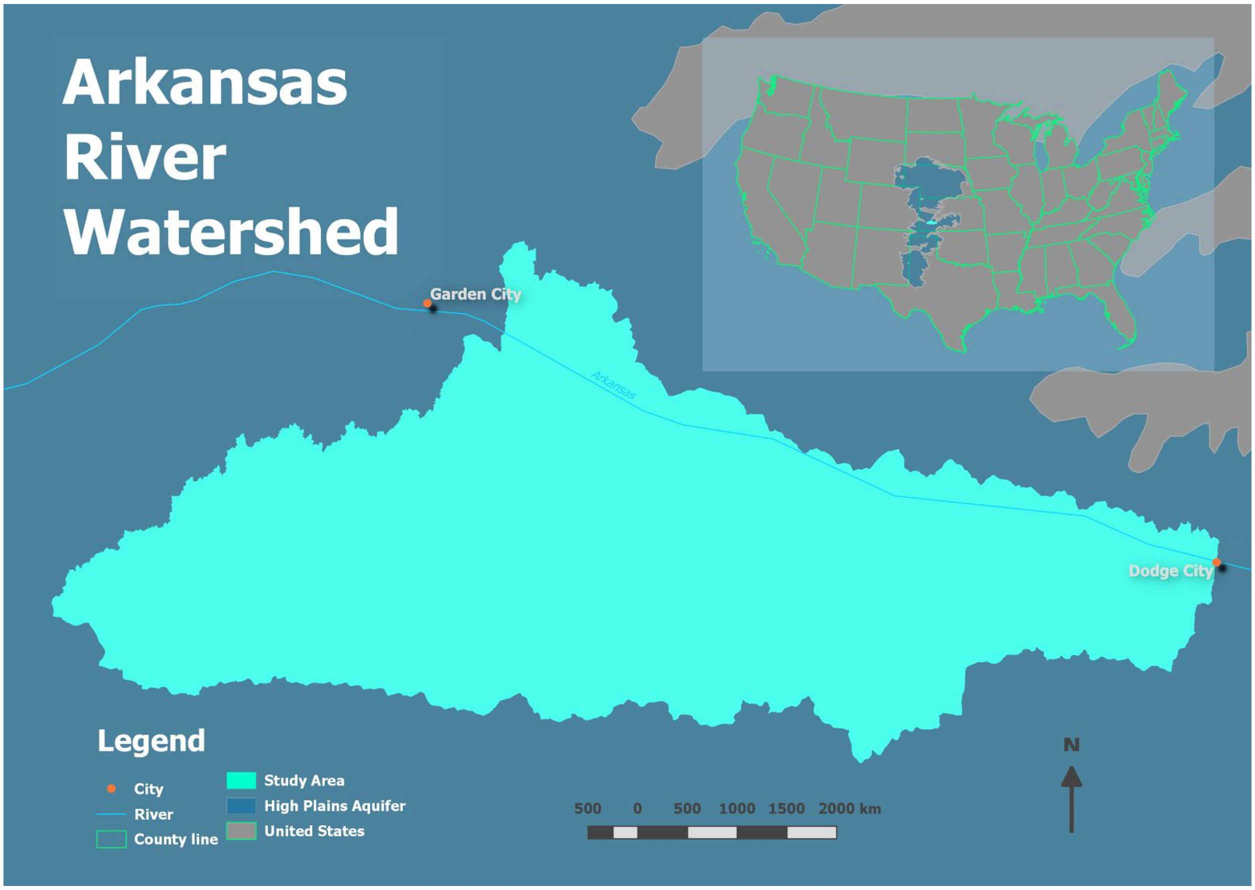
Introduction

The High Plains Aquifer (HPA), or Ogallala Aquifer, is an important hydrological boundary to study in irrigation efficiency because of its unique geography and geologic setting. The aquifer itself covers 174,000 square miles and spans vertically over eight states; South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas (Bickel, 2014). It was formed through processes of erosion and sediment deposition via streams and rivers several million years ago, and is therefore composed primarily of sand, silt, clay, and gravel (Overman). Irrigation efficiency within the HPA is an extremely important topic as it is one of the largest aquifers in the world, and it contains about 27% of the irrigated land and about 30% of the groundwater used for irrigation in the United States (NRCS & USDA, 2012).

With the introduction of Center Pivot irrigation technology after World War II, farmers could begin to cultivate much more water-intensive crops than was previously possible. Today, there about 170,000 wells that tap into this aquifer which contribute to irrigating about 500,000 square kilometers of farmland (Ringer, 2006). While the new technology should have allowed better efficiency at water extraction, farmers instead have begun to produce more water-intensive crops which have continued to lower the aquifers saturation levels. Overall, the saturation level in the HPA has lowered substantially, and USGS studies have indicated continued rapid depletion of groundwater in the area (Steward et al., 2013). In addition, the aquifer's recharge rates are only affected by rainfall and several rivers running through the region. Coupling the fact that the saturation levels are rapidly depleting due to heavy pumping of water for irrigation use, and slow recharge rate of the aquifer, it is paramount to understand where, why, and how this unnecessary water extraction is taking place in order to mitigate dropping saturation levels. Yearly recharge by rainfall recharges only about 15% of water pumper and it is estimated that it would take anywhere from 500 to 1,3000 years for the aquifer to completely recharge (Steward et al., 2013).

For our study, instead of analyzing the entire HPA, we have decided to look at a small region within the aquifer; a portion of the Arkansas River Watershed in Southwestern Kansas, which can be seen from **Figure 1**. This specific study area was chosen because of the high percent cover of irrigated agriculture in the region, and because it's diversity in crop types. After finishing the study we should be able to extrapolate the data to other areas in the region with just a few changes.

Figure 1. Arkansas River Watershed boundary.



Methodology

This study aims to calculate the water efficiency, or total water either over-pumped or under-pumped from our study area. In order to calculate this metric, data layers such as precipitation, crop cover distribution, and water being extracted from the aquifer were crucial. In addition, domain knowledge from Kansas State was necessary in order to calculate a water requirement for each crop type in the study. In order to calculate water efficiency, we first found the necessary water for each crop per growing season. We then subtracted the precipitation for that pixel giving us water necessary from pumping, and finally we subtracted the water being pumped and the water necessary to retrieve the water efficiency metric.

Methodology Step 1: Finding Crop Water Needs

With our study area defined the next step was to define the crops that we would consider in our study. To do this we first decided to look at the 2014 growing season and find classified remotely sensed imagery to give us crop cover for our study area. After some research we found a classified crop cover data layer from the United States Department of Agriculture (USDA). We downloaded the National Cropland Data Layer for 2014 from the USDA's National Statistics Service website. This layer was classified using the Landsat 8 OLI/TIRS sensor and the Disaster Monitoring Constellation (DMC) DEIMOS-1 and UK2 sensors, comes in a 30 meter resolution and has an overall accuracy of 84.5% (USDA, 2014).

Once we had our national Cropland layer, we clipped it to the extent of our study area in order to analyze the dominant crop groups which helped us pick the classes for our study. We found that just six out of thirty two classes covered over 90% of our study area. Out of of these six were Pasture Land and Fallow/Fields. Since we are only interested in irrigated crops we removed these two irrelevant classes and our remaining four classes became Alfalfa, Corn, Sorghum and Winter Wheat. These four classes cover over 50% of our study area, and ultimately are a good representation of the spatial variation of irrigated agriculture in our study area.

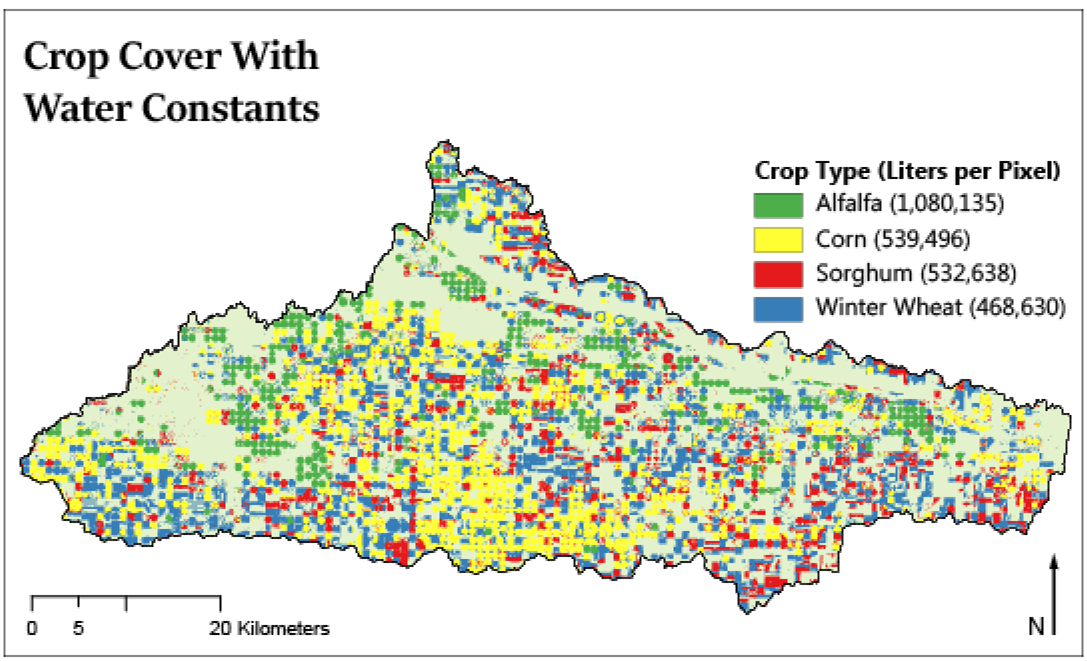
After defining our classes, we needed to come up with water constants that reflect the water needs for each individual crop over the course of a growing season. Using a K-State document advising corn growers, we extracted the recommended range of water required for each of our crop types. These ranges are listed in **Table 1** (Ciampitti et al., 2017). From these ranges we calculated the mean amount of water needed for each crop. This mean was then converted to represent the number of liters that are required to grow 30 square meters of each individual crop type. This 30 square meter area represents the size of a single pixel and gives us a value of liters per pixel.

With this newly calculated value we were able to join the Liters per Pixel information from **Table 1** to our Cropland layer. The result of this join is a raster layer that includes the crop cover and the estimated amount of water that is required for each individual 30 meter pixel. For simplicity we will refer to this layer as the our Water Constants Layer. **Figure 2** shows a large amount of spatial variance of our different crop types and you can also see that these four classes cover a significant portion of our study area. From here we need to normalize this data by using precipitation data.

Table 1. Water constants: the amount of water required for each crop over a growing season.

Crop	Inches	Mean Inches	Liter per Pixel
Alfalfa	31.5 - 63	47.25	1,080,135
Corn	15.6 - 31.6	23.6	539,496
Sorghum	16 - 30.6	23.3	532,638
Winter Wheat	15.4 - 25.6	20.5	468,630

Figure 2. Map of the crop cover and water constants in 2014.

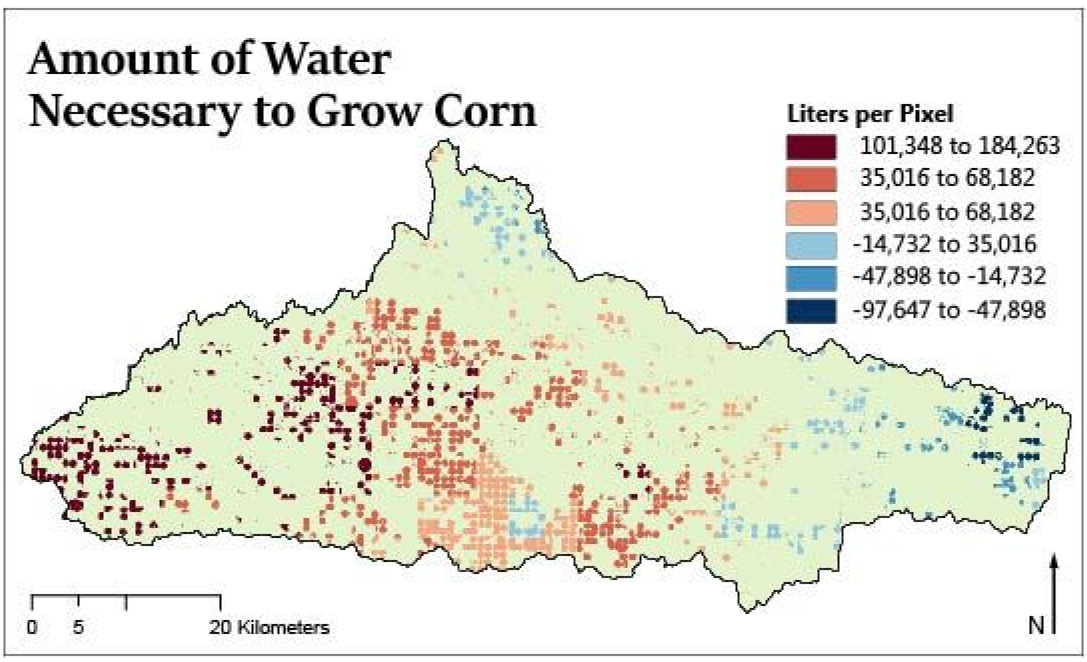


Methodology Step 2: Determining Water Necessary

To determine the amount of water necessary from pumping, the two layers we had to use were the precipitation raster and the water constants layer from our first step in the methodology. These two layers were crucial for this step, as precipitation is the only other source of water in the region. We first reclassified the water constants to create four separate raster layers; one layer for each crop type. This was done to ensure proper matching when performing raster addition; for example when reclassifying and creating the separate corn raster, corn was given a value of 100, and all other crop types were given a value of 1. We then clipped the precipitation raster, and resampled that to the same resolution as the water constants rasters, 30 meter resolution. Resampling the precipitation layer to the same resolution as the water constants is an important step in preparing this layer to be able to perform raster calculations between the two layers. We then took the resampled precipitation raster and reclassified it into twenty equal interval classes. We then calculated the mean values for each interval and assigned it a value of 1, 2, 3 etc. using the reclassify tool. This preparation was necessary to create a value that can be used when making calculations between the precipitation layer and the water constants layer. We then used the raster calculator to add each crop type raster with the precipitation raster layer. This allowed us to see which precipitation interval each water constant pixel was in; for example when working with corn, a completed value of 101 meant it was a corn pixel in the first precipitation interval, a corn pixel that received 262800 liters of rainfall. A completed value of 102 meant it was a corn pixel in the second precipitation interval, and so on. These completed values, when matched with their precipitation interval average values, gave us the amount of rainfall on each pixel. Since the precipitation layer was given in rainfall in millimeters, and out water constants layer was calculated in liters per pixel, we had to convert the rainfall to liters per pixel. From there, we subtracted the precipitation liters per pixel from the water constants liters per pixel to retrieve a value that represents the amount of water necessary to pump for irrigation for a given pixel. This outcome was evaluated in four separate rasters, one raster for each separate crop type of Corn, Alfalfa, Sorghum, and Winter Wheat.

The map in **Figure 2** is an example of one of these four rasters; water necessary from pumped irrigation for the crop type corn. We can see from the legend that the values range from about -97,000 liters per pixel to about 180,000 liters per pixel. The positive values indicate water that is necessary from pumped irrigation in order for the crop to grow, while the negative values indicate that theoretically no extra water is required from pumped irrigation. According to our data, the most water needed to be pumped for corn can be found in the western and south-central portions of the study area, with little to no water required to be pumped from the eastern edge of the study area. These values can be correlated with the amount of rainfall in the area; there is a higher average rainfall in the eastern portion of the study area than the western portion.

Figure 2. Map of water constants minus precipitation in 2014.

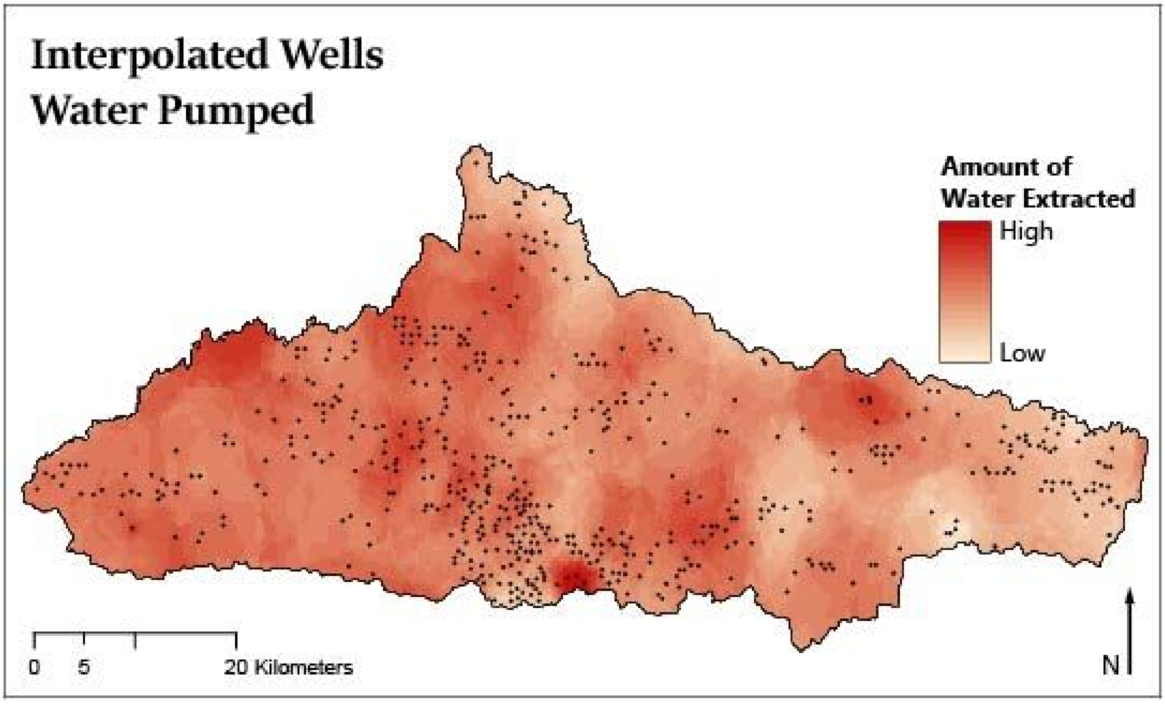


Methodology Step 3: Calculating Water Efficiency

To calculate irrigated water use efficiency, we first had to create a raster layer of the water extracted for irrigation in our study region. To create this water extracted layer, we obtained water well data from the Kansas Geological Survey's Water *Well Completion Database* (Kansas Geologic Survey, 2004). This database allowed us to select wells that met our criteria, including wells found in the six counties that our study area spans, wells used only for irrigation, wells that extract groundwater, and wells that are currently active. We also separated the wells based on which crop it was used to irrigate. This was an important step in the water pumped process because it allowed us to determine exactly how much water was being pumped for irrigation for each of the different crop types. For example, when creating the corn pumped layer, we only used wells that were specifically used for corn irrigation. This allowed us to more accurately calculate the water being pumped for corn, without being skewed by wells pumping water for Sorghum.

From there we interpolated the well data into a raster using an inverse distance weighted (IDW) interpolation with a power of 0.5. Each crop type was interpolated separately using their respective well data layer. These interpolations were then reclassified to 30 meter resolution to match our other raster layers resolution. This gave us the water that was being pumped for each crop type. We then reclassified the water pumped into categories reflecting the liters per pixel, each category of water pumped given a value of 1, 2, 3, etc. This was necessary for raster addition at a later step. We can see from **Figure 3** the resulting raster that was calculated from this step. The highest amount of pumped water can be found in the western and south-central portion of the map, which correlates with the water necessary raster map.

Figure 3: IDW Interpolation of Corn wells in 2014.

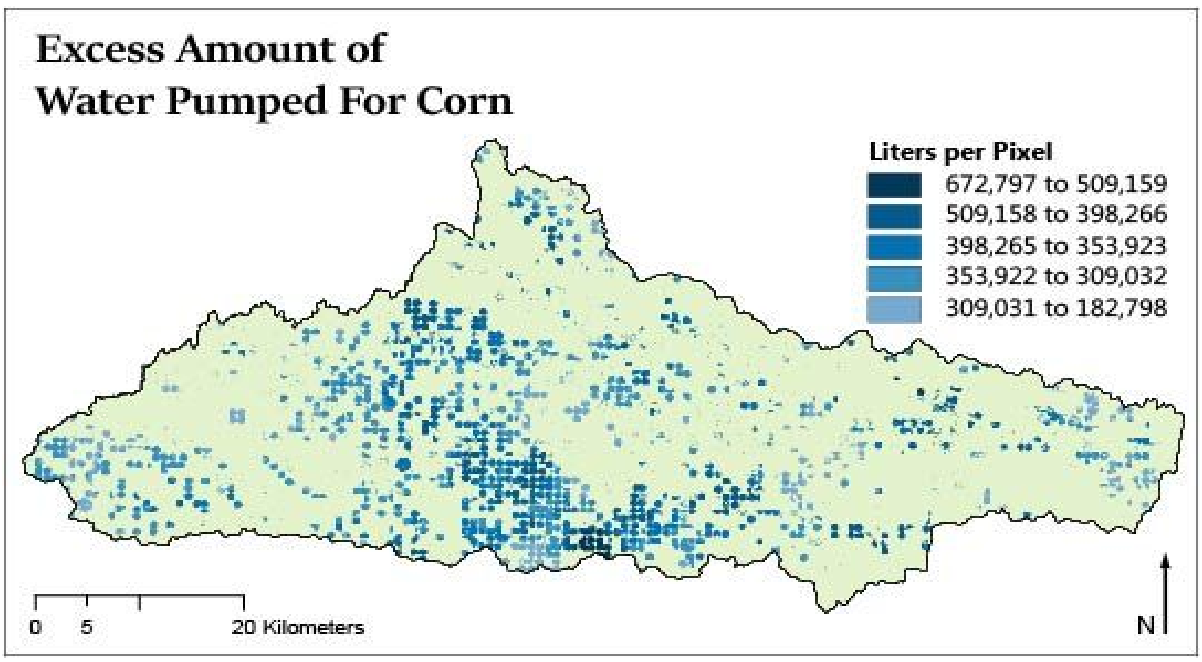


Then, we reclassified the water necessary from pumping into 18 separate files, each file representing how much water is necessary for pixels that are contained within it. The reclassification was done in order to accurately match the water necessary values with the water pumped values; for example, for a water necessary raster layer representing 184,263 liters per pixel, all values of 184,263 within the raster were given a value of 100; all other values were given a value of 1. This was done for each crop type, totaling 72 different raster layers. We then added each of these new classified water necessary from pumping rasters with the classified water pumped raster, to get the water efficiency. The addition of these two rasters created completed values from 101 to 120. These values had significant meaning for the specific raster file for which it was in. For instance, a value of 101 in the 184,263 water necessary raster layer represented all pixels with water necessary of 184,263, and in the first water pumped category; first water category being 165,399 liters of water pumped. For each crop type, the water efficiency map was created by combining these eighteen separate raster files. To calculate the last value of water efficiency, we subtracted the amount of water necessary with the amount of water pumped.

Results

Our final results for corn are shown in **Figure 4**. This map shows the normalized constants minus the interpolated water pumped raster. Our raw data consists of a value that represents the amount of liters either over pumped or pumped in excess, given our normalized water constants, for each individual pixel. Overall there is a fairly large variation in the amount of excess water pumped for corn. However, it appears that areas with a higher concentration of corn fields are associated with higher levels of excess water being pumped. More analysis would be needed to confirm these types of trends.

Figure 4. Unnecessary water pumped for corn in 2014.



We took the raw data from our final results, calculated some statistics, and converted the values into gallons per acre. Our results, shown in Table 2, suggest that while Alfalfa is not receiving enough water, Corn, Sorghum and Winter Wheat are all receiving an excess amount of water. On average Alfalfa is receiving 270 gallons less per acre than is theoretically required for it to grown over a season. On the other hand, Corn is receiving 708 gallons more per acre than is theoretically required over the course of its growing season. Sorghum and Winter Wheat are being watered in excess of an average of 435 and 533 gallons per acre respectively.

We could not calculate a meaningful total of the gallons wasted from our raw data, so we estimated the totals by multiplying the mean gallons per acre by the total acreage for each crop. Corn has the second highest acreage, yet is the largest waster of water. Winter Wheat covers a larger area than corn, but wastes a little bit less water than corn. With a estimated total of 4,801,664 gallons of water wasted between the three classes with excess water pumped, the percentage of the total wasted water is as follows: Corn 43.9%, Winter Wheat 40%, and Sorghum 16.1%.

Table 2. Results

	Alfalfa	Corn	Sorghum	Winter Wheat	Totals
Mean (Gallons/Acre)	-270	708	435	533	351
Acres	1,352	2,976	1,775	3607	9710
Estimated Gallons Wasted	-365,040	2,107,008	772,125	1,92,2531	4,801,664
% Cover	7	15	9	19	50

Discussion

With our results comes some measure of error. First we'll discuss some errors specific to our methodology, and then we'll talk about some broader challenges associated with a studies on irrigation efficiencies. As with any study, our research required some decisions revolving around our methodology that could impact the accuracy of our results.

First it is important to discuss the accuracy of our Cropland Data. The user accuracies for our classes range from 89.12% to 95.69%. Right away we know that our results can only carry a maximum accuracy of 89%, as all of our calculations can only be as accurate our original data. Although we're given some measure of error in our first layer, 89% is a fairly good user accuracy when it comes to classified imagery, so we were pretty confident on the spatial distribution of our crop classes.

Next, it is important to point out the difficulties that arise when working with water data. First, our crop water requirements came in a range. While these ranges are specific to Kansas's climate, day to day weather can alter the crops water needs. By calculating our constants from the mean of our given ranges, we have made the assumption that water needs don't vary much from the mean value which is not true in practice. Along those same lines, we took the mean precipitation for the 2014 growing season. Again daily weather patterns will have an effect on how much water is getting absorbed by the crops, so a taking a mean drastically simplifies a very complex system.

One more source of error could occur as a result of our interpolated well data. An interpolation in and of itself is an estimated value based on a complex calculation between given points. We chose to run an IDW interpolation, however we did not find much literature to back up this decision. Utilizing another type of interpolation would inevitably produce different results and could be more accurate.

A surprising result, however, is that for the crop type alfalfa, there appears to be not enough water being pumped for irrigation, although alfalfa can and certainly should be deemed an outlier in this case study, and for rather straightforward reasons. The Southern Integrated Pest Management (IPM) Center stated in their alfalfa crop profile in 2005 that while the majority of alfalfa hay fields surveyed were grown using irrigation, it can be produced in both irrigated and nonirrigated cropping practices (Jia et al., 2000). Alongside minimal irrigation used in some crop practices, it is often sowed in no-till fields, which can be cited from numerous sources to require less irrigation (West & Marland, 2002). The Kansas Water Office published an irrigation management guide for alfalfa in 2009 that, as a perennial with a deep root system, it is drought tolerant with an extended growing season (Alam & Rogers, xxxx). When we were searching for expected irrigation needs for each crop type, Kansas Extension Corn Management guide for 2017 contained a table (previously referenced) with a range of irrigation values for each crop type we were concerned with, and the amount listed for alfalfa was 31.5 – 63.0 inches seasonally. (Ciampitti et al., 2017) Later in our analysis it was noted that this may not be as reliable as we assumed and eventually conflicting data was found (K-State, 1998).

Conclusion

This study was conducted to determine if groundwater being extracted in the High Plains Aquifer was necessary for irrigated agriculture in the region. Water efficiency in regards to irrigated agriculture is a very important topic going into the future, with agricultural products being in high demand as world population rises. This combination of increased need for agricultural and rising populations takes a large toll on the groundwater aquifers across the United States currently used to irrigate crops. Our study found that an excess amount of water is being pumped, more than is necessary, for irrigation for corn, sorghum, and winter wheat.

Overall, the amount of water being pumped for irrigation, compared with the amount of water necessary for irrigation is not efficient. This finding suggests that further steps should be taken to analyze irrigation efficiencies and develop more sustainable methods of extracting water used for agriculture within the High Plains Aquifer. This should be taken as a top priority in the region, as pumping more water than is necessary is not only more costly, but also risks premature depletion of the High Plains aquifer.

Future Efforts

This study is merely a starting point for those who wish to seek a more in depth understanding of water use, management, and analysis for the future. Traditionally, reliable and effective water use data was either hard to come by and at best, reliable enough for financial records only. This is due to the vast amount of room for error in the collection of this data, as well as the cost for doing so. New tools are being rapidly developed as high resolution, easy to access, and affordable satellite images are published online. One of these tools was developed by NASA and is an open source tool accessible to anyone who has access to ArcMap. This makes it extremely viable for small organizations to use for precise water use analysis, or even individual farmers to perform their own crop analysis without the need for hiring third party analysts.

The METRIC tool, which stands for Mapping Evapotranspiration with Internalized Calibration, is a model that is based upon the SEBAL energy balance process developed in the Netherlands by Bastiaanssen (Allen et al., 2009). In the SEBAL process, near-surface temperature gradients are an indexed function of radiometric surface temperature. What this allows is for the need of absolutely accurate surface temperature to be eliminated, as well as the need for absolute air-temperature measurements. That being said, the METRIC tool does use weather data obtained through nearby weather station data. Besides weather, it also incorporates elevation, soil, and terrain data, which leads to more effective precipitation and irrigation data to calculate the most accurate water content of the crop or vegetation on any particular day of interest. Landsat 8 raster bands are then used for their high resolution and frequently published date ranges. Landsat 8 was launched on February 11, 2013 and has images available all the way up to the present year (2017). With near real time accessibility, farmers can use the data throughout their growing season, eliminating the potential cost of drone or other aerial or ground data collection methods. For now, the METRIC tool is saved for the more tech savvy individuals and organizations with access to ArcMap software. The NASA-developer METRIC git repository already has discussion of how to modify the tool for open source software, such as QGIS. With such a pressing demand for resource management, it is reasonable to assume tools such as this to become more user friendly and readily available.

Precision agriculture is has become a mainstream practice since its emergence in the 80's. While economically viable, it is also beneficial to farmers who wish to practice a much more sustainable approach to their land, without completely changing their systems of production. As population increases, water can easily be defined as a top priority for individuals, governments, and industries alike, making it equally a national security concern, as well as environmental. Tools such as METRIC can expect to be more mainstream with all other precision agriculture systems.

With an open source tool, comes obstacles, such as development upkeep and corrections. For that reason, this tool was not able to be used in this study.

References

Alam, M. & Rogers, D. H. Irrigation Management for Alfalfa. *Irrigation Management Series* (2009). Available at: https://www.bookstore.ksre.ksu.edu/pubs/MF2868.pdf. (Accessed: 1st May 2017)

Allen, R. G., Tasumi, M. & Trezza, R. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC). *Journal of Irrigation and Drainage Engineering* **133,** (2007).

Bickel, A. Water Series: About the Ogallala. *Kansasagland* (2014). Available at: http://www.kansasagland.com/news/water/water-series-about-the-ogallala/article_eed2bc89-8980-5672-9f0f-a388a556a832.html. (Accessed: 4th May 2017)

Ciampitti, I. A., Thompson, C., O'Brien, D., Rogers, D. H., Ruiz Diaz, D. (2017) Kansas Corn Managment 2017. K-STATE Research and Extension, 1-8.

Feeding Climate Change. oxfamamerica.org (2016). Available at: https://www.oxfamamerica.org/static/media/files/bp-feeding-climate-change-270616-en_6jfKSQg.pdf. (Accessed: 5th May 2017)

Haacker, E. M. K., Kendall, A. D., & Hyndman D. W. (2016). Water Level Declines in the High Plains Aquifer: Predevelopment to Resource Senescence. *Groundwater, 54*(2), 231-242.

Hornbeck, R., Keskin, P., (2014). The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought. *American Economic Journal: Applied Economics 1*(6), 190-219.

Jia, F. *et al.* Crop Profile for Alfalfa in Kansas. *National IPM Database* (2005). Available at: https://ipmdata.ipmcenters.org/documents/cropprofiles/KSalfalfa.pdf. (Accessed: 8th May 2017)

Kansas Geological Survey. Well Water Completion Records. *Kansas Geological Survey* (2004). Available at: http://www.kgs.ku.edu/Magellan/WaterWell/. (Accessed: April 2017)

K-State. Alfalfa Production Handbook. *K-State Research and Extension* (1998). Available at: http://www.bookstore.ksre.ksu.edu/pubs/C683.pdf. (Accessed: 8th May 2017)

NASS, U. S. D. A. USDA, National Agricultural Statistics Service. (2015). Available at: https://www.nass.usda.gov/Research_and_Science/Cropland/metadata/metadata_ks14.htm. (Accessed: 28th April 2017)

NRCS, USDA, Ogallala Aquifer Initiative 2011 Report. *Conservation Beyond Bounds* (2012). Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1048827.pdf. (Accessed: 29th April 2017)

Overman, S. R. The High Plains Aquifer. *Regional Updates* Available at: wps.prenhall.com/wps/media/objects/1373/1406592/Regional_Updates/update23.htm. (Accessed: 3rd May 2017)

Ringer, T. Introduction to Hydrogeology,. *The High Plains Aquifer System* (2006). Available at: http://academic.emporia.edu/schulmem/hydro/TERM%20PROJECTS/Ringler/HPA%20system%20web%20page.htm. (Accessed: 1st May 2017)

Steward, D. R. Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110 . *PNAS* 110, (2013).

West, Tristman & Marland, G. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States . *Agriculture, Ecosystems & Environment* **91,** 217–232 (2002).