

Feasibility of Managed Aquifer Recharge (MAR) for Southwest Kansas

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Abstract

This paper investigates the feasibility of managed aquifer recharge (MAR) for Southwest Kansas. Multiple sources of water for MAR were investigated. The sources of water analyzed were stormwater runoff from fields, use of low flow or ephemeral streams, and use of a regional river for infiltration water. The use of the Arkansas River was found to be the most viable source of water in this area. Different methods of MAR were evaluated with the most feasible selected for this local area. The construction of infiltration basins in existing sand mines was found to be the best MAR alternative in this region. The requirement for the retirement of sand mines set out by the State of Kansas comports with the requirements of infiltration basins, and there exists a local ditch system that can convey Arkansas River flows to the infiltration basins with little need of new construction. The salinity of the Arkansas River is of concern as it could reduce crop yields if used for irrigation. This risk could be mitigated by crop choice or other means. This investigation is also relevant throughout the State of Kansas, so perhaps another river would have more suitable conditions.

Keywords: Managed Aquifer Recharge (MAR), High Plains Aquifer, Arkansas River, irrigation, sustainable agriculture

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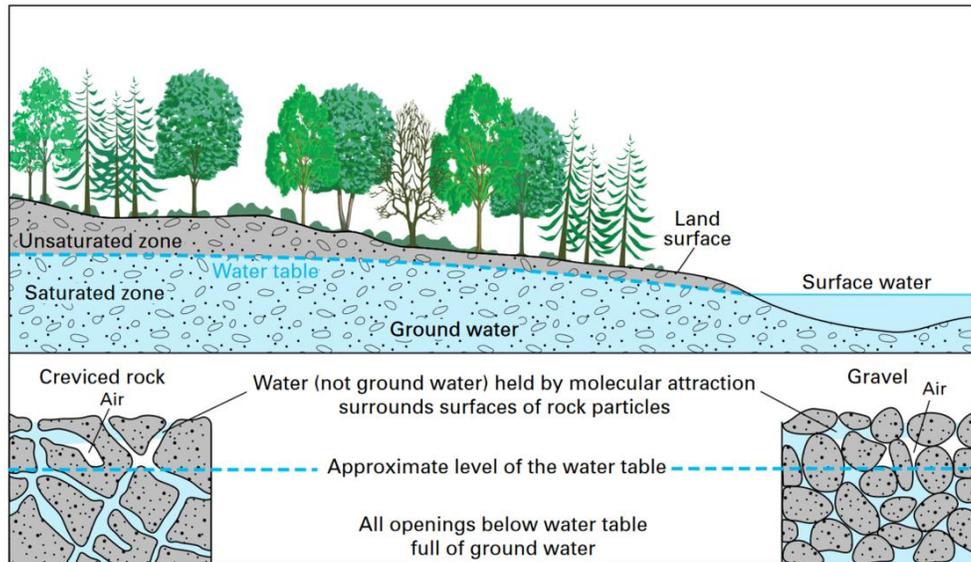
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Feasibility of Managed Aquifer Recharge (MAR) for Southwest Kansas

Groundwater is an important resource. Groundwater is the source of 37% of municipal water supplies, 42% of irrigation water, and 90% of the water supply used by the rural population in the United States (United States Geological Survey [USGS], 2018). The USGS (1963) defines groundwater as “water that is filling the pores or cracks in rocks below ground” (p. 5). Figure 1 shows how groundwater appears under the land surface. Not all groundwater use is sustainable. Many groundwater sources are non-renewable, meaning they are being exploited at a much faster rate than they replenish. One such source is the High Plains Aquifer. The High Plains Aquifer is the largest aquifer in the United States. It underlies an area of 174,000 square miles including parts of Colorado, Kansas, Nebraska, South Dakota, Wyoming, New Mexico, Oklahoma, and Texas (USGS, 2021). This aquifer provides irrigation water for some of the largest agricultural areas in the United States. The High Plains area accounts for nearly 20% of the wheat, 15% of the corn, and feed for 18% of the cattle population produced in the United States (USGS, 2014). Concerningly, the High Plains Aquifer is being depleted at an alarming rate. So far, 30% of the groundwater within the High Plains Aquifer has been depleted, with another 39% estimated to be depleted over the next 50 years under a business-as-usual scenario (Steward et al., 2013). This depletion is not evenly spread across all states; the portion underlying Nebraska has not experienced a significant water table decline (Crosbie et al., 2013).

Figure 1

A Figure Showing a Visualization of Groundwater



How ground water occurs in rocks.

Note. Adapted from *Aquifers and Groundwater* by the United States Geological Survey (USGS), October 2019, para. 5 (<https://www.usgs.gov/special-topics/water-science-school/science/aquifers-and-groundwater>).

One of the root causes of groundwater depletion in the High Plains Aquifer is slow natural recharge compared to the rate of its use; only about 15% of water use in the High Plains Aquifer system is offset by natural recharge (Steward et al., 2013). There are many factors that are relevant to natural recharge of aquifers. The volume of precipitation, soil type, evapotranspiration, and the geology of a region all play important roles in natural replenishment of aquifers (USGS, 1963). It is also possible to artificially promote the movement of water into the aquifer. This is called managed aquifer recharge (MAR) (USGS, 1963). The goal of this Milwaukee School of Engineering (MSOE) Master of Science in Civil Engineering (MSCVE)

capstone project was to determine the most suitable managed aquifer recharge strategy for Southwest Kansas, and determine its potential benefits and costs.

Managed Aquifer Recharge (MAR)

What is Aquifer Recharge?

One of the main ways that groundwater is naturally replenished is through the process of infiltration. Infiltration can be defined as seepage of atmospheric precipitation through a porous aeration zone (Kovalevsky, 2005). In other words, precipitation falling on the ground surface infiltrates and flows downwards through the voids and pores in soil or rock formations. An aquifer is a body of porous rock or sediment saturated with groundwater (USGS, 1963).

What is Managed Aquifer Recharge (MAR)?

MAR can best be described as artificial recharge of groundwater and aquifers, augmenting and increasing the recharge of an aquifer (USGS, 1963). MAR methods usually employ a strategy to direct water toward an infiltration structure; in other cases, the water is directly injected deep into the ground.

In a MAR system, the goal is to be able to transmit water into an aquifer and then later retrieve it with a well. The most common source of water for MAR is treated wastewater because there are few competing interests for its use, but the use of stormwater as a source has been growing (Jakeman et al., 2016).

What Are the Different Methods of MAR?

The United States Geological Survey's 1963 report, *A Primer on Ground Water*, describes the different methods of MAR. All methods of MAR can be classified within two

groups: deep injection and surface infiltration. Deep injection methods rely on an injection well to introduce surface water into the groundwater using pressure. Then, either a single recovery well, or a network of recovery wells, is used to retrieve the water when it is needed. This requires the treatment of the water before injection. Removal of solids is the most common pretreatment because solids suspended in water can easily clog well screens or the aquifer itself, lowering overall performance and increasing operation costs (Vanderzalm, 2020). Often, more treatment is required because the injected water immediately contacts the water in the aquifer, which makes contamination possible (American Society of Civil Engineers [ASCE], 2020). In some cases, the water injected may be unsuitable for some uses, in which case, recovery wells must be located far enough away to allow for the attenuation of any contaminants (Vanderzalm et al., 2010).

Another MAR method features the use of infiltration basins and spreading grounds. Both methods are classified as surface infiltration techniques, as noted in USGS (1963). While there are some slight differences between these two methods, they operate similarly. Infiltration basins are vegetated depressions whose purpose is to store excess stormwater during storm events; they are dry unless there has been a period of rainfall (Environmental Protection Agency, 2021). After a period of rainfall, runoff is collected and then infiltrated gradually into the ground. They infiltrate water on-site, meaning that they are located very near the source of water. Infiltration basins very rarely infiltrate treated wastewater but may be used for stormwater or surface water. One version of an infiltration basin is agricultural-MAR. Agricultural-MAR is the use of existing farm fields as an infiltration basin (Levintal et al., 2022). To mitigate damage to agricultural yields, factors such as crop tolerance to flooding, root depth and soil texture are considered (Ganot & Dahlke, 2021).

A spreading ground is very similar to an infiltration basin with a distinct difference. Spreading grounds are usually supplied water, either in the form of treated wastewater, or diverted stormwater from farther away using canals (Public Works of Los Angeles County, 2023). Spreading grounds are usually used in arid climates with dry soils and with permeable formations that have a hydraulic connection with the underlying aquifer (Schroeder & Anders, 2002). This allows them to infiltrate much more water than an infiltration basin, but it also limits where they can be built. Spreading grounds are also not usually vegetated.

The similarity between these two processes gives both methods similar advantages and disadvantages. They are both relatively simple to construct and offer some pollutant removal (EPA, 2021) Both require geological conditions that can infiltrate water at acceptable rates, which is often the controlling factor in where they can be built (Minnesota Stormwater Steering Committee [MSSC], 2021). Each method also requires large and flat areas. Solids and sediments in the water stream pose a threat to infiltration basins and spreading grounds. Like the direct injection method, these sediments can clog the pores in the soil, which can lower the infiltration rate substantially (Vanderzalm, 2020). To avoid this scenario, a maintenance plan should be put into place. Based on their research, the MSSC (2016) recommend in their stormwater manual that sediment be cleared from infiltration basins every five years as part of normal maintenance. This recommendation has been endorsed by the Environmental Protection Agency (EPA) (2021) in their stormwater best management practice fact sheet.

The final method discussed in this paper is the infiltration gallery. Like infiltration basins and spreading grounds, infiltration galleries are a surface infiltration method. Godwin et al. (2021) describe what an infiltration gallery is and when they are appropriate to be used. Infiltration galleries are used when infiltration rates are not acceptable at the surface. They are constructed

by digging a basin deep enough to contact a more permeable material so that higher infiltration rates can be achieved. This trench is then filled with porous media, such as sand or gravel. The porous media provides the structure for the trench and the pores within the media also provide substantial storage capacity. The backfilled basin is then buried with topsoil to restore the surface to usable condition (Bouwer, 2002). Water is then transmitted directly to the underground porous media through a drain, perforated pipe, or other structure. This method has two advantages over the other surface infiltration methods. First, since the trench is dug to meet a lower media that has an acceptable infiltration rate, this method is less limited by geological conditions. Secondly, since the trench is covered in soil, this means the area can be used for other purposes as well, such as a park (Godwin et al., 2022). This method still has the other advantages of a normal surface infiltration method, as it is simple to construct and provides some contaminant removal. It is much harder to maintain, though, as the sedimentation occurs below ground.

Methods

Alternative Screening

Three alternative water sources were investigated for screening. One alternative was chosen for further analysis, which is described in the Alternatives Analysis section. The initial criterion considered in the alternative screening process was the volume of water available from each alternative, as no MAR can occur if there is no water source with which to recharge the aquifer. Alternative 1 investigated using stormwater runoff from fields themselves as the source of water. Alternative 2 investigated using ephemeral and low flow streams as the source of water. Alternative 3 investigated the use of a river as the source of water.

Before alternative screening can occur, a general region for the application of MAR must be identified. While there are many technical criteria directly related to MAR that are important, non-technical factors such as stakeholders and local interest in groundwater recharge must also be considered. In this capstone project, it was determined that Western Kansas features a positive confluence of all non-technical factors considered. Kansas has a legislative framework to allow for local farmers to come together to form groundwater management districts. These districts would both be interested in MAR and would be an important local stakeholder. A deeper investigation of these factors is found in the Alternative Analysis portion of this capstone project report. This area is also located above the High Plains Aquifer, making it the ideal location to be investigated.

Alternative 1: Infiltrating Storm Runoff From Fields

This alternative would include the construction of infiltration galleries adjacent to fields. The storm runoff from the fields would then be redirected towards the infiltration galleries. This alternative is intended to offset the water use of fields with their own stormwater runoff to provide self-sustainability to their withdrawals. This method would be widely applicable due to its simple construction and local capture area. It would also have limited surface use impacts, as the galleries are underground.

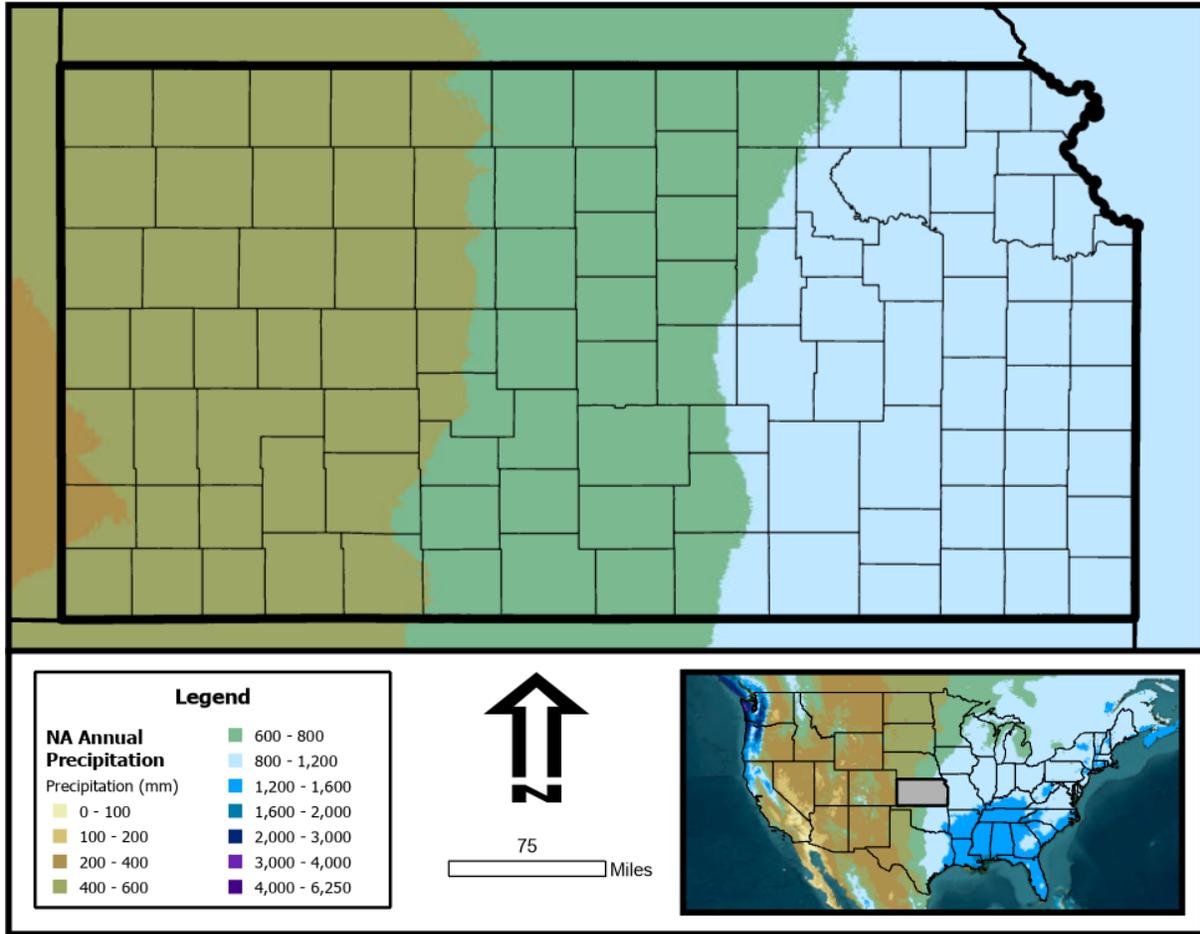
To screen the alternatives, the volume of water that can be infiltrated was compared to the water demand of fields. To determine this ratio, the average area of an irrigated field, the average water consumption of an irrigated field, the average annual depth of rainfall, and the runoff ratio for the area were determined.

First, the average area and water consumption of a representative area was determined. A center pivot field was selected as representative for this project. The Kansas Division of Water Resources (2017) indicates several important characteristics associated with center pivot fields. First, center pivot is the most common kind of irrigation in Kansas by both acres irrigated and volume of water used. Second, center pivot fields using drop nozzles are the most common kind of center pivot irrigation in Kansas. And third, an average center pivot irrigation field using drop nozzles applies 11 inches of water annually. According to the USDA, the average center pivot field is around 125 acres (Evans, n.d.). Combining these factors, it was determined that an average center pivot irrigation system uses just under 115 acre-ft of water a year in Kansas.

Next, the average annual rainfall and the proportion of that rainfall which becomes runoff, the runoff ratio, need to be determined. Figure 2 shows a map of annual precipitation in Kansas. The average value for western Kansas appears to be in the range of 400 to 600 millimeters annually. For this analysis, an average of 500 millimeters or 19.67 inches was used. Figure 3 displays an isoline map of the aggregate runoff ratio between 1971 to 1990. While these data are older, there is little indication that the aggregate runoff ratio would have increased since 1990. A runoff ratio of 0.5% was selected from the map as representative of Western Kansas. Combining the annual rainfall and runoff ratio, it was determined that this area of Kansas produces an average of 0.1 inches of runoff a year. For an average 125-acre field, this would equate to around 1 acre-ft every year of runoff, which is the potential volume capture available for infiltration with MAR.

Figure 2

Normal Annual Precipitation over Kansas, 1991 to 2020



Note. Adapted from “TIGER/Line Geodatabases” by the United States Census Bureau

(<https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-geodatabase-file.html>); “Past

Weather by Zip Code—Data Tables” by the National Oceanic and Atmospheric Administration (NOAA)

(<https://www.climate.gov/maps-data/dataset/past-weather-zip-code-data-table>).

Figure 3

An Isoline Map of the Aggregate Runoff Ratio Across Kansas, 1971 to 1990

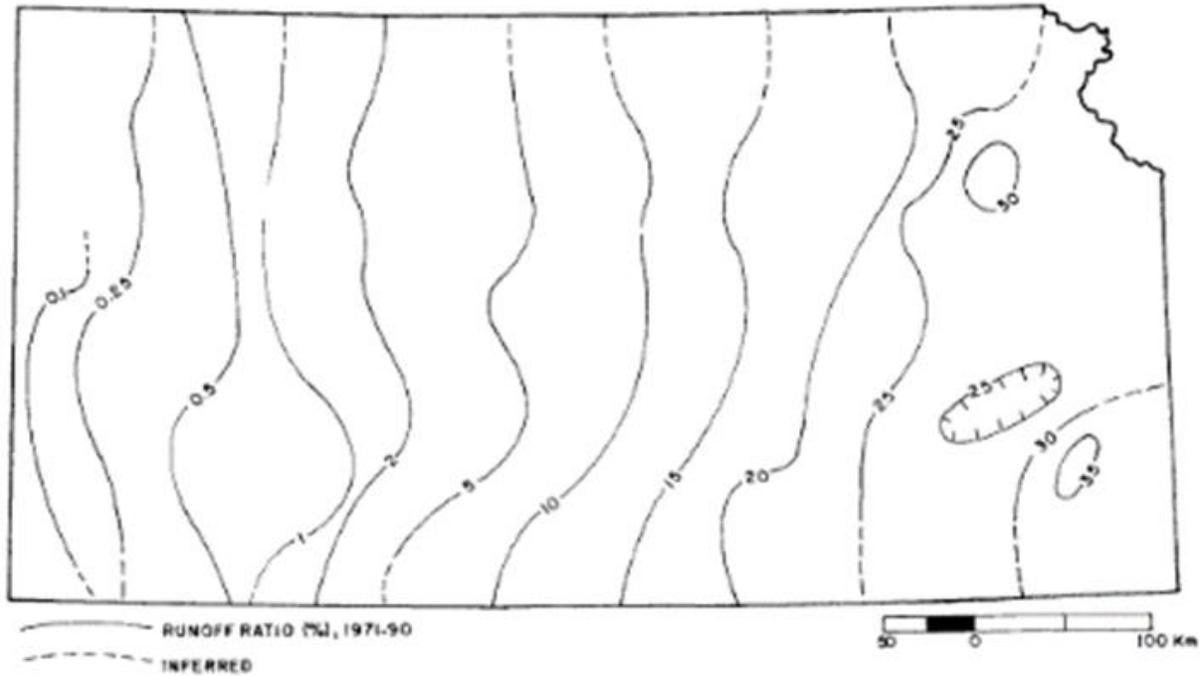


Figure 5. Isoline map of aggregate runoff ratio for 1971–1990.

Note. Adapted from "Mean Annual Precipitation, Runoff and Runoff Ratio for Kansas, 1971-1990," by J. Ratzlaff, October 1994, *Transactions of the Kansas Academy of Sciences*, 97(3-4), p. 99 (<https://doi.org/10.2307/3627776>).

The water consumption of a field versus the potential capture volume is shown in Table 1. Alternative 1 is estimated to offset only 0.9% of the water use of the field. This is not a significant offset of water use. This result eliminates Alternative 1 as a viable alternative. The most significant reasons for the low offset are the low annual precipitation and runoff ratio.

Table 1

Water Use Offset of Alternative 1

Average water use per field (Acre-ft)	115
Average potential water captured per field (Acre-ft)	1.1
Potential offset	0.9%

Alternative 2: Diverting Water from Low Flow and Ephemeral Streams

This alternative would include the construction of low head dams on low flow and ephemeral streams and rivers. When flowing, a percentage of that flow would be diverted into an infiltration structure. The exact type of infiltration structure would be determined on a case-by-case basis depending on the suitable locations for dam construction. The first step of the analysis for this alternative was to determine the potential volume of water captured.

This analysis investigated the Saline River at WaKeeney, Kansas, USGS gauge number 06866900. The Saline River had an annual median flow of 13.3 cubic feet per second (cfs) from 1956 to 1999 and an annual median flow of 5.9 cfs from 2000 to 2022 in this location. The second time period, from 2000 to 2022, was chosen to reflect the drought conditions that have been affecting the western United States since 2000. First, the percentage of flow in the river that would be diverted needed to be assumed. A diversion percentage of 30% was chosen. The

diversion would require the creation of a new water right, and water rights are determined on a case-by-case basis. For screening purposes, 30% was chosen as a reasonable estimate, although it may not reflect what would be available. This analysis employs the same water consumption per 125-acre field, just under 115 acre-ft annually, as the previous analysis.

Extrapolating the median flow from 1956 to 1999 of 13.3 cfs to an annual basis gives a volume of 9630 acre-ft. Extrapolating the median flow from 2000 to 2022 of 5.9 cfs gives an annual volume of 4230 acre-ft. This would mean that diverting 30% of the Saline River would have offset the water use of 25 fields using the 1956 to 1999 flows and would offset 11 fields using the 2000 to 2022 flows. Table 2 displays the total flows, diverted flows, and the number of fields whose water use was offset.

Table 2

Water Use Offset of Alternative 2

	1956 to 1999 Water Flows	2000 to 2022 Water Flows
Total Annual Volume (acre-ft)	9630	4200
Diverted Annual Volume (acre-ft)	4230	1300
Fields Sustained	25	11

While these results are better than Alternative 1, Alternative 2 is also not viable. To sustain less than 20 fields would require the construction of a low head dam, an environmental assessment of the downstream ecosystem, and the creation of a new water right. The benefits would most likely not outweigh the costs.

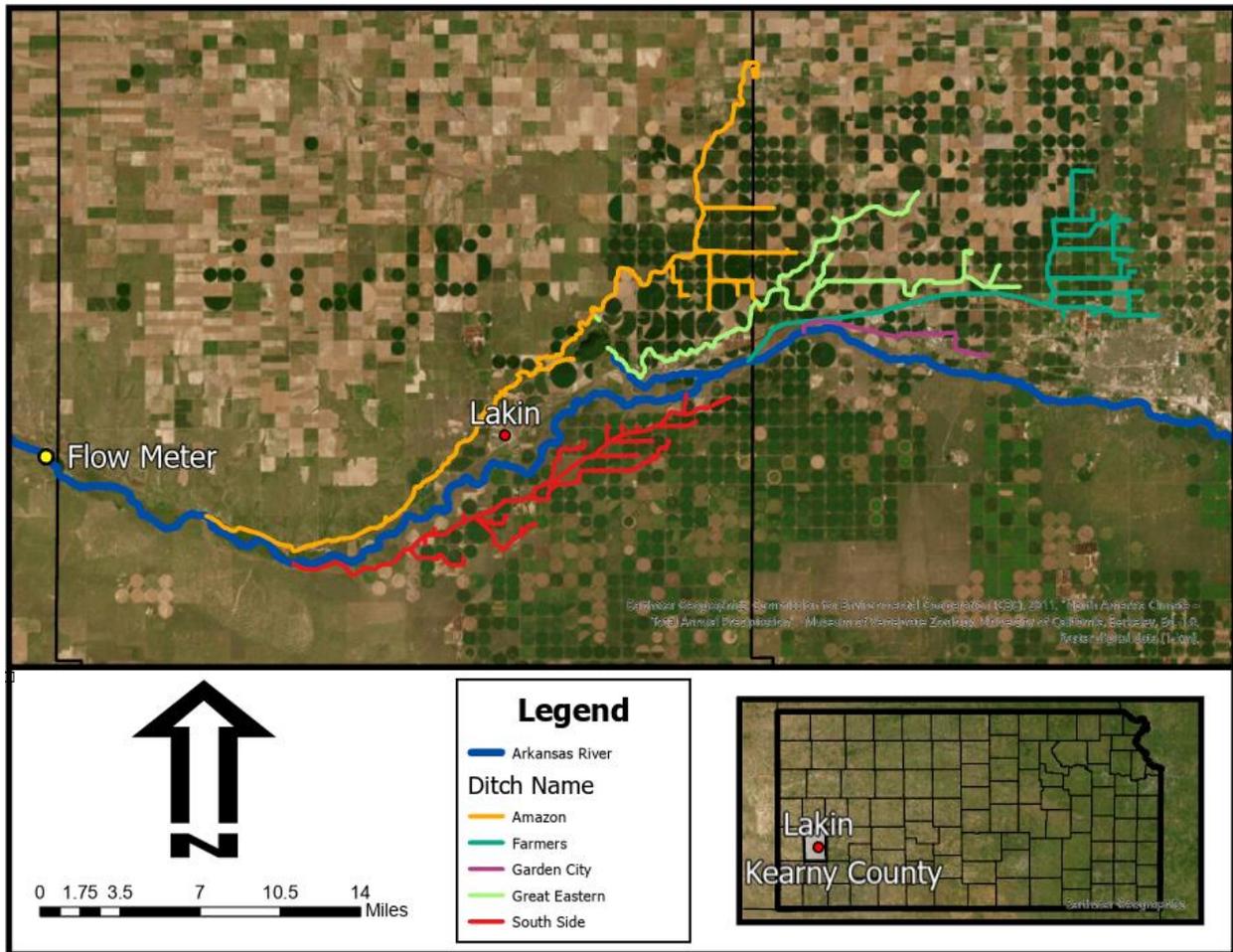
Alternative 3: Diverting Water from River Flows

This alternative's source of water would be larger regional rivers. One of the largest rivers in this region is the Arkansas River, which flows from the Rocky Mountains to the Mississippi River. There are a variety of ways to both divert water from the river and infiltrate it depending on the location along the river that is being investigated. This analysis investigated the Arkansas River at Kendall, Kansas, USGS gauge 07138020.

Near this location is the Associated Ditch System with many different operators for the different ditches. The purpose of the ditch system is to convey water for sprinkler systems. The current withdrawals of the ditches from the river reduce the amount of water available for MAR, while the river diversion and irrigation ditch infrastructure provide an opportunity to transport large volumes of water with little capital investment. The ditches that were considered in this analysis were the Amazon Ditch, the Southside Ditch, the Great Eastern Ditch, the Farmer's Ditch, and the Garden City Ditch. Figure 4 shows the ditch system in relation to the nearby City of Lakin and the flowmeter used for this analysis. The existing water rights of the ditches need to be considered to determine the potential volume of water that is available. Table 3 lists the current water rights of all the ditches.

Figure 4

The Associated Ditch System, Flow Meter, and Arkansas River in Relation to Lakin.



Note. Adapted from data obtained from the Kansas Department of Administration via the Open Records Request Form (<https://admin.ks.gov/offices/chief-counsel/kansas-open-records-act/kansas-open-records-act-request-form>); “USGS Current Water Data for the Nation” by United States Geological Survey, 2023, (<https://waterdata.usgs.gov/nwis/rt>).

Table 3*Water Rights of the Associated Ditch System*

Ditch name	Annual water right (Acre-ft)
Amazon	31,000
Southside	20,000
Great Eastern	60,000
Farmer's	20,000
Garden City	4000

Note. Adapted from data obtained from the Kansas Department of Administration via the Open Records Request Form (<https://admin.ks.gov/offices/chief-counsel/kansas-open-records-act/kansas-open-records-act-request-form>).

The average monthly flow volumes of the Arkansas River were analyzed from 2002 to 2011, as these years had diversion flow volume data available for the ditch system. The flow volumes of the Arkansas River were compared to the diversions of the ditches over the same period. The diversions were retrieved from a study performed over that same period by Spronk Water Engineers (2014). By taking the difference between the monthly flows and the ditch diverted flow, it is possible to determine the excess volume of flow in the Arkansas River. The median of all excess volumes was found. A month was then considered to be high enough flow to have a portion of that flow diverted if it was above the median. A diversion percentage of 30% was used on those excess flows above the median. This approach was taken because water rights need to be considered. It is more likely that a new water right would be granted for period of high flow or unseasonable wetness. Again, there is no clear-cut method to determine the

available water for a water right as they are considered on a case-by-case basis, so this approach was taken. Water rights are discussed in more detail in the legal considerations section of this capstone project report. If the flow exceeded the median excess volume, the median flow was subtracted from it and then a diversion percent of 30% was used to estimate the available volume of water to be diverted. This analysis employed the same field size and water demand as the previous analyses. Table 4 shows the number of months with sufficient flows for diversions per year, the total divertible flows for the year, and the estimated number of fields sustained.

Table 4

Alternative 3 Months with Sufficient Flows for Diversions, Total Annual Excess Flows, and the Number of Fields Sustained

Year	Months with divertible volumes	Diverted volumes (Acre-ft)	Fields sustained
2001	2	3452	30
2002	7	7520	65
2003	0	0	0
2004	6	5666	49
2005	6	5302	46
2006	4	3827	33
2007	11	19,668	171
2008	7	9534	83
2009	7	10,638	93
2010	6	12,170	106
2011	4	3648	32
Median	6	5666	49

The median number of fields sustained for this alternative is 49, making this alternative the most viable of all the alternatives. Therefore, Alternative 3 was further investigated in the alternative analysis process and a preliminary design was completed. The alternative analysis included a further examination of relevant factors such as local water rights, the determination of

a feasible infiltration method based on local factors, and an evaluation of potential stakeholders. The development of the preliminary design featured an assessment of the area required to meet infiltration requirements, use of the Associated Ditch System for transporting the water, the size of the infiltration structure, the cost and benefits of the system, and environmental impacts.

Alternative Analysis

Southwest Kansas on the Arkansas River

The primary area for this study is the area around Lakin in Kearny County, Kansas. This area is shown in Figure 5. This area was chosen as it is near a source of infiltration water, the Arkansas River, and it is associated with a unique feature—an existing system of irrigation ditches. It was thought that the Associated Ditch System may be able to represent a savings for the conveyance of the infiltration water; that is why this particular area was chosen. Figure 4 shows the ditch system outside of Lakin and the location of the flow meter that was used in this analysis. First, the flows of the Arkansas River were analyzed and compared to the diversions from the ditch system. Figure 6 displays the average monthly flow of the Arkansas River at Kendall, Kansas, gauge number 07138020.

Figure 5

Location of the City of Lakin and Kearny County in Kansas, United States

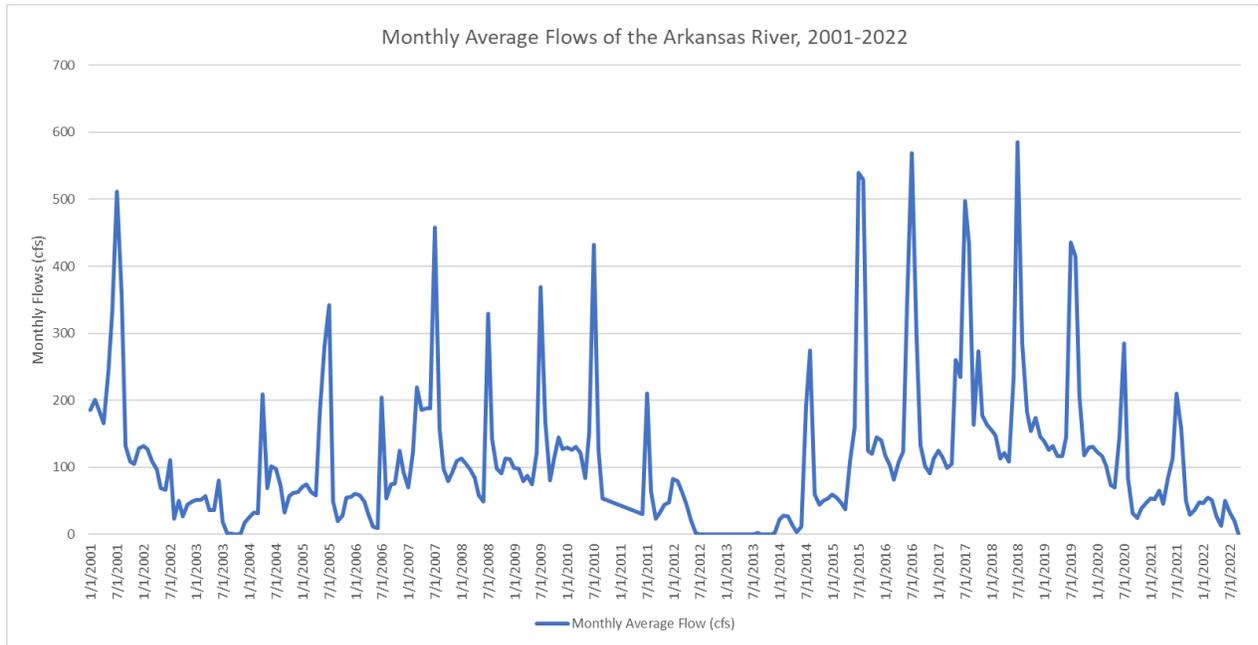


Note. Adapted from “TIGER/Line Geodatabases” by the United States Census Bureau

(<https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-geodatabase-file.html>).

Figure 6

Monthly Average Flows of the Arkansas River, 2001 to 2022



Note. Adapted from “USGS Current Water Data for the Nation” by United States Geological Survey, 2023, (<https://waterdata.usgs.gov/nwis/rt>).

There appears to be some seasonality in the flows of the Arkansas River with June through August having a higher flow than the rest of the year, although flow events occur from March to September. It appears that the baseflow varies over much longer periods of time, with some years seeing no flow in the river at all. Table 5 displays the average monthly flows in the Arkansas River from 2001 to 2022.

Table 5*Average Monthly Flows of the Arkansas River, 2001 to 2022*

Average Monthly Flows of the Arkansas River, 2001 to 2022	
Month	Average Flow (cfs)
January	88.6
February	89.3
March	85.9
April	84.0
May	91.6
June	129.8
July	292.2
August	168.8
September	73.5
October	73.9
November	81.3
December	82.4

Note. Adapted from “Site Inventory for the Nation” by United States Geological Survey, 2023, (<https://waterdata.usgs.gov/nwis/inventory/>).

Table 5 indicates that periods of higher flow start in June and continue through August. This is most likely due to releases from an upstream reservoir for irrigation during the irrigation season. Interestingly the second highest month of flow, August, is immediately followed by the month with the lowest flow, September. Table 6 displays the average monthly precipitation of Kearny County, the county in which the ditch system is located.

Table 6*Average Monthly Precipitation in Kearny County, 1981 to 2010*

Kearny County Average Monthly Precipitation, 1981 to 2010	
Month	Precipitation (in)
January	0.44
February	0.45
March	1.11
April	1.54
May	2.31
June	3.03
July	3.03
August	2.91
September	1.25
October	1.52
November	0.56
December	0.56

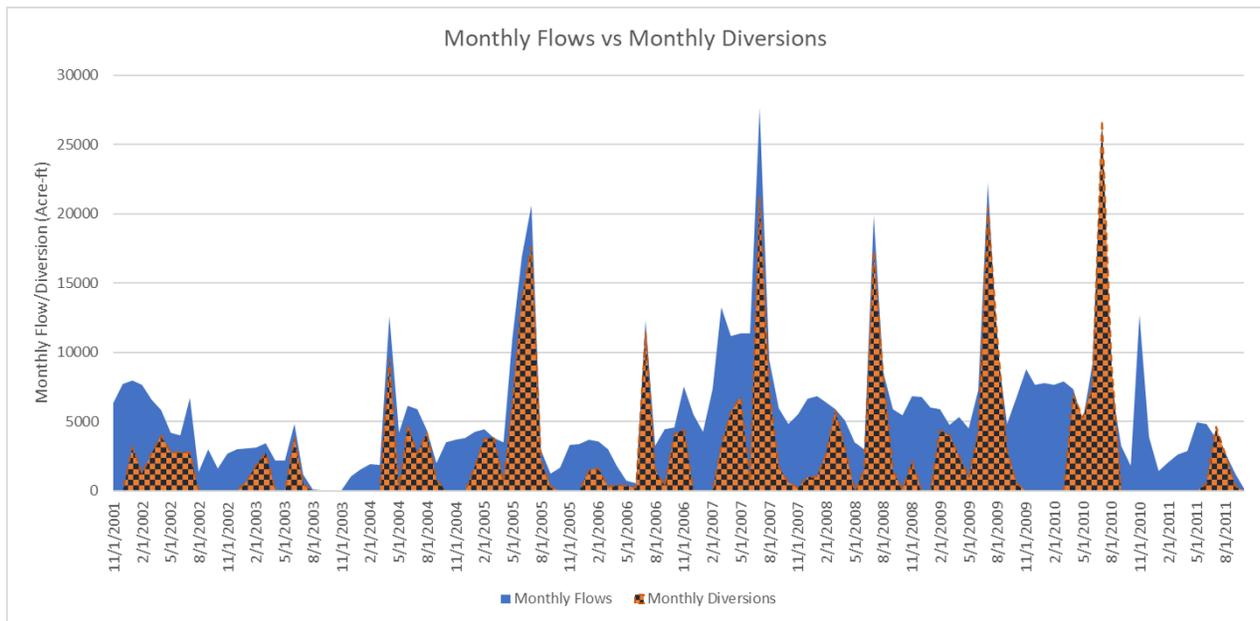
Note. Adapted from “Monthly Precipitation Reports” by Kansas State University, (<https://climate.k-state.edu/precip/county/>).

Table 6 indicates that the highest monthly flows seen in this area coincide with the periods of high rainfall in this area. This indicates that the river is vulnerable to changes in the local climate and may be prone to large shifts. However, there is a difference in the timeframes for Tables 5 and 6. Both have large timeframes that overlap, but they also feature approximately 10 years when they do not overlap. The differences between flow and precipitation during these years are likely negligible.

The most significant factor affecting the potential volume of water that can be infiltrated is the diversions from the nearby ditch system as any new water right would have to consider their diversions. Figure 7 compares the monthly volume of flow, in solid blue, to the monthly volume that was diverted by the ditch system, shown in the hatched.

Figure 7

Comparison of the Volume of Flow in the Arkansas River to the Volume of Diversions, 2001 to 2011



Note. Adapted from “USGS Current Water Data for the Nation” by the United States Geological Survey [USGS], 2023, (<https://waterdata.usgs.gov/nwis/rt>); and *System Optimization Review of the Associated Ditch System in Kearny and Finny Counties, Kansas* by Spronk Water Engineers, Inc. and GEI Consultants, Inc., 2014, (http://www.gmd3.org/wp-content/uploads/2017/07/SOR_Report_September_Final.pdf).

In Figure 7, the solid areas represent the volume of flow that could be diverted for infiltration. The hatched areas represent the diversions from the Associated Ditch System. When

the areas are overlaid, the remaining solid area represents the volume of flow that is left in the river after the diversions are complete. However, the actual flow that can be infiltrated is less, because of downstream water users. Figure 7 shows that the peak flows seen in the river are already almost fully utilized by the ditch system, but there is divertible volume in the periods after peak flows.

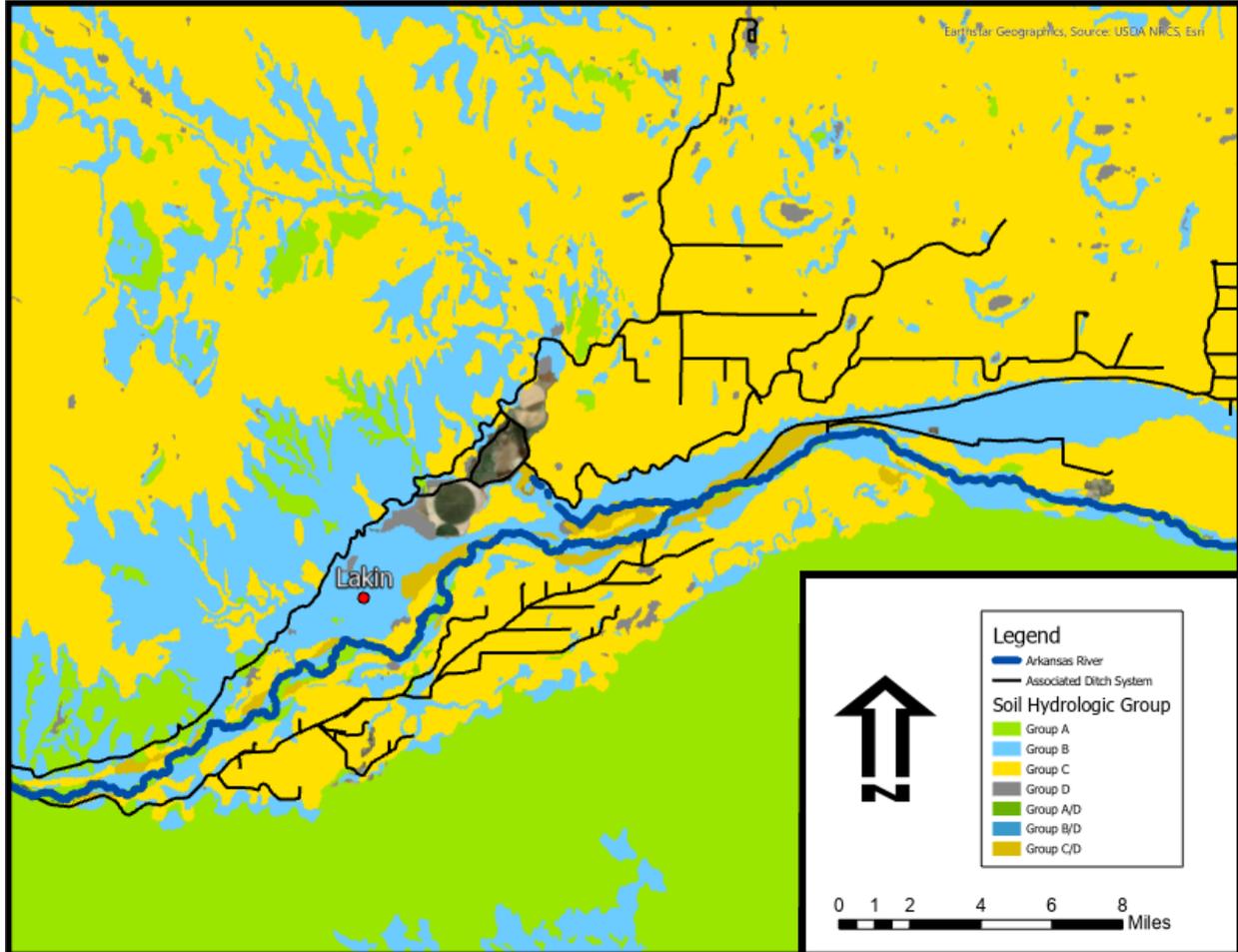
Whittemore (2000) describes the Arkansas River as one of the most saline rivers in the United States and goes on to characterize the constituents within the water and acceptable uses for the Arkansas River. The major constituents, in order of decreasing concentration, are sulfate, sodium, bicarbonate, calcium, magnesium, chloride and silica. The salinity within the Arkansas River makes it unusable for municipal use in all but the highest flows, and the water quality along with periods of no flow renders this portion of the river in Southwest Kansas uncondusive to macroscopic aquatic life.

The constituent that is responsible for most of the salinity in the Arkansas River is sulfate. The use of sulfate-rich water for irrigation has been studied, although not extensively and not with crop types currently commonly grown in Kansas. Papadopoulos (1986) found that saline water high in sulfate significantly reduced the yields of tomatoes and eggplants by an average of 22%, while bell peppers yield was not affected. Lower yield was due to reduced fruit size. The salinity followed two stages, an initial stage where the soil salinity increased, and a second stage where the salinity reached a steady state and changed little. The steady state was due to the sulfate precipitating out of the solution as gypsum. A global meta-analysis of crop yield using saline water for irrigation found a 17.3% reduction in crop yield, although the reduction was much higher for salt-intolerant crops (Cheng et al., 2021). While this analysis investigated saline water, it was not necessarily saline water with sulfate as the primary constituent.

Soil salinity is not a local problem to Kansas. It is estimated that 50% of the arable land globally will be salinized by 2050 (Shrivastava & Kumar, 2014). Shrivastava and Kumar (2014) explain that the salinization of soil can be offset by crop choice, the development of more saline-resistant crops in the future, and by microbiological methods that are currently being investigated. The alternative to irrigation with this saline water is dryland farming. Dryland farming is farming with no use of irrigation (Stewart, 2016). Dryland farming also reduces yields over the long term and makes crops much more susceptible to changes in local climate such as droughts (Kukul & Irmak, 2018).

Acceptable MAR Methods

One of the most important factors in MAR is the infiltration rate. Figure 8 shows the hydrologic soil groups in this region. Hydrologic Soil Groups (HSG) is a classification of soils by their least hydraulically conductive layer. The least conductive layer can be any soil layer that transmits water at a slower rate relative to soils above or below it (National Resources Conservation Service [NRCS], 2007).

Figure 8*Hydrologic Soil Group in the Associated Ditch Area*

Note. Adapted from "Soil Hydrologic Group" by National Resources Conservation Group (NRCS), October 2022, (<https://www.arcgis.com/home/item.html?id=be2124509b064754875b8f0d6176cc4c>).

As is seen in Figure 8, the areas served by the ditch system are primarily in Hydrologic Soil Group (HSG) C. There are some areas in HSG B, but they are under Lakin itself. The portion to the south is HSG A, the best soil group for infiltration, but further analysis revealed it is at a significantly higher elevation than the river and using the ditches to convey water is not possible to those locations. HSG C soils are soils that have a lower hydraulic conductivity and

may not be acceptable for surface infiltration MAR methods. The soil is classified as Group C based on the least conductive soil layer in the top 50 centimeters of soil (NRCS, 2007). It is important to note that the hydraulic conductivity may improve vastly below these 50 centimeters. These areas are likely inundated with silt from Arkansas River floods and are near historic pathways of the river that would have also deposited silt. There may be layers of sediment below the silt that could have a much higher hydraulic conductivity.

Though the surface infiltration rate is a very important factor, it is not the only factor to consider. The soil types deeper within the ground as well as the groundwater table are both important considerations. Soil with high infiltration rates should extend to the water table to allow for the opportunity for increased aquifer recharge. Using the Kansas Water Well Completion Records (WWC5) Database, it is possible to obtain some information about the subsurface. It appears that there is approximately 20 to 35 feet of unsaturated sand and gravel deposits underneath a clay layer of varying thickness. There are even a few sand mining operations in the area. This is an indication that permeable soil deposits are present at depth in the area, allowing increased infiltration rates to the surface aquifer. It would be a suitable candidate for a surface MAR method, if the soil layer of low hydraulic conductivity can be bypassed.

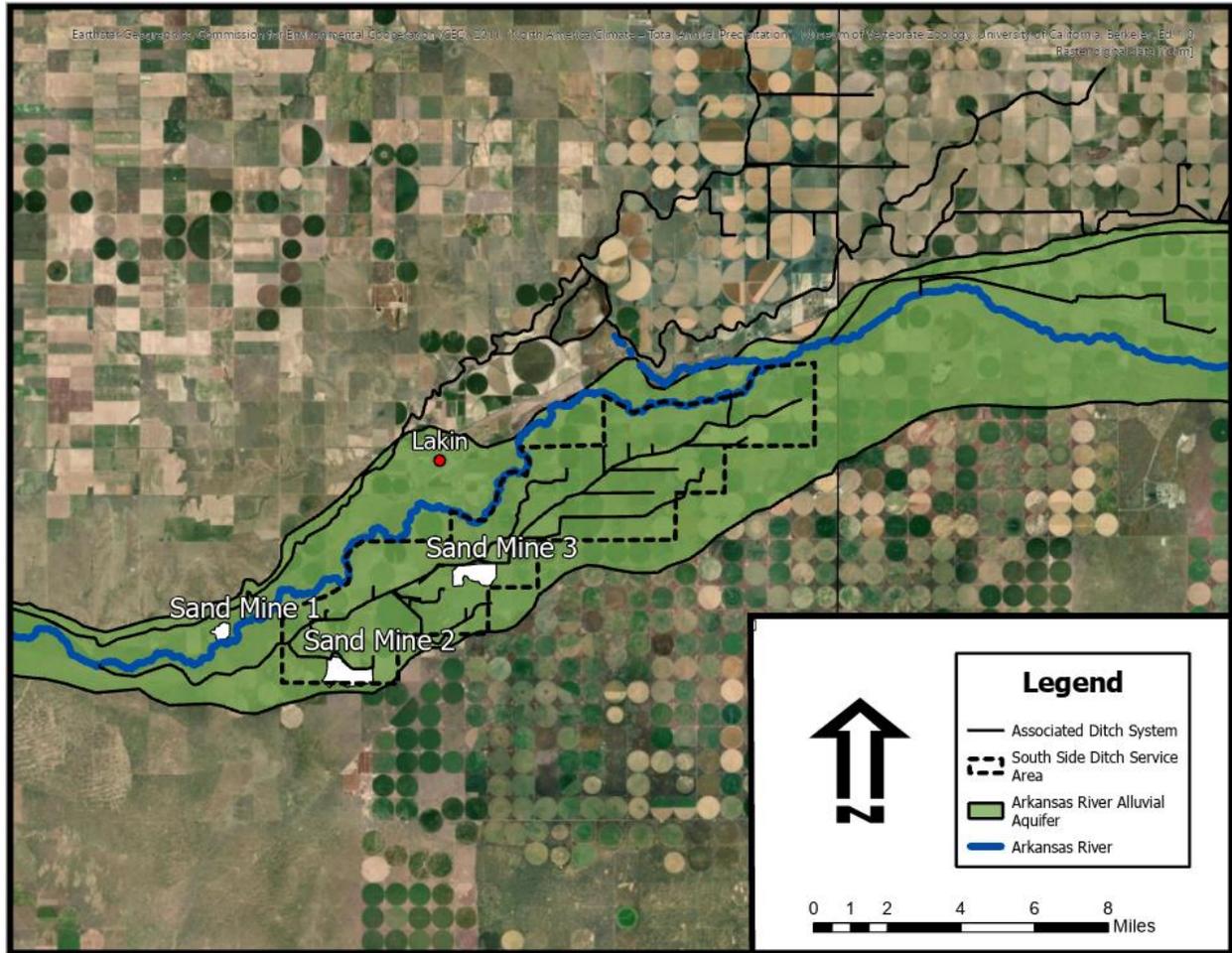
Although there appears to be a suitable surface aquifer, this is the alluvial aquifer of the Arkansas River and not a formation of the High Plains Aquifer. There may be some connectivity between the two in this region. A thick clay layer appears to separate the upper alluvial aquifer and the lower High Plains Aquifer under the Associated Ditch System. This indicates that surface methods of recharge may not significantly recharge the lower aquifer itself. Filling the alluvial aquifer may become an alternative and renewable source of water that can take demand

from the High Plains Aquifer, extending its lifetime. This would be a much simpler and cheaper option, while still providing benefit, versus recharging the High Plains Aquifer itself via deep injection methods. Infiltrating the water would also create large water savings because of the mitigation of evaporation, as the water will be stored underground and not on the surface. This area of Kansas has a 50-inch potential net evaporation (Kansas Department of Agriculture [KDA], 1996). The potential net evaporation is calculated by subtracting the annual precipitation from the annual average evaporation. This represents an opportunity to retain much more water for the local area. Figure 9 shows the extent of the Alluvial Aquifer.

The surface infiltration methods described earlier included an infiltration basin, spreading ground, and an infiltration gallery. The infiltration gallery would be suitable for the local conditions, as there is a layer of low hydraulic conductivity above a much more hydraulically conductive layer. But this method also represents a larger capital cost and higher maintenance costs. Figure 9 shows the locations of sand and gravel mines in the area. These are areas where the layer of soil with a low hydraulic conductivity has been removed, exposing the sand and gravel deposits of the alluvial aquifer. In some instances, depressions that could serve as infiltration basins already exist. In the other cases, it would make excavation of new basins easier. The infrastructure would be classified as an infiltration basin as defined above. It would also be much simpler and cost effective to maintain the infiltration basins. The sand and gravel mines are concentrated in the area served by the South Side Ditch, which makes this area the primary area for the remainder of the analysis. The extents of the service area of the South Side Ditch are shown in Figure 9.

Figure 9

Location of Sand Mining Operations in the Alluvial Aquifer of the Arkansas River and the Service Area of the South Side Ditch



Note. Adapted from data obtained from the Kansas Department of Administration via the Open Records Request Form (<https://admin.ks.gov/offices/chief-counsel/kansas-open-records-act/kansas-open-records-act-request-form>).

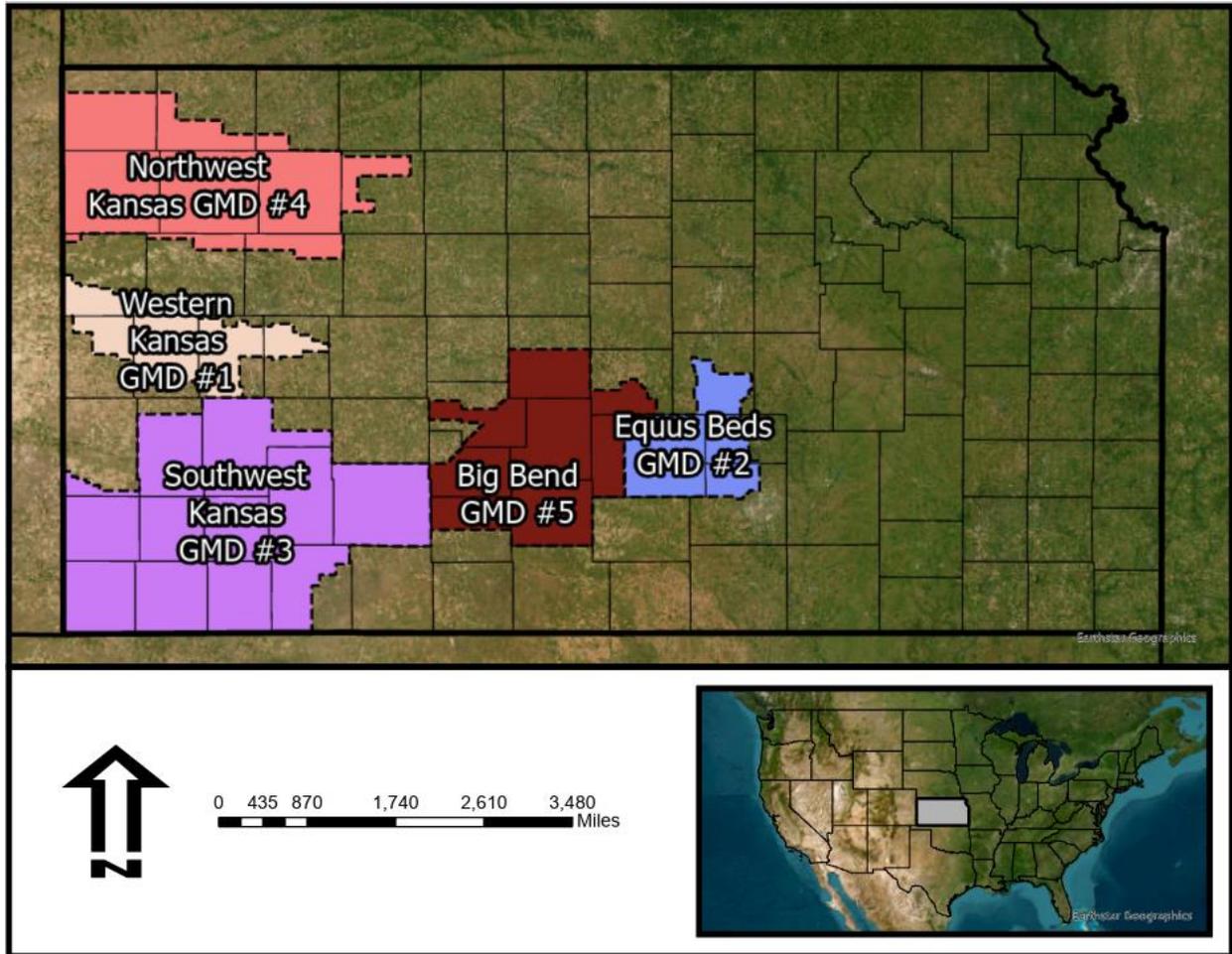
Stakeholders

Because of the depletion of the High Plains Aquifer, Kansas has established a legal framework for the creation of Groundwater Management Districts (GMDs). GMDs are created by groups of landowners who submit their plans to the state engineer for the boundary and member landowners for their district (Kansas Groundwater Management District Act, 1972).

Figure 10 displays the GMDs within Kansas.

Figure 10

Groundwater Management Districts in Kansas



Note. Adapted from data obtained from the Kansas Department of Administration via the Open Records Request Form (<https://admin.ks.gov/offices/chief-counsel/kansas-open-records-act/kansas-open-records-act-request-form>).

The area around Lakin is contained within GMD Number 3. As GMDs are grass-roots organizations of local people who are worried about groundwater conservation, they are a potential stakeholder. GMDs even have the power to construct, operate, and maintain

infrastructure designed to recharge or store water within their borders (Kansas Groundwater Management District Act, 1972). This means that GMD Number 3 would be able to manage any infrastructure itself. GMDs also could raise or seek funding for these projects. They can raise funds through water charges or issuing bonds and they are also able to incur debt (Kansas Groundwater Management District Act, 1972).

There is some precedence for GMDs to pursue projects related to water conservation completely independently. GMD Number 3 has started a pilot project of small-scale water transportation. The initial test conducted in 2021 moved water within the state from the Missouri River to the Arkansas River basin (Rude, 2021). The test was a single 6,000-gallon truck tanker, but the GMD is working with the state engineer to approve further appropriations, both from within Kansas and from neighboring states.

Other potential stakeholders include the Division of Water Resources (DWR) and the sand mine property owner. The DWR includes the state engineer who would need to approve any new water appropriations or rights. The sand mine property owner is overseen by the Division of Conservation (DOC), which enforces the Surface Mining Land Conservation and Reclamation Act. This act regulates the operation and reclamation of sand and gravel mines. Requirements for a closed sand or gravel mine include re-grading of the site as well as replacing any topsoil and revegetation. These requirements will all have to be met while considering the design requirements of the infiltration basin, but the requirements are similar. This means that the sand mine owner could be incentivized to sell the land cheaply, as the construction of infiltration basins meets the same requirements as the reclamation of the basins.

Legal Considerations

A water right is a legal document that gives an entity the right to appropriate surface or groundwater and is required for any water use in Kansas. Water rights are assigned on a prior appropriation doctrine in Kansas. This means that water rights operate on a “first in time, first in right” basis (Rogers et al., 2013). Older water rights have seniority, and junior water rights can be restricted or even eliminated if they are found to be impacting these earlier rights. Water rights can also be eliminated if they are not used. Rogers et al. (2013) list six main attributes of a water right:

- 1) Priority Date
- 2) Maximum Rate of Diversion
- 3) Maximum Annual Quantity
- 4) Point of Diversion
- 5) Place of Use
- 6) Type of Beneficial Use

The first step in obtaining a water right is filing an application. The application is filed with the State Engineer who reviews it, and the application is also reviewed by a GMD if the water right is within one. If a permit is approved, the water right then needs to be “perfected” before it is granted. For a period of five years, water use at the new water right is measured. The year of the highest beneficial water use, up to the maximum of the original application, is then the volume of the new water right (Rogers et al., 2013). This could pose an issue for MAR. If the perfection period is one that is significantly drier than usual, the actual water right granted may be much less. However, it is possible to apply for an extension of the perfection period. The maximum annual quantity of water being requested is very important. The volume of water that

was found to be divertible in Alternative 3, as seen in Table 3, is much less than the other water rights in the area for the ditch systems, as seen in Table 2. The maximum annual quantity of water requested would be rounded up to 6000 acre-ft a year.

Preliminary Design

In this capstone project, infiltration basins were found to be the most feasible MAR method for this area. To design them, an estimated flow will have to be calculated and used with a design infiltration rate to determine their size. A suitable location for the basins will also have to be selected.

Estimated Flows

The estimates in this section employ the same flow volume found in the Alternative 3 section. The median flow for 2001 to 2011 was combined with the diversion percentage of 30% to calculate an estimate of 5666 acre-ft a year that would be available for diversion. Although this is a volume that could be used for determining a potential water right and for projecting the fields sustained over many years, it does not reflect a shorter period of higher flow. This estimate was further investigated to determine a flow rate for design. Table 7 shows the average divertible flows by month. February has the highest average divertible flow of all months. Therefore, the infiltration basin was sized to infiltrate 1113 acre-ft a month. It was assumed that the flow would be spread evenly across the entire month, giving a flowrate of 18 cfs. This assumption was made because of observations in Figure 7, which showed that much of the available water for diversion was not during the peak flows, but rather the period of elevated flows after the peak flow. This flow is also well within the capacity of the South Side Ditch, which is 200 cfs (Spronk Water Engineers & GEI Consultants, Inc., 2014).

Table 7*Average Divertible Flows by Month, 2001 to 2022*

Divertible Monthly Flows of the Arkansas River, 2001 to 2022	
Month	Average Divertible Flow (Acre-ft)
January	939
February	1113
March	848
April	251
May	499
June	790
July	463
August	0
September	370
October	661
November	909
December	804

Infiltration Basin

In the Alternatives Analysis section, the sand mining operations in the service area of the South Side Ditch were identified as the best places to locate the infiltration basins. There are three sand mining operations in this area, shown in Figure 9. The most suitable sand mine was

selected. Sand Mine Number 1 is located adjacent to the river. This position is not optimal because any water infiltrated will almost immediately contribute to the flow of the river, giving little chance for its beneficial use. Sand Mine Number 3 has standing water that is visible through aerial photography. A review of historical aerial photography makes it apparent that this water is always present. This could indicate possible impediments. For example, it could indicate that this mine has been lined with a low permeability material to turn it into a pond, which would not be suitable for infiltration. It could also indicate that the sand mining operation is deep enough to contact groundwater. The EPA (2021) recommends at least four feet of separation between the bottom of the infiltration basin and the seasonally high groundwater table. This recommendation allows for some attenuation of any contaminants within the infiltration water; having standing water would also lead to more evaporation losses. If the pond seen in Sand Mine Number 3 is the result of high groundwater levels, this would also make it an unsuitable location for an infiltration basin. Sand Mine Number 2 is adjacent to the South Side Ditch, making it cost effective to use the existing ditch to convey infiltration water. It is also far enough away from the river to allow for the beneficial use of its infiltration water. This scenario renders Sand Mine Number 2 as the best possible location for the infiltration basin.

The first step in designing the infiltration basin was to determine a reasonable infiltration rate to use for the investigation. Results from the Web Soil Survey, created by the NRCS (2019), were used to find the dominant soil type under Sand Mine Number 2 from two to ten feet below ground surface. The area of Sand Mine Number 2 is dominated by Las Animas loamy sand. This soil has an estimated infiltration rate of 0.83 ft/hr. A safety factor of 4 was applied to consider the potential of future sedimentation between maintenance periods as well as unexpected

geological characteristics not captured by the Web Soil Survey. This gives the infiltration rate of 0.21 ft/hr that was used for the design in this capstone project.

Next, the time of infiltration was determined. The Minnesota Stormwater Committee (MSSC) (2021) recommends that standing water not be allowed to stay for longer than 48 hours. This is because of concerns about mosquitoes and damage to plantings within the basin. This recommendation was used to size the basin in this project.

Finally, with the sizing of the basin, the dimensions can be determined. The first dimension was the depth. The MSSC (2021) indicates that Equation (1) can be employed to calculate the depth of the infiltration basin:

$$D = I \times T \quad , \quad (1)$$

where:

D is the maximum allowable depth (ft),

I is the infiltration rate (ft/hr),

T is the drawdown time (hr).

The design infiltration rate was 0.21 ft/hr and the design time was 48 hours. This gives a maximum allowable depth of 10 feet. Equation (2) from the MSSC (2021) is employed to calculate the required area for infiltration:

$$A = V/D \quad , \quad (2)$$

where:

A is the required area for infiltration (square feet [sf]),

V is the infiltration volume (cubic feet [cf]),

D is the maximum allowable depth (ft).

The design flowrate of 18 cfs was turned into volume over the course of 48 hours. This indicated a volume of 3,110,000 cubic feet. Combining these values gives a required area of 311,000 sf. Two basins in parallel were constructed in tis capstone project design. The reason is that while one is being filled for its 48-hour period of inundation, the other can be draining to meet the time constraint. This design also adds redundancy to the system while maintenance is being performed.

The MSSC gives little guidance for the dimensions of the basin once the area has been identified. The Wisconsin Department of Natural Resources (WDNR) (2004) suggests a long rectangular shape with a length to width ratio of three to one. Equation (3) and (4) are adapted from WDNR (2004):

$$A = 3W^2 \quad , \quad (3)$$

where:

A is the required area of infiltration (sf),

W is the width of the infiltration basin (ft).

The length of the basin is determined as follows:

$$L = 3W \quad , \quad (4)$$

where:

L is the length of the infiltration basin (ft),

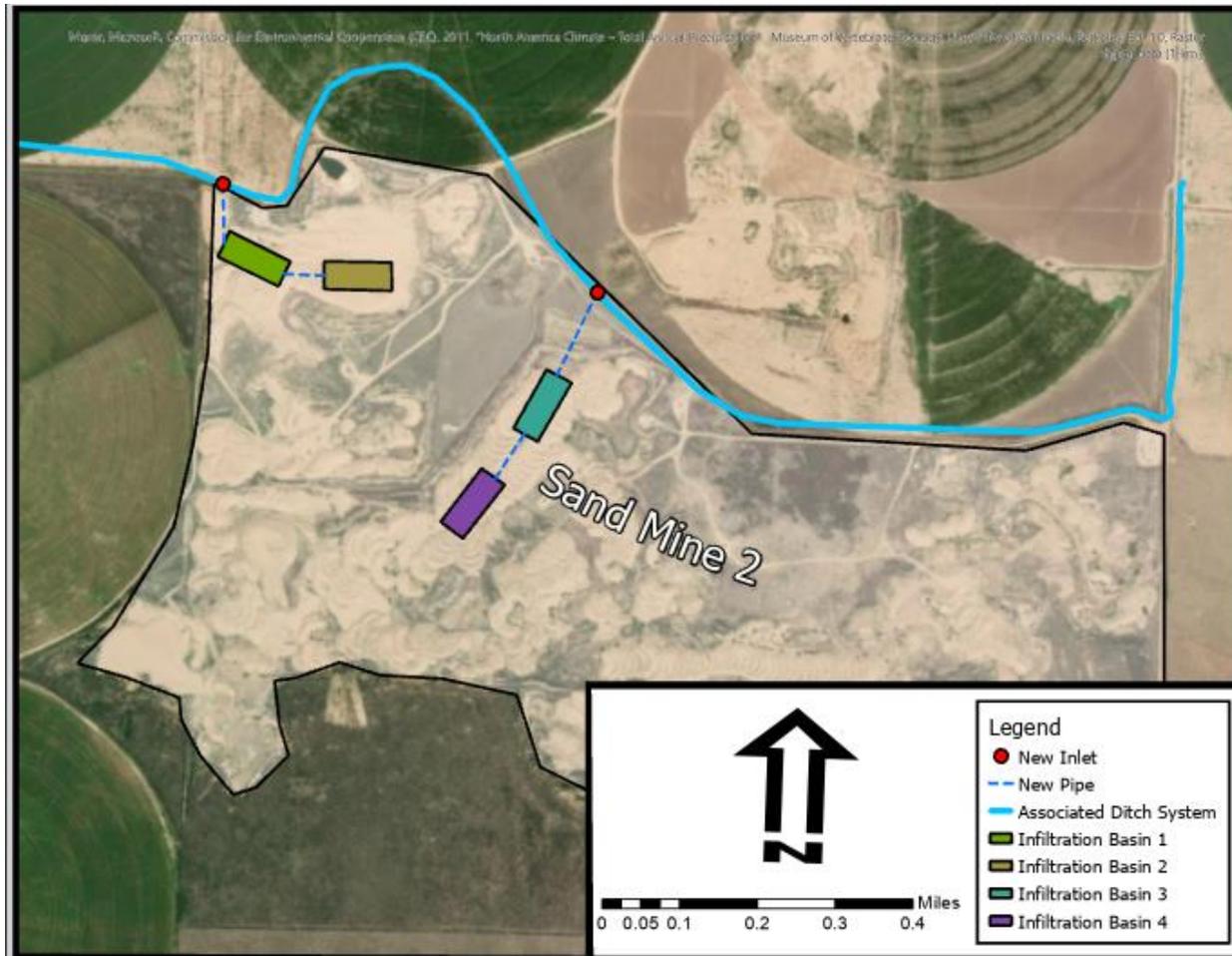
W is the width of the infiltration basin (ft).

Using Equations (3) and (4), the width was calculated to be 186 feet, and the length was calculated to be 558 feet. These numbers were rounded up to 190 and 560 feet for simplicity. These are the dimensions of the bottom of the basin, but there are sloped sides as well. The extra storage volume provided by the sloped sides was considered to add another factor of safety to the design. The MSSC (2021) suggests a maximum of a 3:1 side slope for an infiltration basin. This capstone project design employed a 4:1 slope to make maintenance of the infiltration basins easier. This gives an upper width of 230 feet and an upper length of 600 feet.

The MSSC (2021) mandates that a treatment basin volume of 100% be used when the native soil's infiltration rate exceeds 0.5 ft/hr. Although the capstone project design infiltration rate was less than that, the real infiltration rate exceeds 0.5 ft/hr. This means that a basin of the same size will precede each infiltration basin to remove sediment and suspended solids. Maintenance can then be focused on these initial basins, as most of the sediment will have fallen within them. Figure 11 shows the placement of the basins within Sand Mine Number 2.

Figure 11

Infiltration Basins within Sand Mine Number 2



Note. Adapted from data obtained from the Kansas Department of Administration via the Open Records Request Form (<https://admin.ks.gov/offices/chief-counsel/kansas-open-records-act/kansas-open-records-act-request-form>).

The MSSC (2021) suggests that native plants be prioritized for planting within infiltration basins. It also suggests that salt-tolerant plantings be utilized in areas where saline water may be encountered. As the water in the Arkansas River is saline, plants that are salt tolerant and native

to Kansas were prioritized. The Kansas Agricultural Extension located in Kearny County provided a list of salt tolerant native plants. The list was then filtered for grasses and flowering plants that would make an acceptable ground cover. Salt tolerant native plants that fit these criteria are Butterfly Weed, Swamp Milkweed, Common Milkweed, Missouri Evening Primrose, Little Bluestem, Foxglove Beardtongue, Aromatic Aster, Big Bluestem, Solidago, Wild Bergamot, Coneflower (Jessica Sharp, personal communication, May 8, 2023).

Cost Analysis

Table 8 shows the cost estimate associated with the construction of the four basins. It also includes the seeding of the entire Sand Pit Number 2 area. Table 9 shows the estimated annual operations and maintenance costs associated with the infiltration basins. Both estimates were created with line items from the MSSC (2022). The unit costs were taken from the RSMMeans (2023) database. Maintenance primarily revolves around fixing erosion and replanting, with sediment removal every five years. Table 10 shows the estimated annual benefit of the system. The estimated benefits were created with prices from the Irrigation and Water Management Survey (United States Department of Agriculture [USDA], 2018). The estimated benefits must be tempered with the fact that it is very hard to put a price on water, especially in this arid area. Off-farm irrigation water may not be available in this area at any price. Nonetheless, the total cost was estimated to be approximately \$978,000 and the benefit was estimated to slightly less than \$140,000. This result gives a break-even point of approximately seven and a half years.

The cost per acre-ft of water using infiltration basins can be compared with the cost from an alternative project. The Kansas Aqueduct is a massive pipeline to transfer water from the Missouri River to Western Kansas (United States Army Corp of Engineering [USACE], 1983). The estimated upfront cost of the Aqueduct is \$18 Billion with an estimated \$1 Billion dollar

annual operation cost and would provide 3.4 Million acre-ft of irrigation water (USACE, 1983).

Table 11 shows a per acre-ft cost comparison between infiltration and the Kansas Aqueduct over a 20-year period. While there are some differences between the two projects, they both represent means to the same end: reducing dependency on the High Plains Aquifer to a sustainable level.

Table 11 indicates that the normalized cost data (in U.S. dollars per acre-feet) for both projects reveal that the proposed use of infiltration basins in this capstone project results in a savings of two orders of magnitude.

Table 8*Preliminary Estimate for Construction of the Basins*

<u>Description</u>	<u>Units</u>	<u>Quantity</u>	<u>Unit Cost</u>	<u>Estimated Price</u>
Site Preparation				
Infiltration Area Protection - Silt Fence	Lineal Foot	3320	\$ 3.31	\$ 10,989
Site Formation				
Excavation - 1 C.Y. Excavator 6'- 10' Sand	Cubic Yard	74724	\$ 5.54	\$ 413,971
Grading - Steep Slopes	Square Yard	2631	\$ 0.35	\$ 921
Hauling off-site	Cubic Yard	74724	\$ 5.11	\$ 381,840
Structural Components				
Inlet Structure	Each	2	\$ 1,500	\$ 3,000
Site Restoration				
Backfill - 1'	Cubic Yard	11811	\$ 2.10	\$ 24,803
Seeding - above basin	M.S.F	12	\$ 20.50	\$ 237
Planting - within basin	Square Yard	5111	\$ 30	\$ 153,333
Subtotal				\$ 989,093
10% Contingencies				\$ 98,909
Total Cost				\$ 1,088,003

Table 9*Preliminary Estimate for Maintenance of the Basins*

<u>Description</u>	<u>Units</u>	<u>Quantity</u>	<u>Unit Cost</u>	<u>Estimated Price</u>
Replace Planting Media	S.Y.	185	\$ 12	\$ 2222
Debris Removal	per visit	4	\$ 50	\$ 200
Sediment Removal	Annually	1	\$ 1000	\$ 1000
Erosion Repair	S.Y.	185	\$ 50	\$ 9255
Total Annual Cost				\$ 12,677

Table 10*Estimated Cost Benefit of the Infiltration Basins*

Volume of water infiltrated annually (Acre-ft)	Cost of 1 Acre-ft of irrigation water in this region	Total Benefit
5,666	\$24.66	\$139,723

Table 11

Per Acre-ft Cost Comparison Between the Kansas Aqueduct and Infiltration Basins over a 20-Year Period Using a 7% Interest Rate

Method	Total Water Provided (Acre-ft)	Total Cost	Normalized cost (\$/acre-ft)
Infiltration Basins	113,320	\$ 3,072,000	\$ 27
Kansas Aqueduct	68,000,000	\$ 72,650,000,000	\$ 1068

Environmental Impacts

Hurd et al. (1999) predicted that the Great Plains region would be one of the first areas in the United States to experience severe hydrologic disruption because of long term climate change. This region is already experiencing the disappearance of streams and other surface water bodies because of groundwater depletion (Sophocleous, 2000). This means that water will be scarcer than ever in Southwestern Kansas. One of the most important causes of losses of water stored in surface reservoirs is evaporation; on average, federally operated reservoirs in Western Kansas lost 54% of their inflow because of evaporation (Brikowski, 2000). This is a major drawback associated with surface reservoirs, but water storage is still required. The subsurface storage of water using MAR would be able to reduce this evaporation.

Creating new methods of storage will be more important than ever as rainfall becomes more erratic. The EPA (2016) notes that in Kansas “Average rainfall during the summer is likely to decrease, the longest period without rain each year is likely to increase by three or four days” (p. 1) and “During the last 50 years the amount of rain falling during the wettest four days of the

year has increased by 15%” (p. 2). This means that while the drier periods are drier, the wetter periods are wetter. This scenario could lead to flooding and will lead to an increase in demand for storage opportunities to weather the dry periods.

Ponce and Lindquist (1990) describe baseflow augmentation as the temporary storage of subsurface water in the area in and around rivers and streams. This includes floodplains, streambanks, and stream bottoms. The stored water then increases the low flow in the river, giving it the ability to flow for longer and at a higher volume. As not all the water infiltrated will be retrieved for irrigation, a large amount of the “missed” water would make its way back to the river, boosting and stabilizing its normal flows. This water could then be retrieved by other beneficial users in ditch systems further downstream.

Results

This capstone project analysis found that a design featuring four basins—two pretreatment basins and two infiltration basins—would be the most feasible MAR method in Southwest Kansas. There would be two systems of basins in parallel with two basins in series to make a system. The preliminary design has an estimated cost of over \$1,000,000 to sustain 49 fields. The return on investment is a 7.5-year period. This analysis also assumed that all water that is infiltrated is then retrieved by wells for the beneficial use of those who have paid for the infiltration basins. It needs to be acknowledged, though, that it is impossible to control groundwater, and some will most likely be retrieved by those who did not contribute.

The preliminary design in this project is also very conservative. Safety factors were applied to the infiltration rate, and the basins were sized without consideration of the triangular area of the sloped sides to create a design that would definitely work. The pretreatment basins

would also act as infiltration basins, increasing the infiltration capacity. The design had to be conservative as field sampling and testing did not take place in this project. If a more focused design could be completed, the cost would most likely be lower.

This design also recharges the alluvial aquifer instead of the High Plains Aquifer itself. While this could lead to stress reduction on the High Plains Aquifer, it is not solving the root problem in the High Plains Aquifer itself.

Finally, Arkansas River water is very saline, and its use for irrigation without significant mitigation strategies could lead to long term reduction in yields. However, agricultural yields drop regardless, since the switch to dryland farming will become a necessity as the High Plains Aquifer depletes. It is possible that the use of saline water with a mitigation strategy would still produce better yields than dryland farming.

Conclusions

In conclusion, this capstone project resulted in the determination of a MAR strategy that is suitable for the High Plains Aquifer region. It was found that larger regional rivers are most likely the best possible candidate to supply water for MAR. The particular river in this investigation, the Arkansas River, is very saline, with limited potential uses. Infiltration basins were determined to be the most suitable MAR method for this area, and sand mines were determined to be the best location for them. Stakeholders who would be interested in constructing MAR implementations were identified, as well as stakeholders who would need to regulate the MAR process.

Recommendations

Because of the factors discussed in this capstone project, Kansas is a prime location for future MAR projects, but the Arkansas River may be too saline. Investigating other major rivers in Kansas, such as the Smoky Hill, Solomon, or Republican Rivers, may identify an area even more suitable for MAR.

As the main issue with using the Arkansas River for MAR is salinity, any research into ways to mitigate salinity would add viability to this project. This could include switching crops currently grown to focus on saline-resistant varieties, as well as microbiological developments, or the use of genetic modification of existing crop types common in this region.

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Civil Engineering

Capstone Report Approval Form

Master of Science in Civil Engineering – MSCVE

Milwaukee School of Engineering

This capstone report, titled “Feasibility of Managed Aquifer Recharge (MAR) for Southwest Kansas,” submitted by the student Jack A. Ferrante, has been approved by the following committee:

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