PHREATOPHYTES IN SOUTHWEST KANSAS USED AS A TOOL FOR PREDICTING HYDROLOGIC PROPERTIES

by

TREVOR S. AHRING

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Major Professor
Dr. David Steward

Abstract

The Ogallala Aquifer is a supply of water for several municipalities in western Kansas, as well as an irrigation source for local farmers. Since the 1950's, when the aquifer started to be pumped for irrigation, the region has seen steady declines of the groundwater table. These declines have reduced streamflow in the Arkansas and Cimarrron Rivers, and caused a redistribution of riparian phreatophytes. This thesis studies this redistribution of phreatophytes, and develops statistical relationships relating a phreatophyte's location to depth to groundwater, increase in depth to groundwater, distance from a stream or river, and hydrologic soil group. Remote sensing was used to determine tree locations on predevelopment and post-development aerial photography. These locations were mapped using ArcGIS, and ArcAEM was used to model groundwater flow in six riparian regions taking root uptake into account. It was found that once the depth to groundwater becomes greater than about 3 m, tree population will decrease as depth to water increases. Trees were located within 700 m of the river. Areas with a dense tree population (>10% tree cover) occurred where the average depth to water ranged from 0.24-1.4 m. Areas with moderate tree density (5-10% tree cover) corresponded to an average depth to water ranging from 2.1-19 m. Areas with a low tree density (<5% tree cover) corresponded to an average depth to water ranging from 11-28 m. It was found that phreatophytes have a high likelihood of growing on hydrologic soil group A and a low likelihood of growing on hydrologic soil group B. The number of trees located on hydrologic soil group D was what would be statistically expected if tree location were independent of soil type. It was also found that tree locations could be used as an indicator of good hydraulic connectivity between surface water and groundwater.

This information can be used to help guide future installation of monitoring networks and expand research projects from central Kansas to western Kansas.

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1. Introduction

The Ogallala Aquifer in western Kansas provides a stable foundation for irrigated agriculture as well as potable water for municipalities and some industry. This semiarid grassland ecosystem has limited precipitation and water demands exceed natural recharge rates. Consequently, streams have experienced declining flows and riparian habitat has experienced changes in species and composition. Since most of the riparian tree species are phreatophytic and use great quantities of water, it can be assumed that altering tree location and density would affect the local water table. This thesis studies how groundwater movement has changed since irrigation development (development) and the relationships between tree locations and depth to groundwater, distance from the river, and hydraulic connectivity.

The ecology of western Kansas has been altered by settlement patterns over the past century. When the settlers arrived, western Kansas was a short grass prairie ecosystem and the bison and antelope populations grazed to the near exclusion of trees. Once the native ungulates were replaced by farms and cattle, cottonwood tree populations expanded along the rivers. In the 1950's, the Ogallala Aquifer began to be seen as a potential source of irrigation water. The water level over much of the aquifer has decreased significantly since the 1950's (KGS 2006). The stream flows of the Cimarron and Arkansas Rivers have also declined (USGS 2008). The riparian ecology has been affected by these changes and the riparian zones, once dominated by cottonwood trees, now support fewer trees. The trees that remain are mostly saltcedar. This change in ecology may have an impact on the water balance because both species of trees are phreatophytic and can use great quantities of water.

The two dominant phreatophytic riparian tree species in the region are cottonwood (populus deltoides) and saltcedar (tamarix). These species have differences in water source, rooting depth, and tolerance to salinity (Butler 2007, Canadell 1996, Shafroth 2005). Only minimal differences were found in water usage, but several differences were found in the source of that water (Butler 2007, Busch 1992, Cleverly 2006, Owens 2007).

When water is available in the vadose zone, cottonwood trees will use it. Field studies show that when the water table is shallow, a one meter strip of cottonwood trees extending across the riparian zone will consume 0.62 m^3 of groundwater per day, which is equivalent to wells spaced 5.3 km apart continuously pumping 3.3E3 m^3/day over the width of the riparian zone. If the water table is below the root network, less groundwater is consumed (Butler 2007).

Tamarix trees generally maintain a high level of ET during periods of stress, unlike cottonwoods (Busch 1992). Water table depth seemingly has no effect on tamarix, even at depths below 10 m, and tamarix is not affected by moderately dry soil. Tamarix roots can grow at a rate that is faster than soil drains (Cleverly 2006). Early studies have found that a single saltcedar tree can use up to 757 L of water per day (Holdenbach 1987). This has led to massive control and removal efforts. However, more recent studies conclude that a more reasonable estimate for a single tree is a maximum of 122 L of water per day. This 85% decrease in the estimated transpiration rate of tamarisk indicates that the benefits for the control and removal have been grossly overestimated (Owens 2007).

Canadell et al (1996) conducted a study to determine the rooting depth of many species of trees, including cottonwood. It was determined that cottonwood trees in a deciduous forest have a maximum rooting depth of 2.6 m. Cooper et al (2003) later found that cottonwood trees root to the depth of the annual floodplain water table low. It was found that the roots would not penetrate deeper because the hydraulic conductivity was too low.

Cottonwood trees require floods to propagate, so they are typically found in flood plains and riparian zones (Nagler 2005). In western Montana, Law (2000) found that cottonwoods generally establish on sandy soils, on slopes ranging from 0.9^o to 1.0^o. The sandy texture is consistent with the finding of Cooper et al. (2003) that cottonwood roots do not penetrate soils with low hydraulic conductivity.

Saltcedar leaves can contain a high salt content, so when these leaves drop onto the ground, soil salinity increases. Saltcedar is highly resistant to soil salinity, but some native species are not. This can make it difficult for a native species to thrive once saltcedar has invaded (Shafroth 2005).

The Ogallala Aquifer recharges at a very slow rate due to low annual precipitation and declining streamflows (Sophocleous 2005). Whenever an aquifer is not pumped or pumping is sustainable, the aquifer is at equilibrium and

$$R = P + D \qquad \textbf{(1)}$$

where

R = recharge

P = pumping rate

D = discharge

If the aquifer is pumped at a rate that is not sustainable, as is the case with the Ogallala Aquifer, then

$$R < P + D \qquad \textbf{(2)}$$

It is difficult to estimate recharge in this case because pumping usually causes a decrease in discharge but occasionally causes an increase in recharge (Devlin 2004).

Sophocleous (2005) analyzed the results of multiple studies on recharge of the Kansas High Plains Aquifer. These studies included two major regional climatic soil-water balance studies by the USGS, one for Kansas and one for the entire High Plains Aquifer, a study using a finite difference model to estimate recharge both prior to and after development, a county-scale groundwater study for Finney County, and a field-based experimental recharge study. Analysis of data from all western Kansas Counties based on Kansas Geological Survey (KGS) bulletin publications provided an average recharge of nearly 8 mm/yr with a standard deviation of less than 4 mm/yr. A similar analysis using data from the Kansas Water Resources Board (KWRB) resulted in a mean recharge of nearly 7 mm/yr with a standard deviation of about 3 mm/yr. The regional climatic soil-water balance studies and regional groundwater modeling studies resulted in similar recharge values, both less than 10 mm/yr. The field-based studies resulted in variable recharge depending on the climatic-soil-vegetation system of the area. It is difficult to say which method provides the most accurate recharge, so a combination of the methodologies was chosen as the preferred way to deal with the issue. The overall consensus was that the average recharge of the Ogallala Aquifer in Kansas is less than 10 mm/yr. This rate is not enough to support the irrigation pumping in the area, given current rates of extraction (Sophocleous 2005).

The most important factors in predicting the locations of phreatophytes are proximity to a floodplain (Nagler 2005), soil type (Law 2000, Cooper 2003), and water availability (Butler 2007, Cleverly 2006, Owens 2007).

Very few studies have attempted to use tree locations for groundwater modeling purposes. Steward et al (2007) used the analytic element method to model groundwater uptake by phreatophytes in a small study area near Larned, KS. In this study, individual cottonwood trees were digitized on ArcMap by drawing circles around trees on aerial photography. The spatial data from these circles was then imported into a script that traced the source of each tree's water supply and quantified water usage.

Brunke et al (1997) reviewed factors controlling connectivity between river and groundwater ecosystems, viewing them as linked components of the hydrologic ecosystem. Beneath any stream or river, a hyporheic zone exists. This zone is defined as "a saturated, subterranean matrix of interstitial spaces characterized by permanent darkness, low current velocities, and high substrate stability." Unlike groundwater, it is partially composed of surface water with other qualities. The permeability of the hyporheic zone depends on the hydraulic conductivity of the alluvium.

The exchange process between groundwater and surface water is most influenced by geological and anthropogenic genesis of the catchment area, hydrology, climate, and geomorphology. The interaction between a river and groundwater will either be through infiltration or exfiltration into the saturated zones. The direction of the exchange is dependent on hydraulic head gradient, and the rate of flow is dependent on sediment permeability (Brunke 1997). With low precipitation, baseflow is typically composed primarily of groundwater because the groundwater will have a higher hydraulic head than the surface water. With high precipitation, runoff and interflow increase, leading to higher hydraulic pressures in the lower stream reaches, and causing the river to infiltrate into the groundwater. Excessive pumping of an aquifer can lead to colmation, an excessive rate of fine sediment deposition into streambeds, which reduces the function of the hyporheic zone and makes infiltration less likely even with the presence of streamflow. Reducing the infiltration reduces recharge to the groundwater, causing the water table to decrease even further, possibly killing off riparian vegetation and increasing erosion (Brunke 1997).

No information documenting specific phreatophyte locations prior to development was readily available. Aerial photography was chosen as the method of determining phreatophyte locations prior to development. Several past studies have taken this approach to map tree locations using remote sensing software. Studies conducted by Akita et al (2008) and Suarez et al (2005) used the software package eCognition. Both studies used infrared imagery, which is unavailable for predevelopment photography.

The goal of this thesis is to explore the relationships between phreatophytes and the water balance in western Kansas by using aerial photography to determine both current and predevelopment phreatophyte locations. Remote sensing software is used to digitize tree locations. ArcGIS tools are used to determine statistical relationships between tree location and soil type, depth to water, and change in depth to water. ArcAEM is used to model groundwater uptake by phreatophytes. Prior studies used a remote sensing approach to investigate groundwater (Ahmad et al 2004, Becker 2006, Jiang et al 2008, Münch et al 2007, Rodell et al 2006), but no prior research has taken a remote sensing approach to investigate phreatophyte distribution. This thesis analyzes hydrologic properties and interactions of locations that are populated with phreatophytes, and determines if these locations indicate hydraulic connectivity, hydraulic conductivity of soil, and groundwater table depth.

2. Methods

This section first overviews the methods used for this study; the specific steps follow. Statistical methods were used to determine the relationship between tree location, depth to water, and hydraulic connectivity. This is important because tree distributions could potentially be used to estimate hydrologic properties of an area. Depth to water, change in depth to water, soil type, and distance to a stream or river were chosen as parameters for the statistical comparison. These parameters were chosen based on a literature review (Butler 2007, Cleverly 2006, Cooper 2003, Law 2000, Nagler 2005, Owens 2007) and observing aerial photography taken by the United States Department of Agriculture (USDA) Commodity Stabilization Service (1957) and the USDA Agricultural Stabilization and Conservation Service (1965, 1967).

Aerial photography was used to determine both pre-development and current phreatophyte distributions. This was the chosen method because there are no detailed records of pre-development phreatophyte distribution in western Kansas, and while records do exist for current conditions, the photography was used to maintain consistency in the type of data being analyzed. Also, current technology allows for photography to be classified using remote sensing software that is compatible with GIS software.

Six study areas, all in different counties, were selected for a small scale examination of the role of phreatophytes in the hydrologic balance. These study areas all had differences in tree distribution, depth to water, increase in depth to water, and soil type. These regions can be seen in Fig. 1.

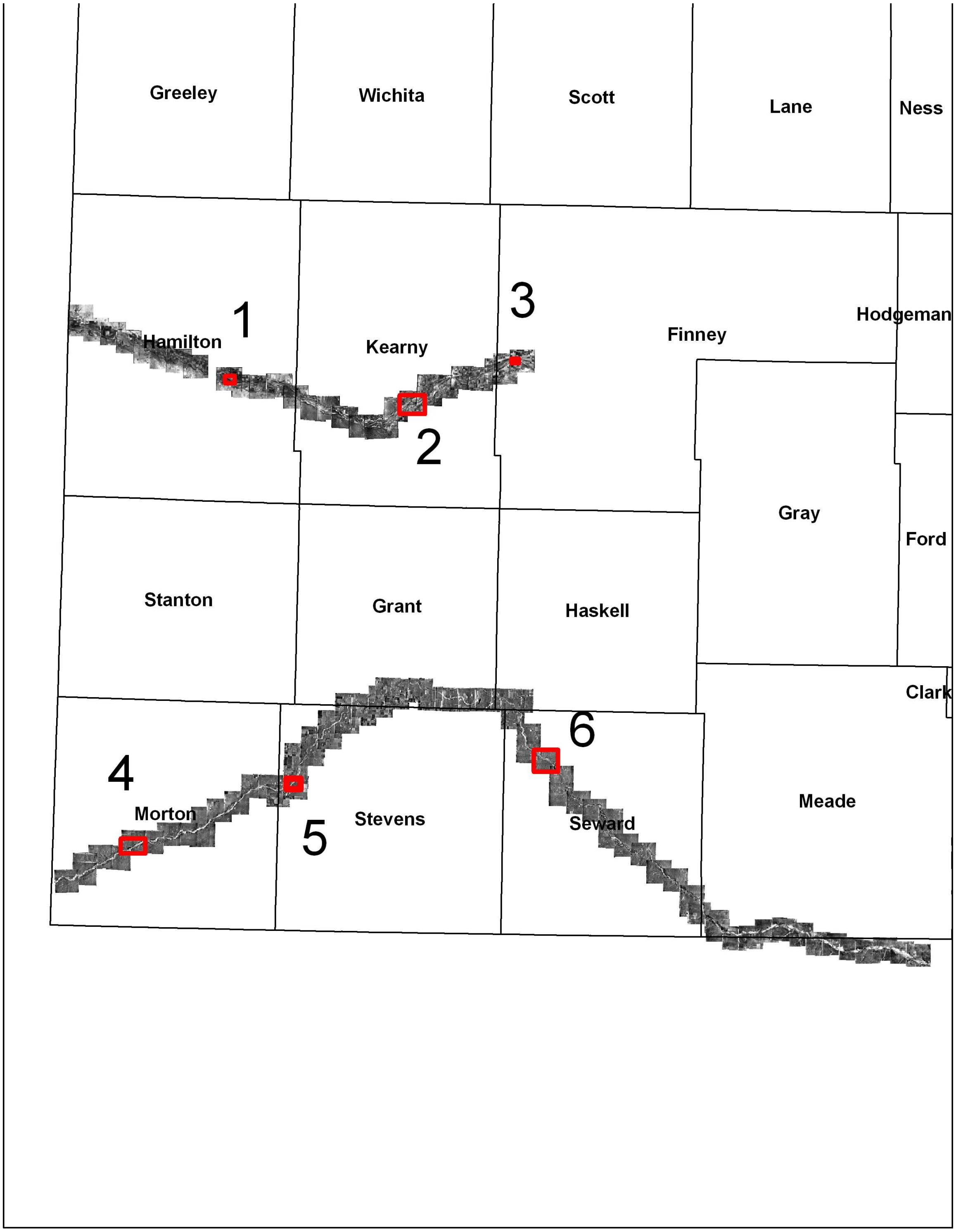


Figure 1: Locations of Study Areas along the Arkansas and Cimarron Rivers.

Predevelopment photography was georeferenced into ArcGIS using roadways. Post-development photography was available already georeferenced from the Kansas Geospatial Commons. All photography was mosaicked and clipped along both the Arkansas and Cimarron River corridors, then exported as TIF files for use with remote sensing software.

Tree classification was performed by using remote sensing software on the aerial photography. This software works by segmenting an image into polygons by using different shape and scale factors input by the user. Then, a class hierarchy is developed for classification purposes, and samples are selected for each class. After a sufficient amount of samples have been selected, the entire photograph can be classified automatically using the fuzzy nearest neighbor method developed by Keller et al (1985). This data is then exported as a vector shapefile.

A continuous depth to water raster shapefile was used to obtain depth to water data for all areas of interest. To obtain this raster shapefile, points of diversion were downloaded from the Water Information Storage and Retrieval Database (WIZARD). This point vector shapefile was then converted to a continuous raster by kriging. See the methods section for more information on the kriging procedure.

Soils data was obtained from the Soil Survey Geographic (SSURGO) Database Data Mart. This data is available to the general public in database format, and can be used in ArcGIS by joining the desired table to the provided shapefile. Data was downloaded for Hamilton, Kearney, Finney, Morton, Stevens, Grant, Haskell, Seward, and Meade Counties.

ArcAEM was used to model groundwater flow in each of the six study areas for both pre- and post-development. Recharge, root uptake from the trees, and the location and head of the river were modeled at each study site. Reverse tracking of groundwater particles was used to indicate the source of water for the trees at each location.

Four shapefiles were created, including pre- and post-development Arkansas River trees and pre- and post-development Cimarron River trees. These shapefiles were merged with depth to water data, soils data, and proximity to surface water data so that their attribute tables would reflect all considered parameters. These attribute tables were exported as .dbf files so that they could be used in Microsoft Excel.

Microsoft Excel was used to calculate the mean and standard deviation of depth to water, change in depth to water, and distance from a river for trees in all four tables. These values were all weighted by the areas of their related polygons. The standard deviation was used to develop a range of expected values using a Gaussian distribution curve. The total areas of soils belonging to Hydrologic Soil Groups A, B, C, and D were also calculated.

Georeferencing of Photography

Pre- irrigation development (predevelopment) aerial photography taken by the USDA Commodity Stabilization Service (1957) and the USDA Stabilization and Conservation Service (1965, 1967) was available in Hale Library as 8 x 10 photographs for every county in Kansas. Due to storage constraints and the fact that phreatophytes are riparian trees, these photographs were sorted and only photographs that showed riparian regions of Hamilton, Kearney, Finney, Morton, Stevens, and Seward counties were scanned and saved as 360 dpi jpeg files using Adobe Photoshop. Complete sets of photography were not available for each year, so the oldest complete set was used for each county. The dates that the predevelopment photography was taken are as follows:

- Photography for Hamilton County was from September, 1957.
- Photography from Kearney County was from July, 1965.
- Photography for Finney County was from August, 1957.
- Photography from Morton, Stevens, and Seward Counties was from May, 1967.

Post-development photography for every county in Kansas from September, 2006 was available at the Kansas Geospatial Community Commons website. This photography was taken by the Farm Service Agency (FSA) National Agriculture Imagery Program. It was available in MrSID format and was already georeferenced. Photography for Hamilton, Kearney, Finney, Morton, Stevens, and Seward Counties was downloaded.

In order to georeference the old photography, the shapefile tiger_2000_roadways was downloaded from the Kansas Geospatial Community Commons website. This shapefile was created by the U.S. Census Bureau and shows Kansas roadways in 2000. It was then imported into ArcMap. A photograph was then imported into ArcMap and, using the georeferencing toolbar, it was fit to the display. Then, the “Add Control Points” button was selected, and road intersections were lined up with the intersections on the tiger_2000_roadways shapefile. After the photograph was spatially accurate, it was rectified and saved under the GRID format. This process was repeated for each photograph. In some instances, there was not enough roadway data to accurately georeference a photograph. In this case, the photographs were skipped. Then, the overlap between photographs was used for georeferencing. Since the recent photography had already been georeferenced, it only needed to be imported into ArcMap. An example of photography lining up with the roadway shapefile can be seen in Fig. 2.

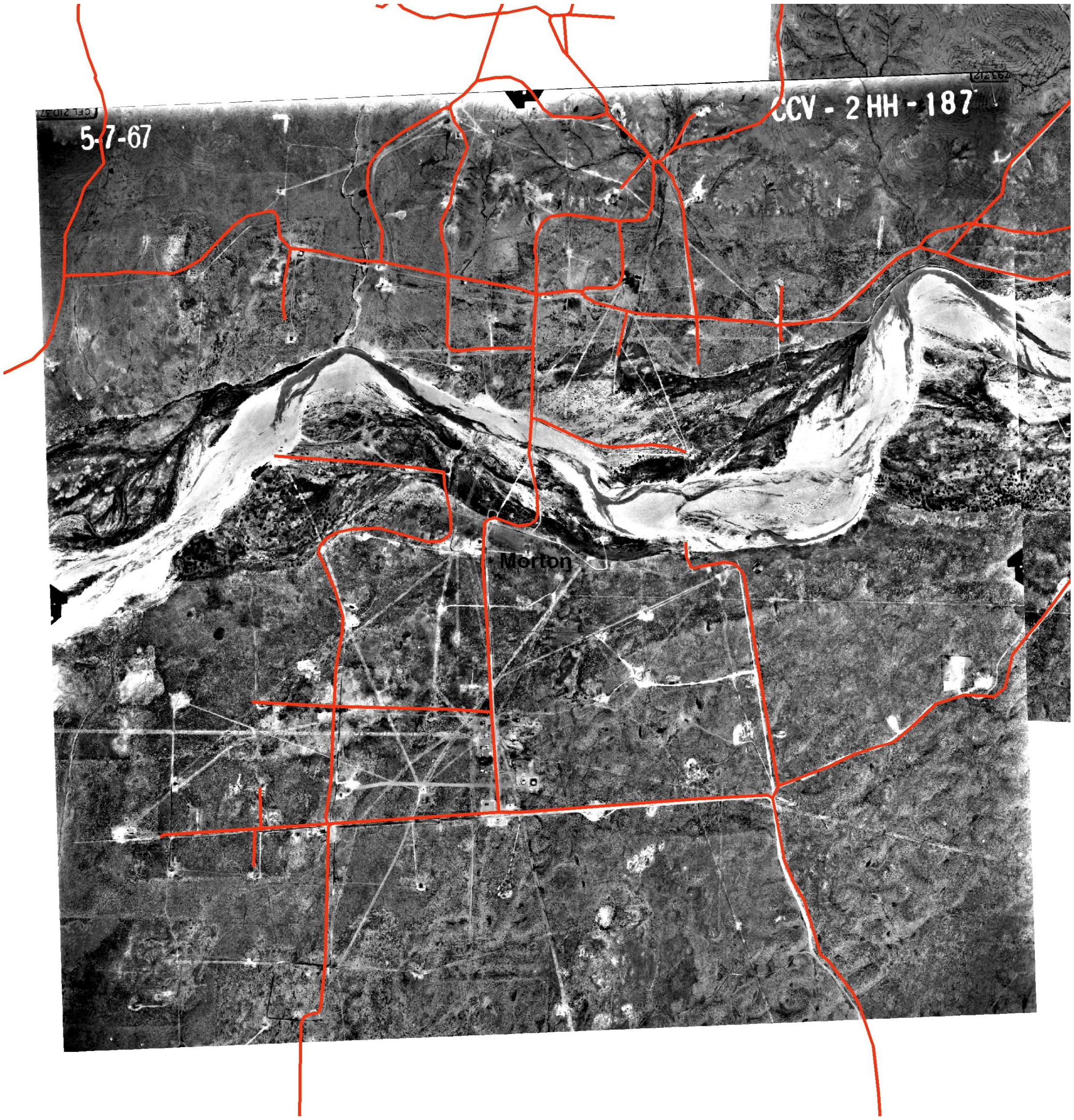


Figure 2: A Typical Overlay of an Aerial Photograph with the tiger_2000_roadways Shapefile.

Obtaining and Merging Data

Soils data was downloaded as databases from the Soils Data Mart created by the SSURGO Database. Data for Hamilton, Kearney, Finney, Morton, Stevens, Gray, Haskell, Seward, and Meade Counties was downloaded. These databases were imported into ArcMap, along with shapefiles that were downloaded from the SSURGO Soils Data Mart. The table “muaggatt” in each database was joined to the corresponding county shapefile using the field “mukey”. The soil shapefiles for each county were then imported into ArcMap. The Merge tool, located in the Data Management Tools toolbox, was used to combine soils data for Morton, Stevens, Gray, Seward and Meade Counties, as well as Hamilton, Kearney, and Finney Counties.

Streamflow data was taken at the nearest gauging stations to each study area. This data was available at the United States Geological Survey (USGS) website. Graphs of this data can be found in Fig. 3.

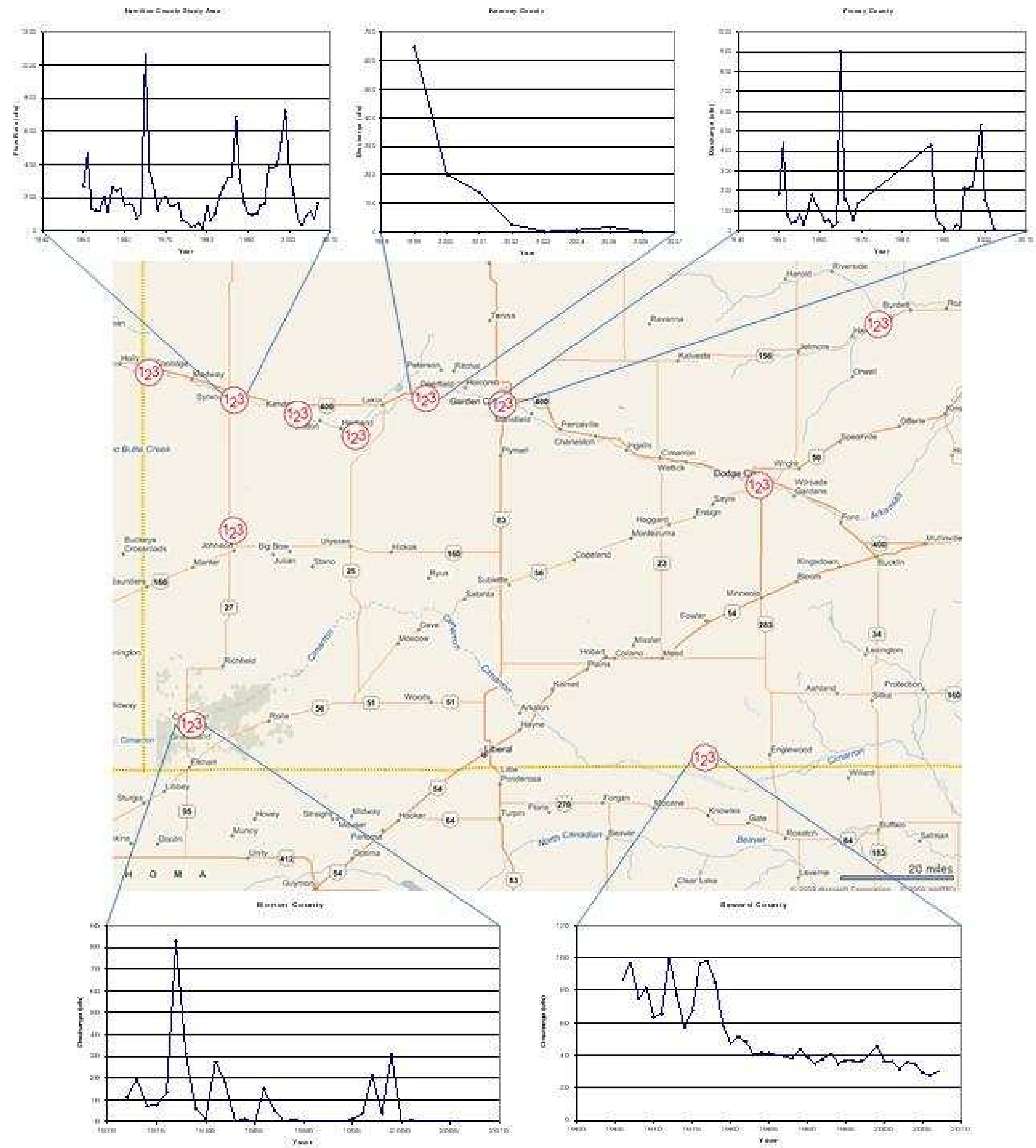
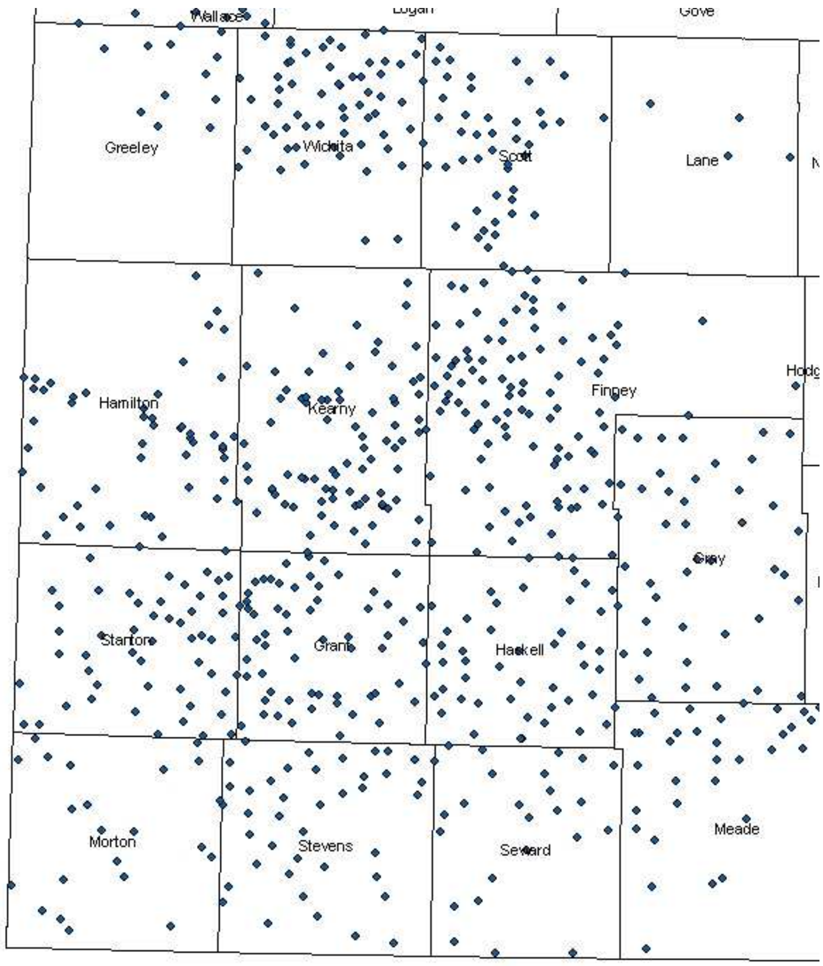
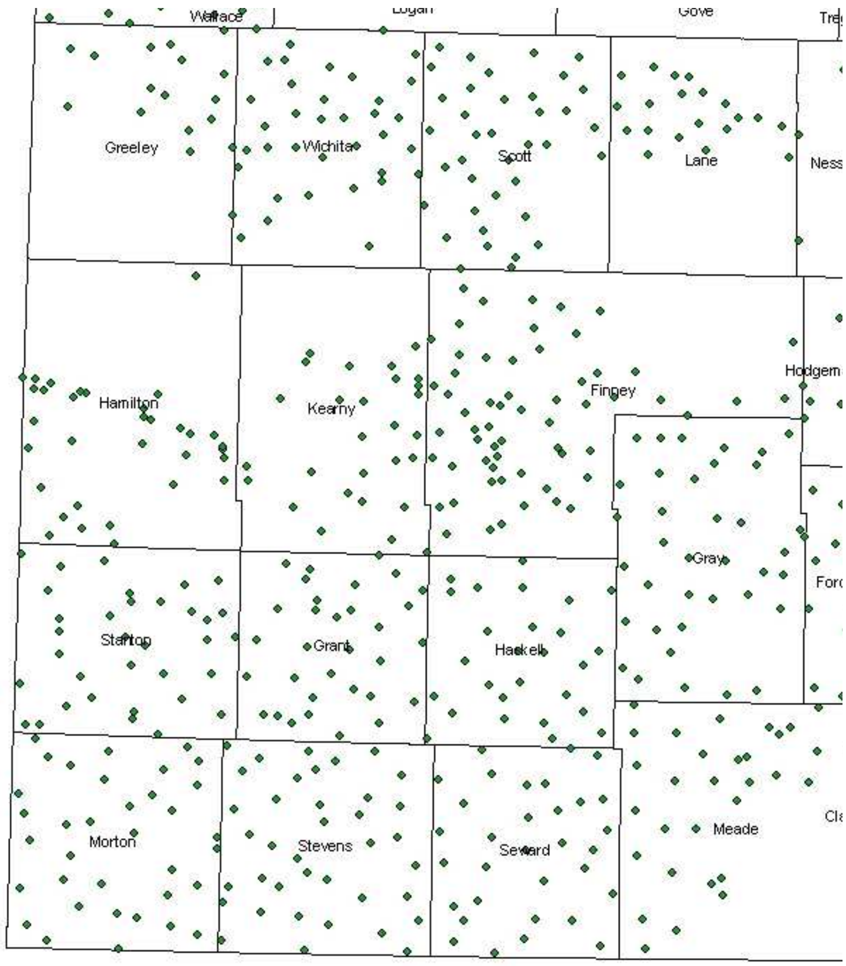


Figure 3: Locations of Gauging Stations near Study Sites and their Respective Discharges.

The WIZARD database was used to determine the location of observation wells and depths to water in those wells. A 30 m Digital Elevation Model (DEM) was downloaded from the USGS website. The Extract Values to Points Tool, located in the Spatial Analyst Tools toolbox was used to get the surface elevation at WIZARD well locations. Kriging was used to create a raster showing water table elevation across all of western Kansas. To do this, four rectangular polygons were created and overlapped so that each area would have enough wells in it to create accurate Kriging results. The Geostatistical Wizard toolbar was then used to calculate water table elevation across each rectangular polygon using kriging. These results were then mosaicked into a single grid using the Mosaic to New Raster Tool, located in the Data Management Tools toolbox. The raster calculator was used to create a depth to water raster by subtracting the water table elevation from the surface elevation provided by the DEM. Kriging is applicable for generating a groundwater depth raster because groundwater level generally changes smoothly without any sudden jumps. The accuracy of the groundwater depths obtained from kriging decreases as the distance from the nearest well increases. See Fig. 4 for maps of all wells used for the kriging in 1965 and 2005. This work was completed by Dr. Xiaoying Yang, a Post-Doctoral Research Associate working for Dr. David Steward at Kansas State University.


Wallace
Logan
Gove
Greeley
Wichita
Scott
Lane
Hamilton
Kearny
Finney
Stanton
Grant
Haskell
Gray
Morton
Stevens
Seward
Meade

a



b

Figure 4: Distribution of Wells used for Kriging in (a) 1965 and (b) 2005.

Water level data for 1965 and 2000 and the 30 m DEM from USGS were then imported into ArcMap. Depth to water in both 1965 and 2000 was calculated by subtracting the water level elevation from the DEM. Increase in depth to water was calculated by subtracting the 1965 depth to water from the 2000 depth to water. To ease future computation, rectangular polygon shapefiles were created and drawn around the extent of both the Arkansas and Cimarron River corridors. These shapefiles were used to clip the depth to water and increase in depth to water raster files by using the Clip Raster tool in the Data Management Toolbox.

Selection of Study Areas

One study area was selected in each county. Emphasis was placed on study areas displaying differences in soil type, depth to water, increase in depth to water, and tree distribution. Locations of study areas are shown in Fig. 1. Study areas were chosen to fit within one of the old photographs to avoid potential problems due to the overlap and trying to clip multiple raster files.

Remote Sensing

Remote sensing software was used to create shapefiles that show tree locations in each study area. At first, an entire study area was attempted, achieving poor results. It was noted that the software accurately determined tree locations near the river, where trees were prevalent, but produced many false positives away from the river, where trees were nonexistent. To fix this problem, the photographs were clipped so that nothing beyond the boundary of the tree locations was shown. This process is delineated in the following steps:

1. Six polygons, one for each study area, were created using ArcCatalog and imported into ArcMap.
2. An editing session was created for one of the polygons, and the sketch tool was used to draw a boundary around the outermost tree locations in Study Area 1.
3. The toolbox “Hawth’s Analysis Tools for ArcGIS” was downloaded from the website www.spatialecology.com. The Clip Raster by Polygons function of this tool was used to clip each black and white photograph to the drawn polygon shapefiles. In each case, a horizontal line came across the screen from the top of the polygon to the right edge of the original raster. This was not an issue because

although remote sensing results were produced along this line, these results would be outside of the polygon shapefile and could easily be deleted. The process was repeated with new polygons for the color photographs. In this case, Hawth's Tools changed the colors and produced diagonal bands across the clipped raster. This caused some trees to be different colors than other trees, and since color is important when categorizing photography, it was deemed unacceptable.

4. As an alternative to Hawth's Tools for post-development photography, White boxes with white borders were drawn along the edges of the riparian zone with trees, essentially creating a clipped polygon. Then, maps displaying each study area were exported as tiff files from ArcMap. The Convert Raster to Other Format (multiple) tool located in the Conversion Tools toolbox was used to convert the black and white polygons to tiff files while keeping their spatial reference. Paint was used to turn everything on the outside of the photo completely white.
5. All of the area clipped from the photography using Hawth's Tools was given a value of "NoData". Because the software package used for remote sensing, eCognition, cannot handle the value "NoData", the Reclassify button in the Spatial Analyst Toolbar was used to reclassify all fields containing "NoData" to zero.

All images were imported into remote sensing software, which was used to classify tree locations. This process involved a lot of trial and error using various parameters until desired results were achieved. The method and values used for each study area are delineated below.

1. Shape factor, compactness, smoothness, and scale parameter were required inputs to perform multiresolution segmentation, and these values were determined via trial and error until polygons were created that effectively delineated boundaries of tree areas. See Table 1 for these values and Fig. 5 for a visual sample of remote sensing results.

Table 1: Parameters Used to Determine Multiresolution Segmentation in Study Areas for Predevelopment Photography.

Study Area	Shape Factor	Compactness	Smoothness	Scale Parameter
1	0.5	0.5	0.5	10
2	0.5	0.5	0.5	10
3	0.5	0.5	0.5	20
4	0.5	0.5	0.5	20
5	0.5	0.5	0.5	10
6	0.5	0.5	0.5	10

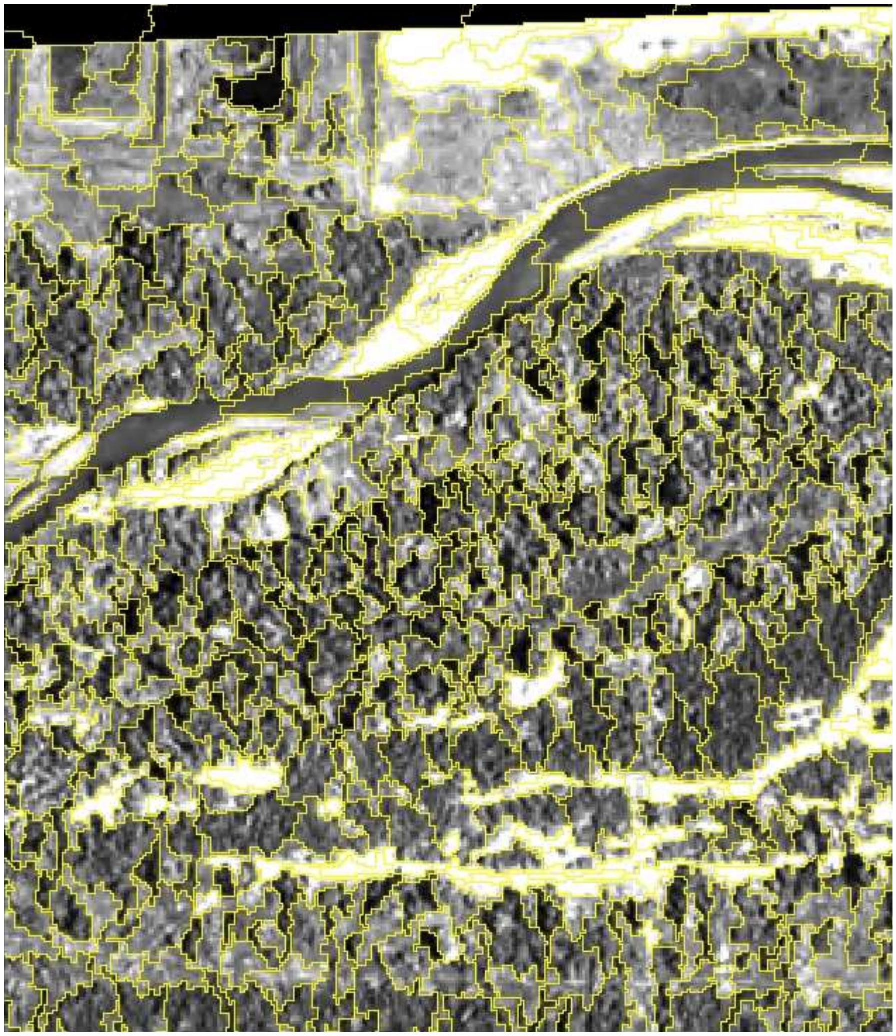


Figure 5: A Sample of the Multiresolution Segmentation Produced by the Remote Sensing Software.

2. A class hierarchy was originally created with classes named Bare Ground, Black, Sand Bar, Shrub, Tree, and Water. The Bare Ground and Sand Bar classes were meant to classify locations without trees or water. Darker ground was classified as Bare Ground, and the white ground near the river was classified as sand bar. Also, darker cropland was classified as bare ground and very light cropland was classified as sand bar. The reason for two separate classes for ground was to focus the bare ground class to darker areas, which kept the darker areas from being classified as trees. The Black class was created to classify the black background

outside of the study area so that it would not be classified as trees. The Tree class was used to identify tall trees, and the shrub class was used to identify short trees. The reason for having two different tree classes was to eliminate false positives by keeping the class from becoming too diverse. The water class was used to identify the river. It was determined that all classes could be differentiated based on color, nearest neighbor, and homogeneity. For each class, the operator mean (arithm.) was used. The expression Gray-Level Co-Occurrence Matrix (GLCM) Homogeneity (all dir.) was added with default values, and the expression standard nearest neighbor (generated) was also used. For the Shrub class, the expression similarity to class: tree was used. These expression values were determined based upon trial and error with more expressions being added until desirable results were achieved.

3. The sample editor was set to display the features standard nearest neighbor and GLCM Homogeneity (all dir.). This made it possible to see similarities between classes and helped to determine if other classes needed to be created or existing classes needed to be modified.
4. Several samples were taken for each class, and then the fuzzy nearest neighbor method (Keller 1985) was used to automatically classify the entire photograph based on these samples.
5. When desirable results were obtained, polygons were created and the image objects were exported as a vector shapefile.

The post-development images were classified similarly to the predevelopment images. Since they were modified in Paint and not exported as georeferenced TIF files, there was no issue with unclassified cells in eCognition. Unlike the predevelopment photography, not all study areas used the same class hierarchy. The process and parameters used for segmentation and classification are delineated below. Multiresolution segmentation parameters were determined by trial and error until the created polygons accurately delineated tree areas. The parameters used for each study area can be found in Table 2.

Table 2: Parameters Used to Determine Multiresolution Segmentation in Study Areas for Post-Development Photography

Study Area	Shape Factor	Compactness	Smoothness	Scale Parameter
1	0.5	0.5	0.5	10
2	0.5	0.5	0.5	5
3	0.5	0.5	0.5	10
4	0.5	0.5	0.5	10
5	0.5	0.5	0.5	10
6	0.5	0.5	0.5	10

2. Class hierarchies were created for each county to properly classify tree locations. Each study area did not use the same class hierarchy because some study areas had different features than others, such as different-colored grass, varying tree thicknesses, etc. Each class in all study areas used the operator mean (arithm.), and the expressions GLCM Homogeneity (all dir.) and Standard Nearest Neighbor (generated). The classes Cropland, Ground, Tree, and Water were created for study areas 1, 3, 4, 5, and 6. The classes Grass, Tree, Ground, and Water were created for study area 2.
3. Samples were taken in each study area, and then the samples in each study area were classified using the fuzzy nearest neighbor method.
4. Polygons were created, and the image objects were exported as a vector shapefile.

Remote Sensing Output

Remote sensing results were imported into ArcMap. Surprisingly, the results from the predevelopment photographs were not properly georeferenced when they were imported. This should not have been the case since they were exported with a geographic reference and the cause of the problem could not be determined. The Spatial Adjustment Toolbar was attached to ArcMap in order to properly georeference each set of image objects. All corners of the results were lined up with their corresponding corners on the polygon that was created for the initial clip. The post-development results were adjusted in the same manner.

Statistical analysis was conducted on the remote sensing results for each study area to determine the accuracy of the results. A sample size of 204 was chosen to be taken for each study area. This was based on the formula for the binomial probability theory:

$$N = \frac{Z^2(p)(q)}{E^2} \tag{3}$$

Where:

N = sample size

Z = 2 from the standard normal deviate of 1.96 for the 95% two-sided confidence level

p = expected percent accuracy of the entire map

q = 100 – p

E = allowable error

For this project, the values of these coefficients were chosen as follows:

Z = 2

p = 85

q = 15

E = 5

Kappa Analysis, a discrete multivariate technique of use in accuracy assessment, was conducted on the remote sensing results. An error matrix was constructed as shown in Fig. 6.

	Ground Reference Test Information					
	Class	**1**	**2**	**3**	**k**	**Row Total**
Remote Sensing Classification	**1**	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,k}$	x_{1+}
	2	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,k}$	x_{2+}
	3	$x_{3,1}$	$x_{3,2}$	$x_{3,3}$	$x_{3,k}$	x_{3+}
	k	$x_{k,1}$	$x_{k,2}$	$x_{k,3}$	$x_{k,k}$	x_{k+}
	Column Total	x_{+1}	x_{+2}	x_{+3}	x_{+k}	**N**

Figure 6: Calculation of the K_{hat} Coefficient

From this error matrix, a K_{hat} coefficient of agreement was calculated as follows:

$$Khat = \frac{N\sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k}\left(x_{i+} * x_{+i}\right)}{N^2 - \sum_{i=1}^{k}\left(x_{i+} * x_{+i}\right)} \qquad \textbf{(4)}$$

Where

k = number of rows in the matrix

x_{ii} = the number of observations in row i and column i,

x_{i+} and x_{+i} = marginal totals for row i and column i, respectively

N = total number of observations

According to Jensen (2005), K_{hat} values >0.80 represent strong agreement or accuracy between the classification map and ground reference. Values between 0.40 and 0.80

represent moderate agreement, and values <0.40 represent poor agreement. The calculated K_{hat} values showed that in most cases, moderate agreement existed between the classification map and ground reference. However, because tree locations were the only classification that was important, a second error matrix was constructed combining all classifications other than trees into one field. This provided a better K_{hat} result in every case. Specific error matrices and K_{hat} values for each study area can be found in Appendix A. Remote sensing tree locations can be found in Figs. B4, B7, B10, B13, B16, and B19.

Modeling

ArcAEM was used to model groundwater uptake by phreatophytes in each study area, both pre- and post-development. 10 x 10 grids of particles were created for tracking at locations within each study area. Due to limitations in the SPLIT script utilized by ArcAEM, tree polygons were simplified. Up to six groups of trees in each study area were chosen for modeling. Post-development Study Area 6 had so few trees that no polygons were created for modeling, and tree uptake was ignored. A rectangular polygon was drawn around each study area and assigned a recharge value based upon Hansen (1991). Modeling parameters input for each area are shown in Table 3. The root uptake of 40 cm/yr was obtained from Steward et al (2009), and the hydraulic conductivity of 30 m/day and variable recharge rates were obtained from Gutentag et al (1984) and Hansen (1991), respectively. An aquifer thickness of 200 m was used at every location because the aquifer is unconfined, and as long as the aquifer thickness modeled is greater than or equal to actual aquifer thickness, the model will not be affected by its value. Aquifer base elevation was found by Kriging the bedrock elevations in the Enhanced Ogallala Bedrock

Database provided by Dr. Xiaoying Yang. The default porosity of 0.3 was used in every case. Q_x and Q_y were determined by Darcy's Law, which states

$$Q_x = -kH \frac{d\phi}{dx}, \tag{5}$$

and

$$Q_y = -kH \frac{d\phi}{dy} \tag{6}$$

where

Q_x = Uniform Flow in the x-Direction

Q_y = Uniform Flow in the y-Direction

k = Hydraulic Conductivity

H = Saturated Thickness of the Aquifer

ϕ = Hydraulic Head

Table 3: Modeling Parameters for Study Sites 1-6, Pre- and Post-Development, for Use in ArcAEM.

Study Area	Bedrock Elevation	Aquifer Thickness	Q_x	Q_y	Porosity	Recharge
Study Area 1, Predevelopment	950 m	200 m	1.0 m/day	0.23 m/day	0.3	3.5E-5 m/day
Study Area 1, Post-Development	950 m	200 m	0.99 m/day	0.69 m/day	0.3	3.5E-5 m/day
Study Area 2, Predevelopment	840 m	200 m	3.0 m/day	-0.75 m/day	0.3	5.6E-5 m/day
Study Area 2, Post-Development	840 m	200 m	4.4 m/day	-2.3 m/day	0.3	5.6E-5 m/day
Study Area 3, Predevelopment	780 m	200 m	5.5 m/day	1.4 m/day	0.3	6.3E-5 m/day
Study Area 3, Post-Development	780 m	200 m	6.4 m/day	-0.11 m/day	0.3	6.3E-5 m/day
Study Area 4, Predevelopment	1000 m	200 m	2.3 m/day	-0.66 m/day	0.3	3.5E-5 m/day
Study Area 4, Post-Development	1000 m	200 m	2.8 m/day	-0.64 m/day	0.3	3.5E-5 m/day
Study Area 5, Predevelopment	880 m	200 m	2.9 m/day	1.9 m/day	0.3	5.2E-5 m/day
Study Area 5, Post-Development	880 m	200 m	3.9 m/day	4.4 m/day	0.3	5.2E-5 m/day
Study Area 6, Predevelopment	750 m	200 m	2.2 m/day	-2.5 m/day	0.3	7.0E-5 m/day
Study Area 6, Post-Development	750 m	200 m	1.8 m/day	-0.63 m/day	0.3	7.0E-5 m/day

The model created a grid which was used to create head contour lines spread at 0.5 m intervals and track particles using backward tracing (See Figs. 8-19). These particle traces showed the source of water for phreatophytes. The head contour lines and particle traces also showed if the stream was gaining or losing.

Tree Locations for Extent of Cimarron and Arkansas Rivers

Aerial photography was used to determine pre- and post-development tree locations along the Arkansas and Cimarron Rivers. Predeveolpment photography was mosaicked using the Mosaic tool located in the Data Management Tools toolbox in ArcMap. Polygons were drawn around the extent of riparian trees for both rivers, both for predevelopment and post-development. To reduce the size of the files that computations would be run on, six polygons, each with a slight overlap, were created along the Cimarron River, and four polygons were created along the Arkansas River.

Each polygon was selected as the Spatial Analyst Mask and used to clip the photography by entering the raster into the raster calculator. Due to computation limitations, only Band 1 of the 2006 aerial photography was clipped. This caused the output to be black and white. All cells in these new rasters with the value “NoData” were reclassified to “0” using the Reclassify button on the Spatial Analyst Toolbar. All of these rasters were then exported as tiff files. These images were then imported into remote sensing software.

Once in the remote sensing software, all photographs were subjected to multiresolution segmentation and classification. The steps involved in these processes are delineated below.

1. For multiresolution segmentation, all images used a shape factor of 0.5, compactness of 0.5, smoothness of 0.5, and scale parameter of 20. This scale parameter produced good results in some locations, but in others, it caused the polygons to be bigger than tree areas. This could not be fixed because due to the size of the imagery being used, 20 was the smallest scale parameter that could be used without memory errors.
2. The same class hierarchy was used for all 20 images. This hierarchy included the operator mean (arithm.) with the expressions GLCM Homogeneity (all dir.), Standard Nearest Neighbor (all dir.), and Shape: Area Compactness (all dir.). Classes included Tree, Light Tree, Ground, Light Ground, Ditch, and Water.

3. Samples were taken for each class, and the fuzzy nearest neighbor (Keller 1985) method was used to automatically classify each image.
4. Polygons were created and the image objects were exported as vector shapefiles. This process was repeated for each image.

The vector shapefiles created by the remote sensing software were imported into ArcMap. They each maintained the geospatial data of the exported TIF file, so the Spatial Adjustment Toolbar was not needed. All data along the Cimarron and Arkansas Rivers for both pre-and post-development was merged into four new shapefiles using the Merge tool in the Data Management Tools toolbox.

Statistical analysis was conducted to determine the validity of the results. A sample size of 204 was selected using Eqn. 3, and the process shown in Fig. 6 and Eq. 4 was used to calculate K_{hat} coefficients. K_{hat} coefficient calculations for all sets of results can be found in Appendix A.

Working with Remote Sensing Results

In the attribute table, “Select by Attributes” was used under the options button to select all polygons where the BestClass field contained either the value “Tree” or “Light Tree”. The selected data was then exported as a new shapefile which was then imported into ArcMap. This created a shapefile that only included data for tree locations, and not the other classifications. This process was repeated for all four shapefiles.

The depth to water and change in depth to water rasters were converted to polygon shapefiles. To do this, the raster calculator was used to multiply the values by 1000. Then, the Int tool, located in the Spatial Analysit Tools toolbox, was used to convert all values to integers. The Raster to Polygon tool in the Conversion Tools toolbox was used to create the polygon shapefile. A new field was created in the attribute table of the polygon shapefile of type “Float”. Then, the field calculator was used to divide the integer output from the rasters by 1000. This gave the original values from the depth to water rasters.

The Near tool in the Analysis Tools toolbox was used to calculate the distance of each tree polygon to the nearest stream or river. NHD Flowlines were used for stream and river locations. This process was repeated for each tree location shapefile.

The intersect tool in the Analysis Tools toolbox was used to create a single shapefile with tree locations, soils data, depth to water, change in depth to water (for post-development shapefiles), and distance from a stream or river in its attribute table. This attribute table was then exported as a .dbf file for use with Microsoft Excel. This process was repeated for each river, both predevelopment and post-development.

Total available soil areas within 700 m of each river were calculated by creating a buffer around the river shapefile in ArcMap by using the Buffer tool in the Analysis Tools toolbox. Buffers were also made for areas with 620 m of the river segment at each study area. The distance values were chosen based on the extent of the 95% confidence intervals for tree distance in the river, shown in Tables 5 and 6.

Statistical Analysis

Some polygons contained multiple trees. Therefore, it was decided that all statistical analysis should be weighted by the area of the polygon. Weighted mean and weighted standard deviation of depth to water and change in depth to water was calculated for each case. The weighted mean depth and change in depth were defined as follows:

$$\overline{D}_w = \frac{\sum_{n=1}^{n} A_n * D_n}{\sum_{n=1}^{n} A_n} \quad \textbf{(7)}$$

Where

$\overline{D}_w$ = Weighted Mean Depth to Water

A_n = Area of the n^{th} Polygon

D_n = Depth to Water of the n^{th} Polygon

The weighted standard deviation was calculated by:

$$\sigma_w = \sqrt{\frac{\sum_{n=1}^{N} A_n * (D_n - \overline{D}_w)^2}{\frac{(N-1) * \sum_{n=1}^{N} A_n}{N}}} \quad \textbf{(8)}$$

Where

σ_w = Weighted Standard Deviation

A_n = Area of the n^{th} Polygon

D_n = Depth to Water of the n^{th} Polygon

$\overline{D}_w$ = Weighted Mean Depth to Water

N = Total Number of Samples

The weighted mean and standard deviation distance to a stream or river were also calculated using eqs. 7 and 8, only D stood for distance instead of depth.

The total areas of tree cover over hydrologic soil groups A, B, C, and D were calculated. These hydrologic soil groups are defined by chapter 3 of the Soil Survey Manual (Soil Survey Division Staff 1993) as follows:

- Soil Group A: Saturated hydraulic conductivity is very high or in the upper half of high and internal free water occurrence is very deep.
- Soil Group B: Saturated hydraulic conductivity is in the lower half of high or in the upper half of moderately high and free water occurrence is deep or very deep.
- Soil Group C: Soil hydraulic conductivity is in the lower half of moderately high or in the upper half of moderately low and internal free water occurrence is deeper than shallow.
- Soil Group D: Saturated hydraulic conductivity is below the upper half of moderately low, and/or internal free water occurrence is shallow or very shallow and transitory through permanent.

Soil Group A is usually sand, loamy sand, or sandy loam, Soil Group B is usually silt loam or loam, Soil Group C is usually sandy clay loam, and Soil Group D is usually clay loam, silty clay loam, sandy clay, silty clay, or clay.

All data was fit to the probability density function for a normal distribution, given by:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{(x-\mu)^2}{2\sigma^2}) \qquad \textbf{(9)}$$

Where

p(x) = The Probability Density Function

σ = The Standard Deviation

μ = The mean

An example of a normal distribution curve, using the weighted mean and standard deviation for depth to water along the Arkansas River post-development can be seen in Fig. 7.

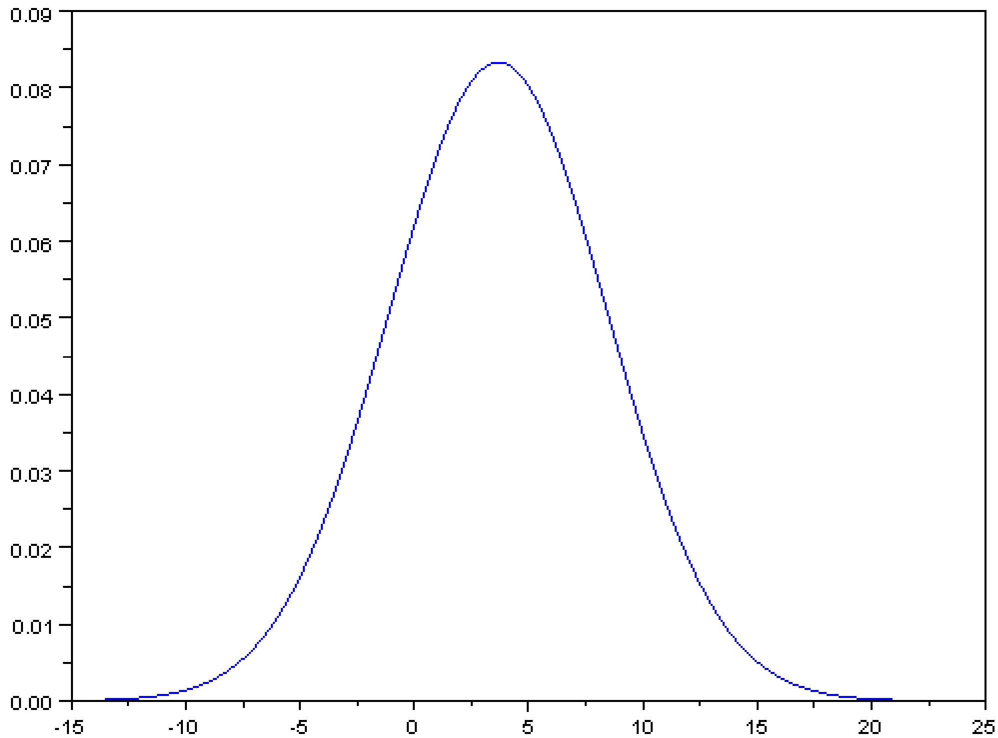


Figure 7. The Normal Distribution Curve. Created Using Scilab with Weighted Mean and Standard Deviation of Depth to Water Data along the Arkansas River Post-Development

This distribution was used to create a range that encompasses 95% of all values for depth to water, change in depth to water, and distance from a stream or river.

3. Results

The modeling Results for pre- and post-development Study Areas 1-6 show that the trees get their water from the river. These results indicate a losing stream because the head contours cross the river opening concavely toward the upstream end of the river. It should also be noted that in every case, a greater head gradient exists around the stream, as is evidenced by the contour intervals being closer together. Modeling results can be seen in Figs. 8-19. It should be noted that the particle tracks trace backwards in time, but do not take depth into consideration; i.e., they are traced at the bottom of the aquifer and stay at the base.

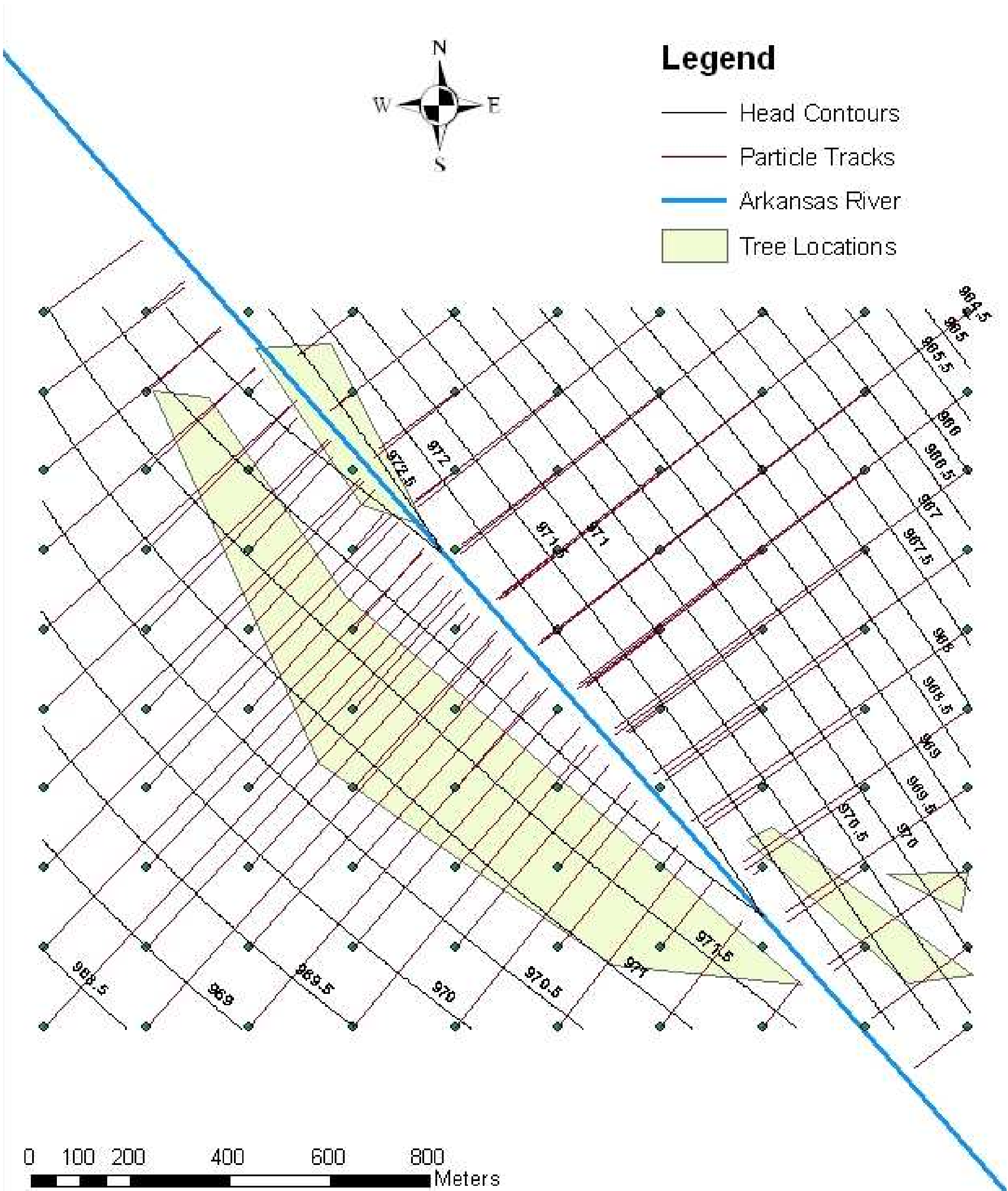


Figure 8: Modeling Results for Predevelopment Study Site 1.

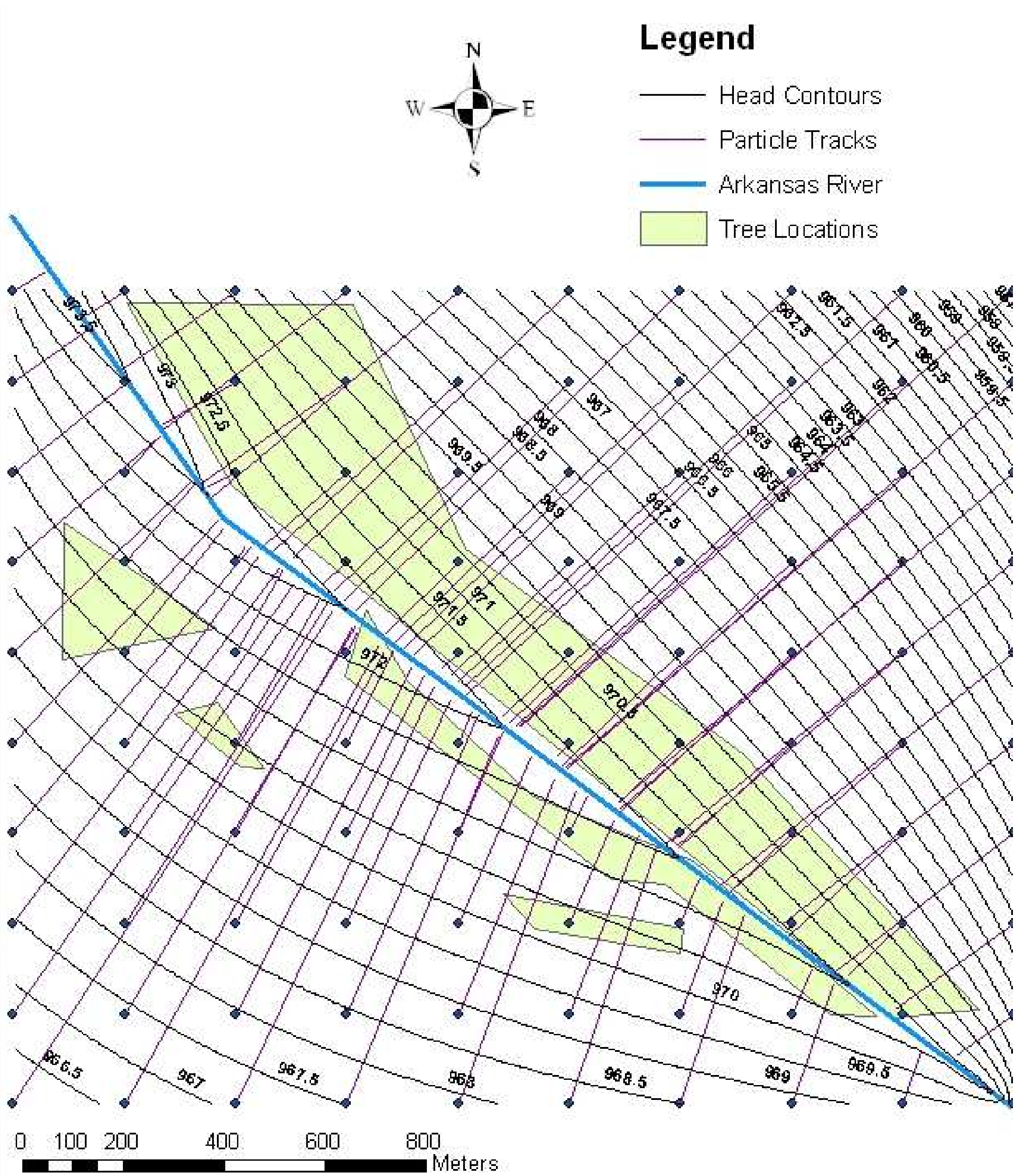


Figure 9: Modeling Results for Post-Development Study Site 1.

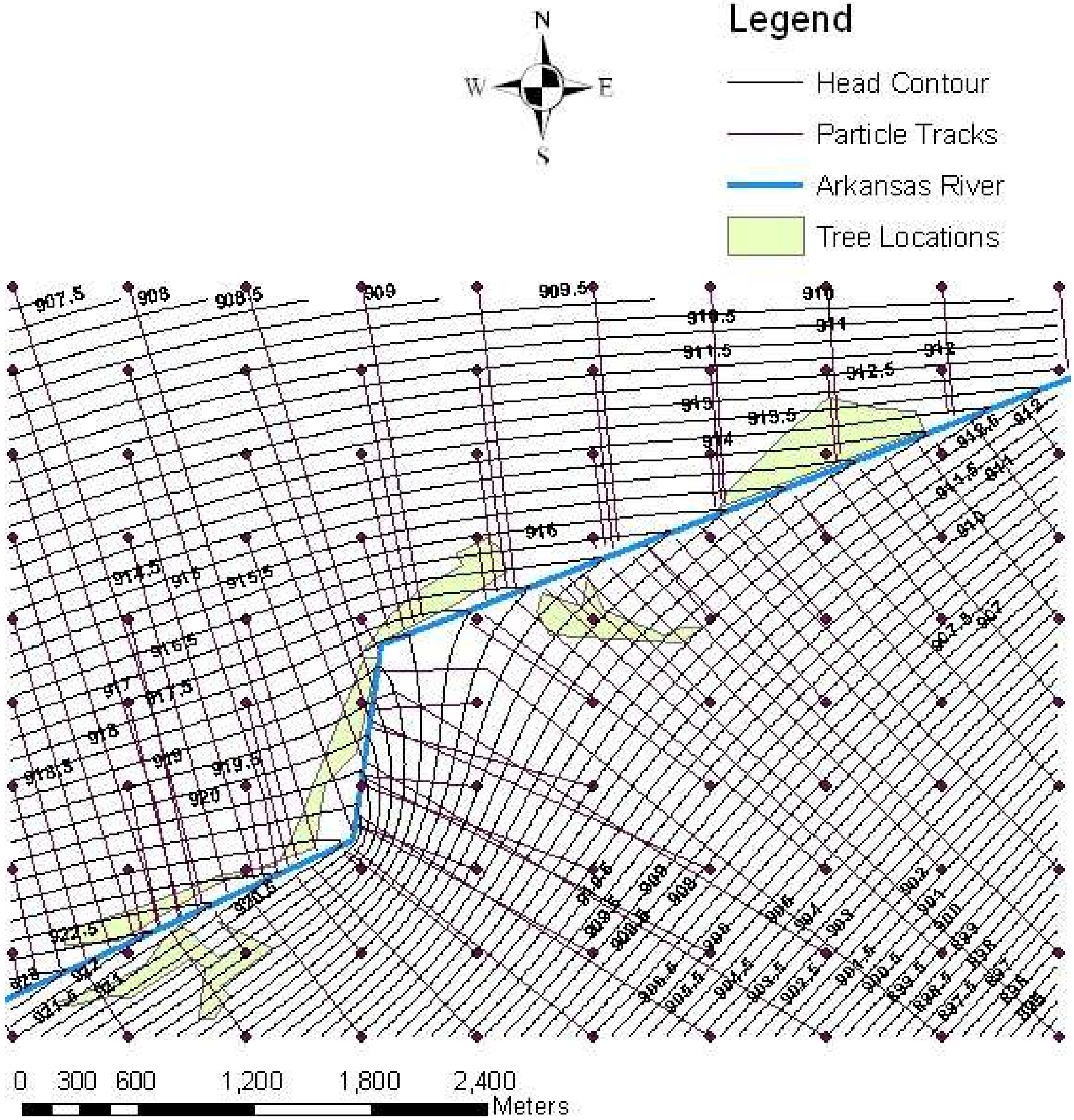


Figure 10: Modeling Results for Predevelopment Study Site 2.

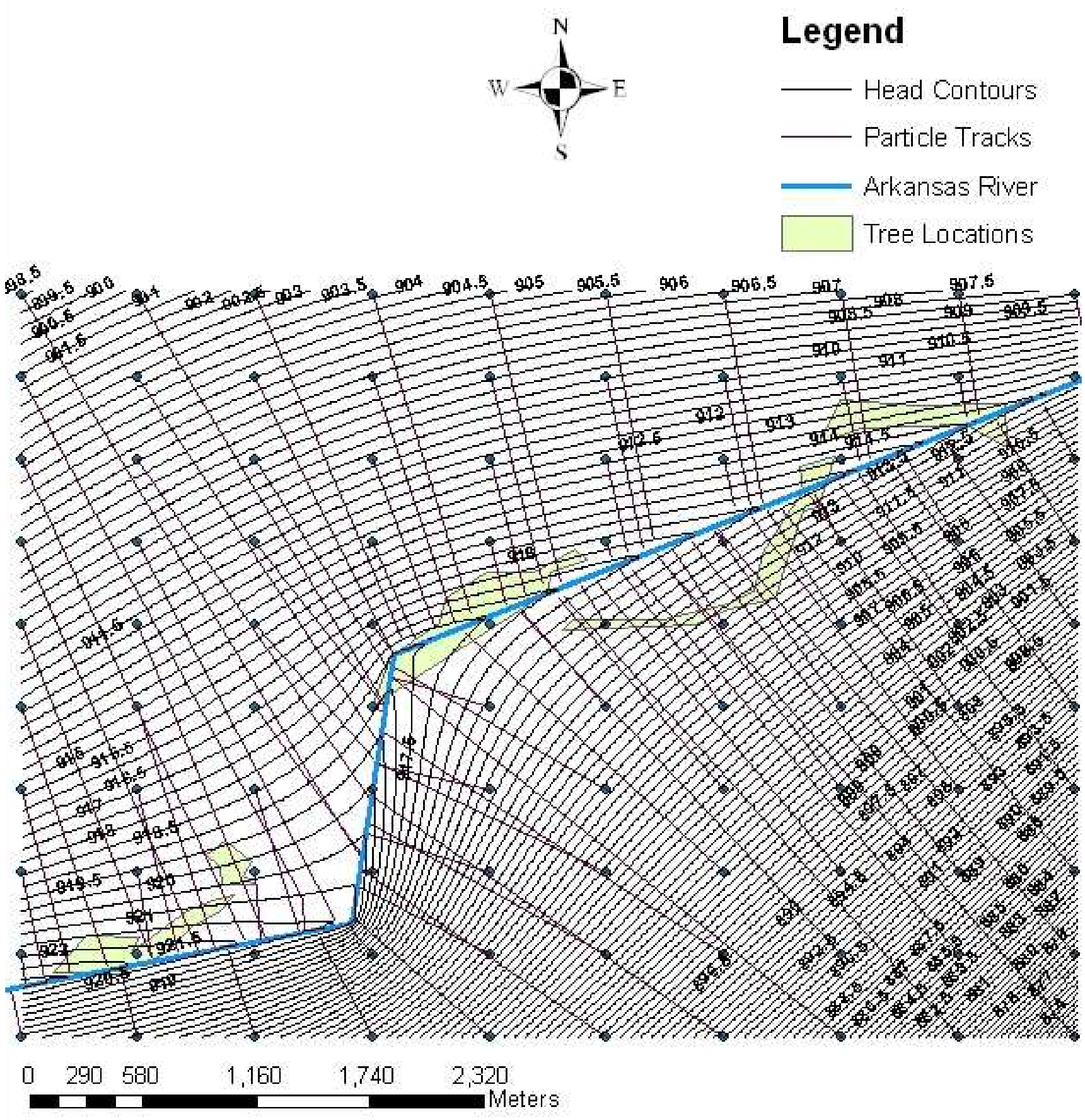


Figure 11: Modeling Results for Post-Development Study Site 2.

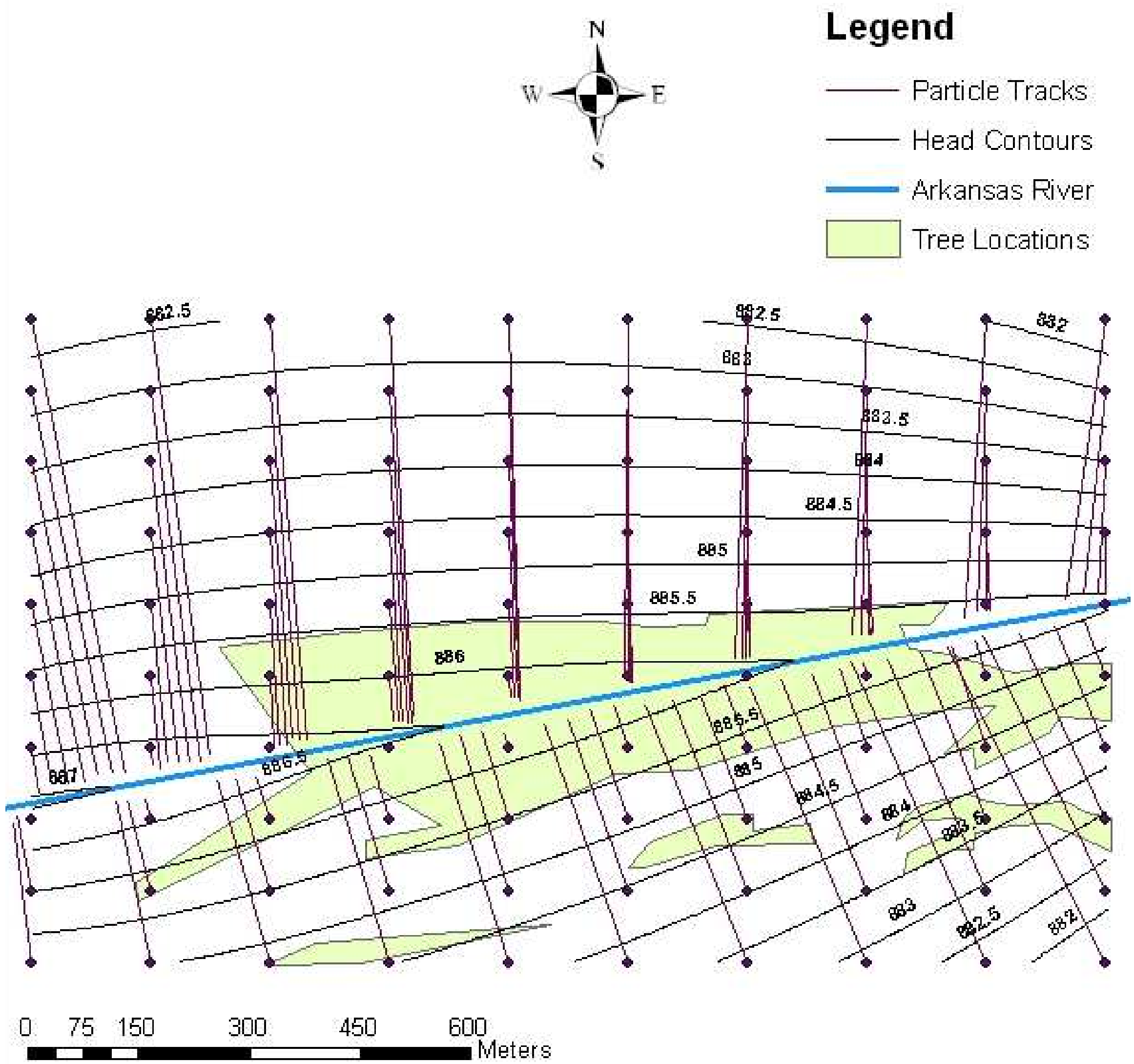


Figure 12: Modeling Results for Predevelopment Study Site 3.

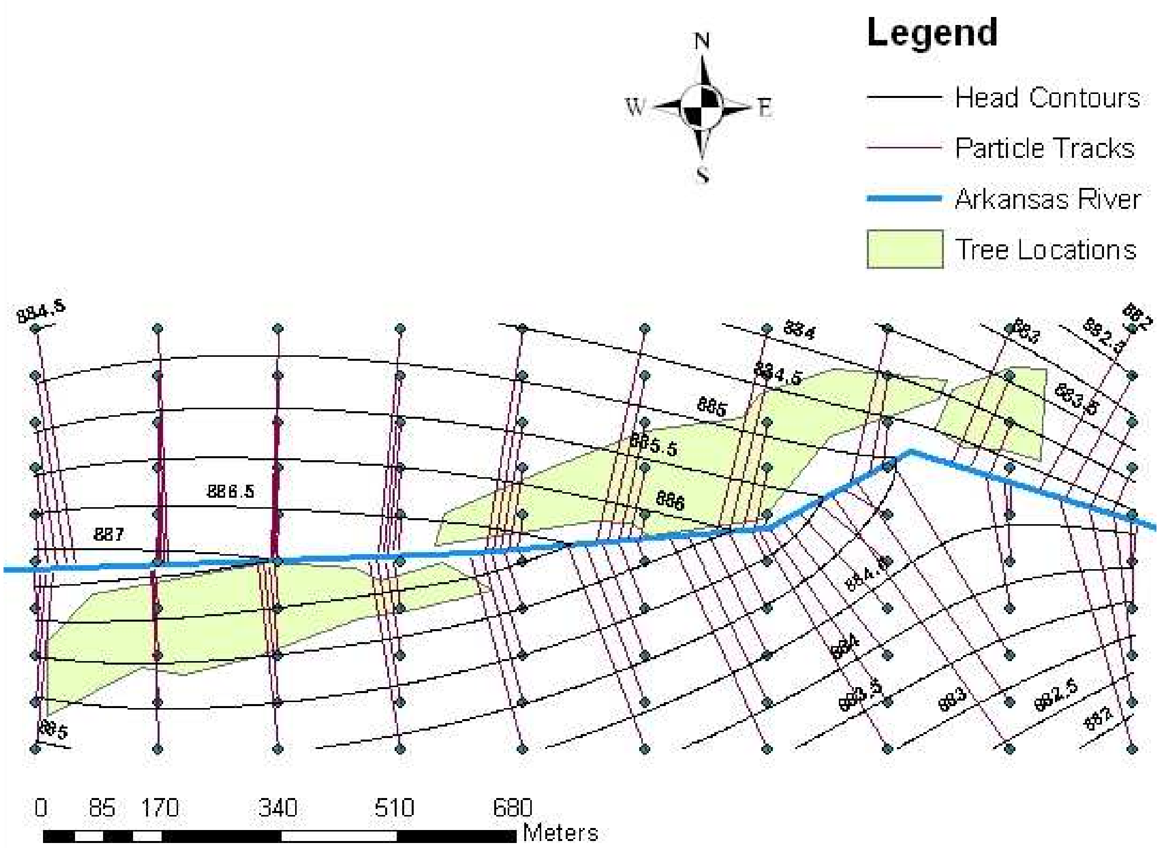


Figure 13: Modeling Results for Post-Development Study Site 3.

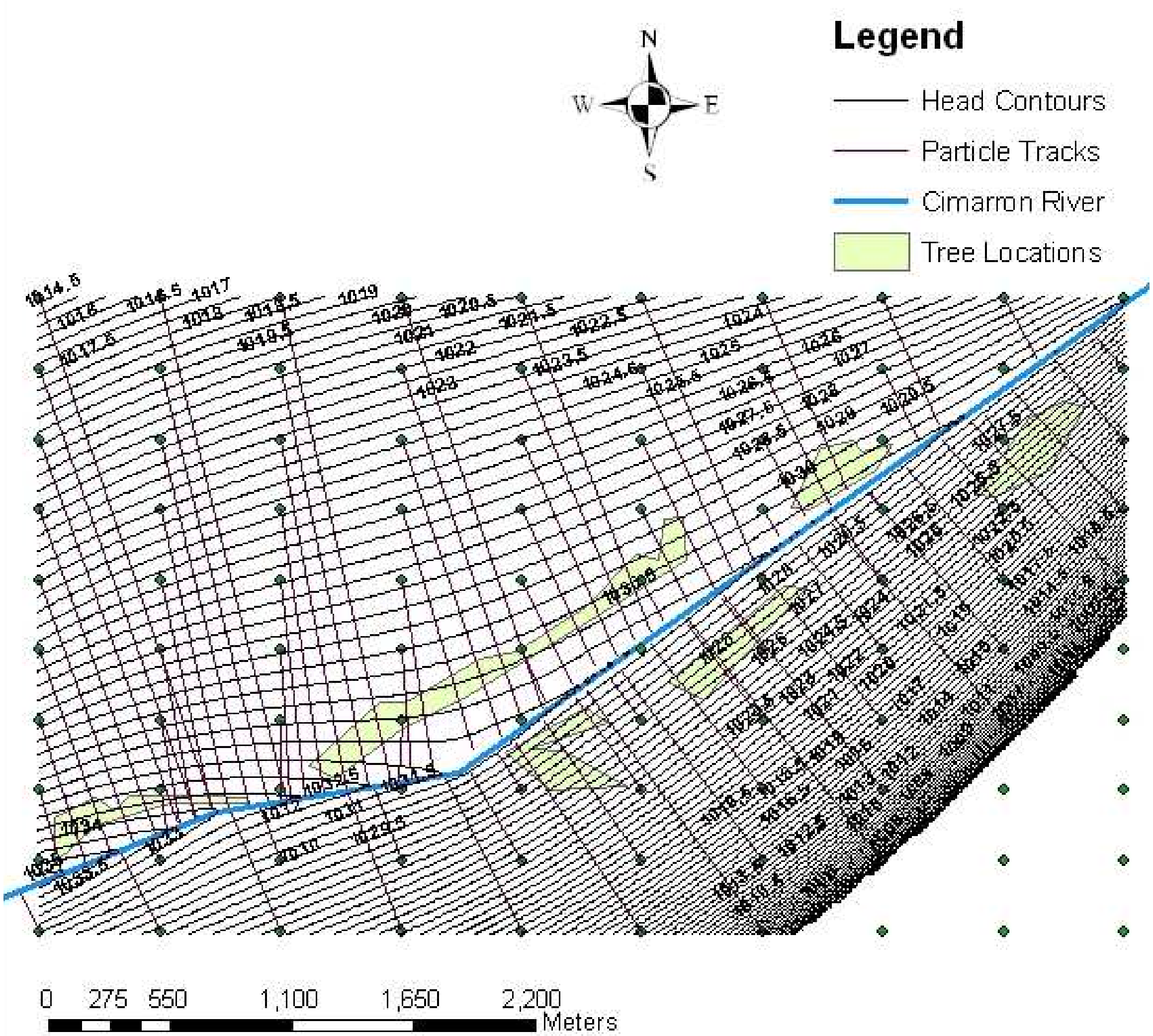


Figure 14: Modeling Results for Predevelopment Study Site 4.

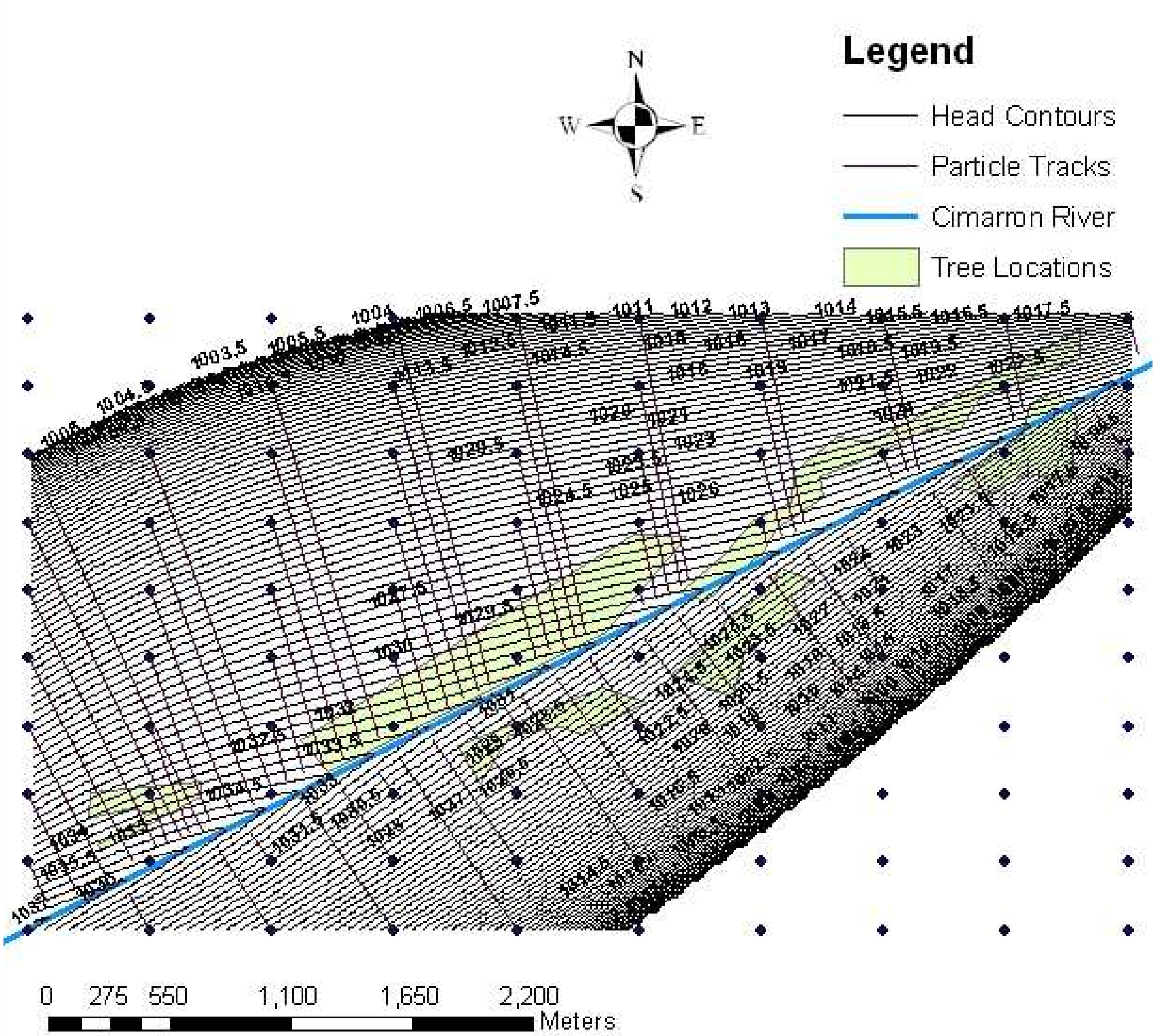


Figure 15: Modeling Results for Post-Development Study Site 4.

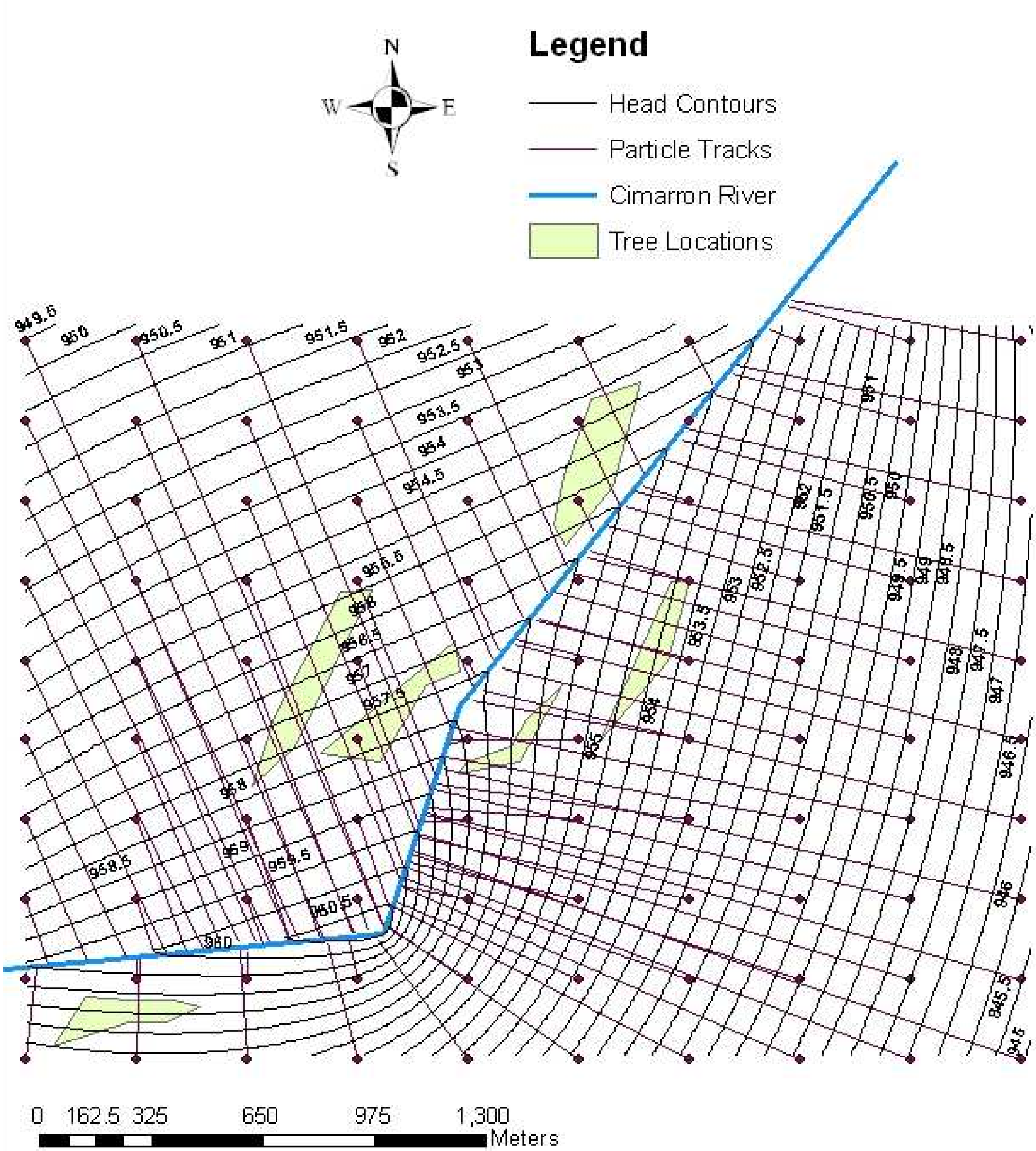


Figure 16: Modeling Results for Predevelopment Study Site 5.

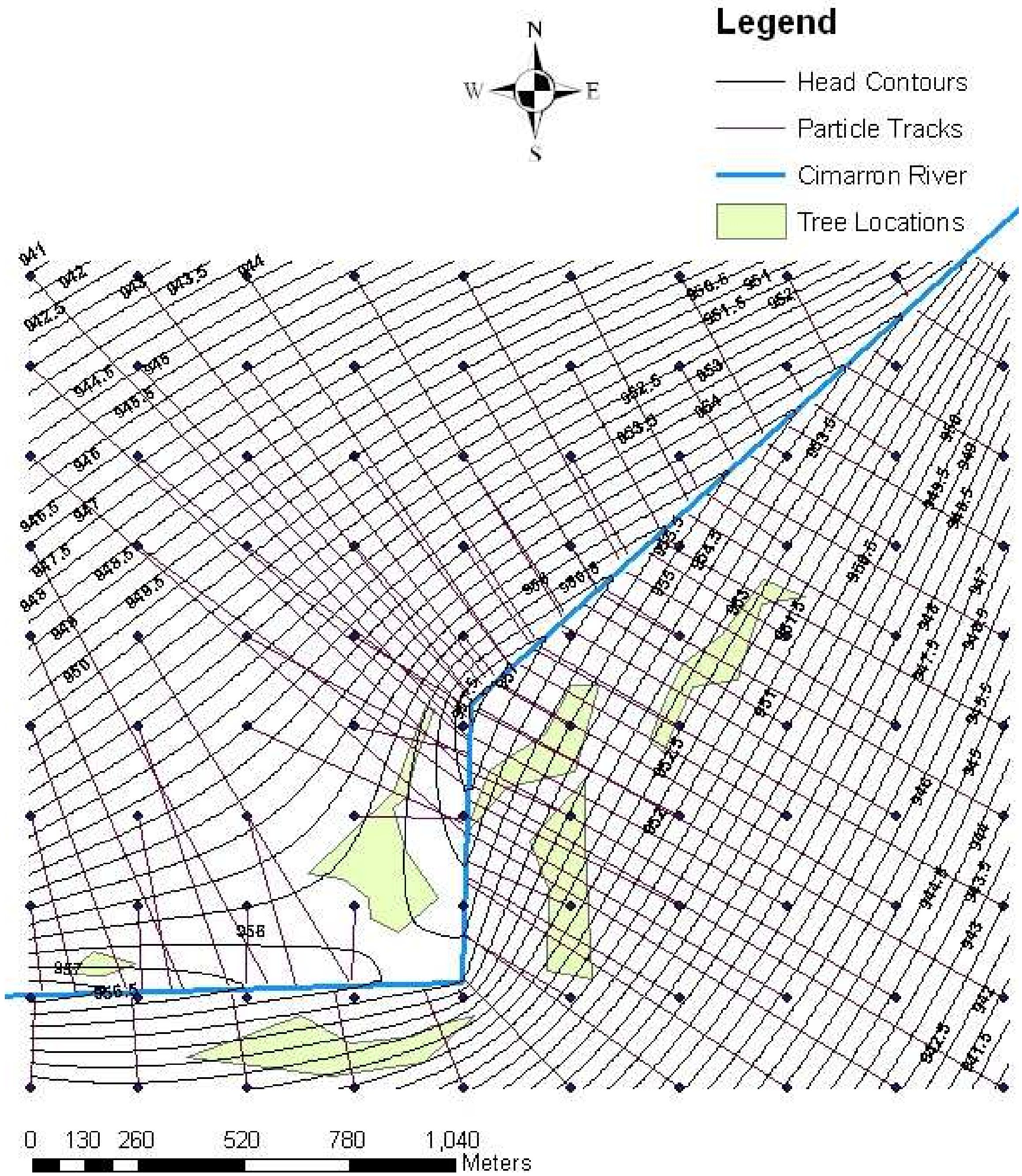


Figure 17: Modeling Results for Post-Development Study Site 5.

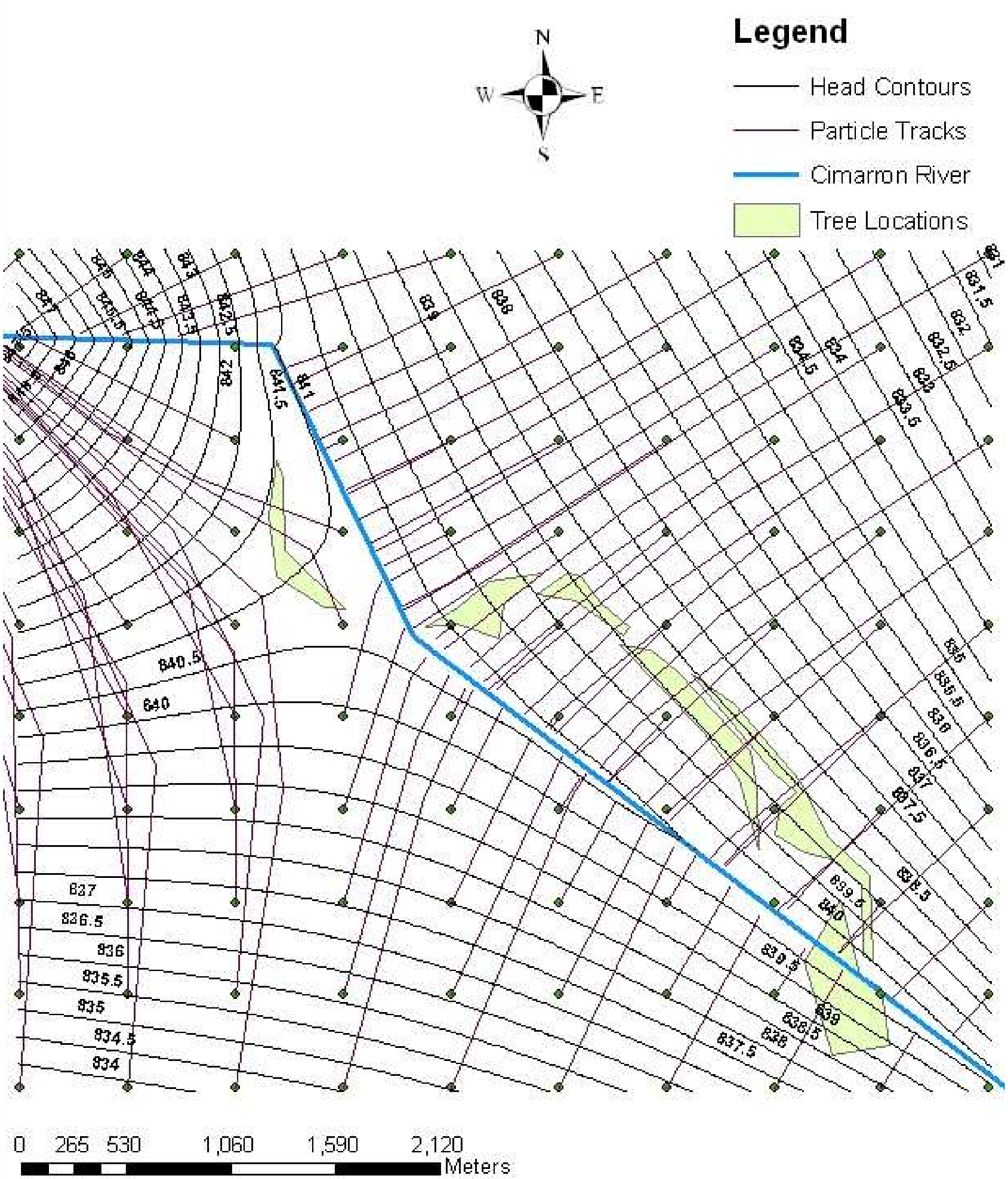


Figure 18: Modeling Results for Predevelopment Study Site 6.

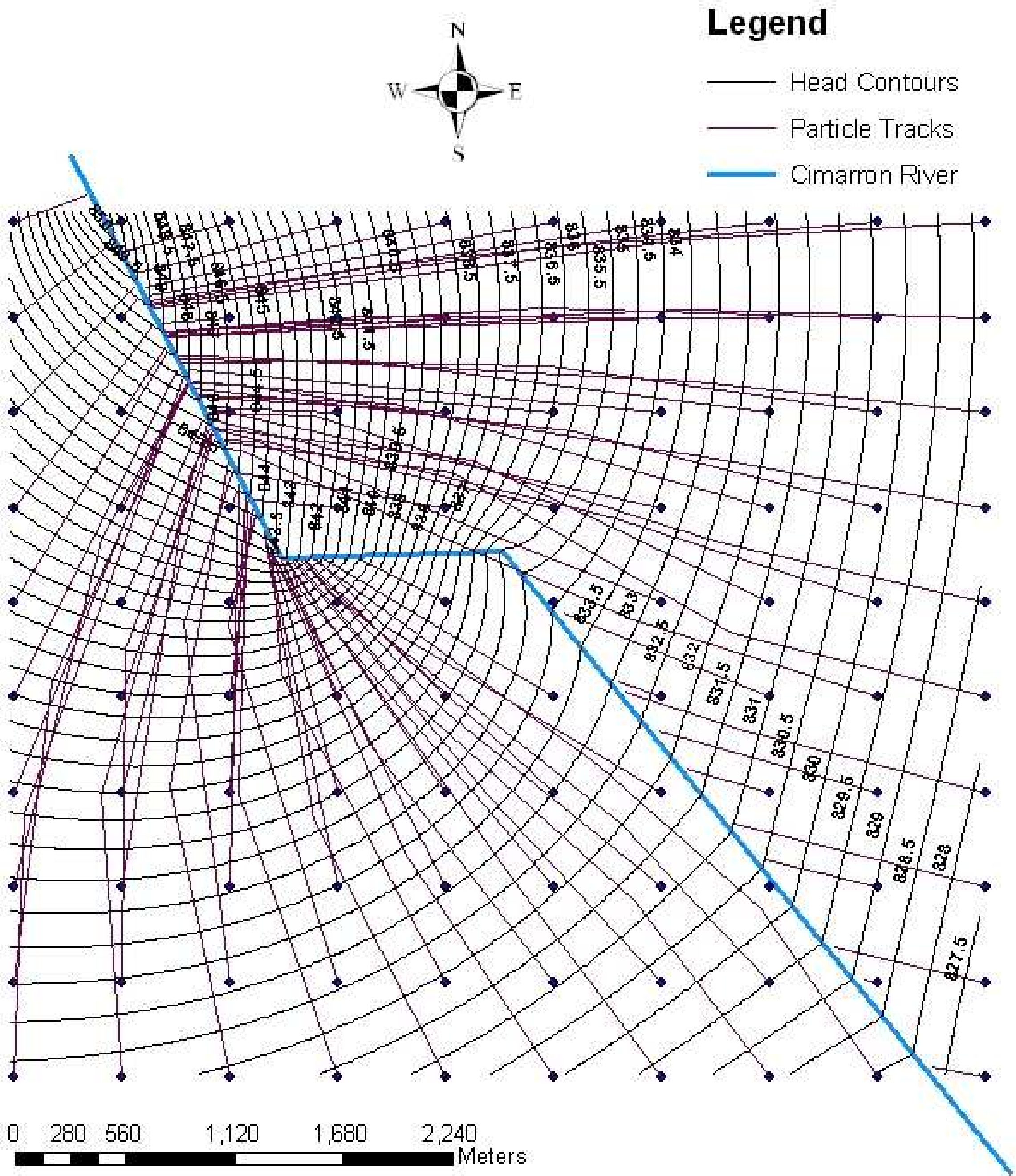


Figure 19: Modeling Results for Post-Development Study Site 6.

The remaining portion of this section gives data in tabular format with brief explanations as to what data is shown. This section does not include an interpretation of data. All data will be interpreted in the discussion.

Table 4 shows pre- and post-development total tree canopy areas along the Cimarron and Arkansas River corridors. This information shows that tree canopy areas declined along the Cimarron and Arkansas Rivers by 46% and 60%, respectively.

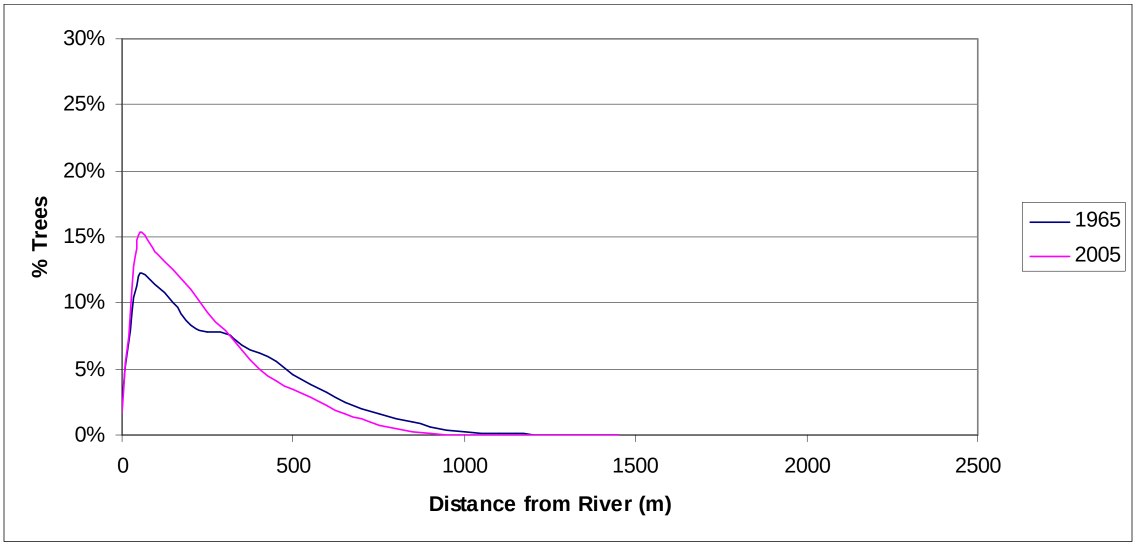
Table 4: Total Tree Canopy Areas along the Cimarron and Arkansas River Corridors Pre- and Post-Development

Study Site	Predevelopment Area	Post-Development Area
Cimarron River	5200 acres	3300 acres
Arkansas River	4000 acres	3700 acres

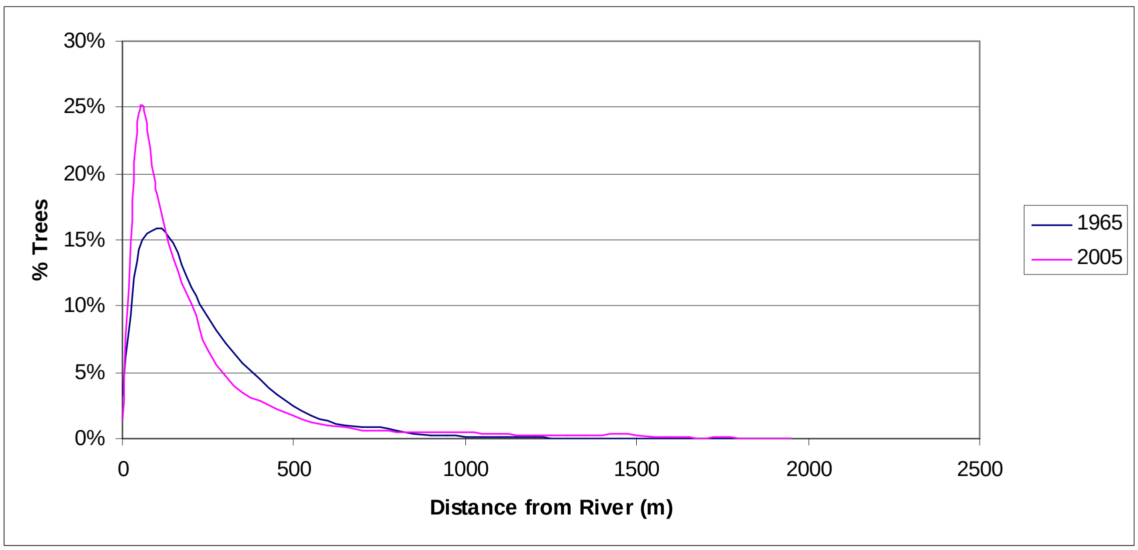
Table 5 shows the weighted means and standard deviations, as well as a 95% confidence interval for distance to a stream or river for trees along the Arkansas and Cimarron River corridors. Fig. 20 is a histogram showing the distribution of distance to the river for all trees. While this data shows that the average distance between trees and surface water has increased, it has not increased by much along either the Cimarron or Arkansas River corridors. Also, the 95% confidence interval for the Arkansas extends further post-development than it did prior to development.

Table 5: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Tree Distance from a Stream or River along the Cimarron and Arkansas River Corridors.

Study Site	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
Predevelopment Cimarron	260 m	220 m	0-700 m
Predevelopment Arkansas	210 m	200 m	0-600 m
Post-Development Cimarron	230 m	190 m	0-600 m
Post-Development Arkansas	190 m	250 m	0-685 m



a



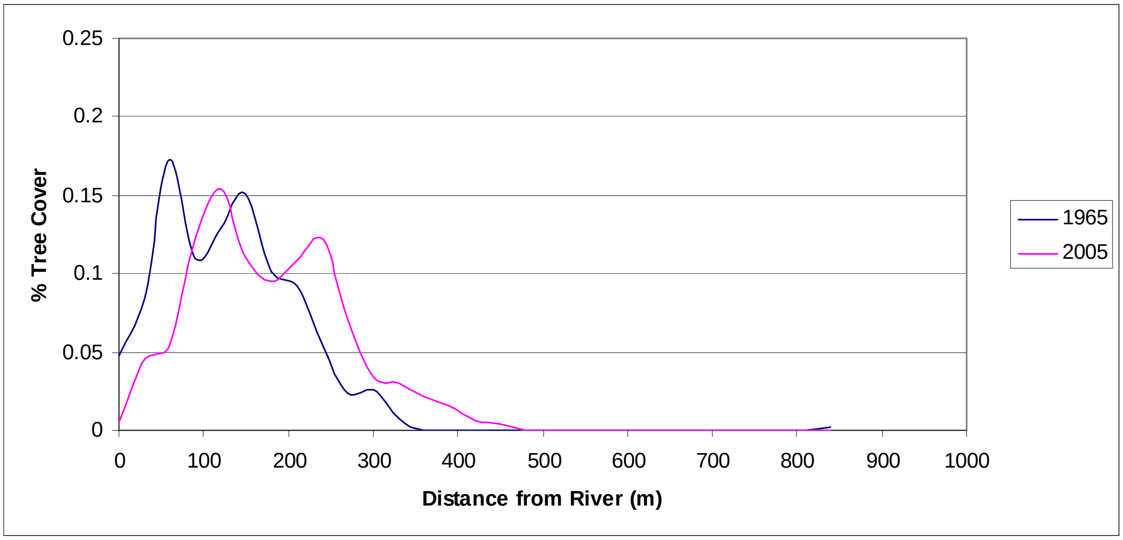
b

Figure 20: Distribution of Distance from the River for all Trees (a) along the Cimarron River and (b) along the Arkansas River.

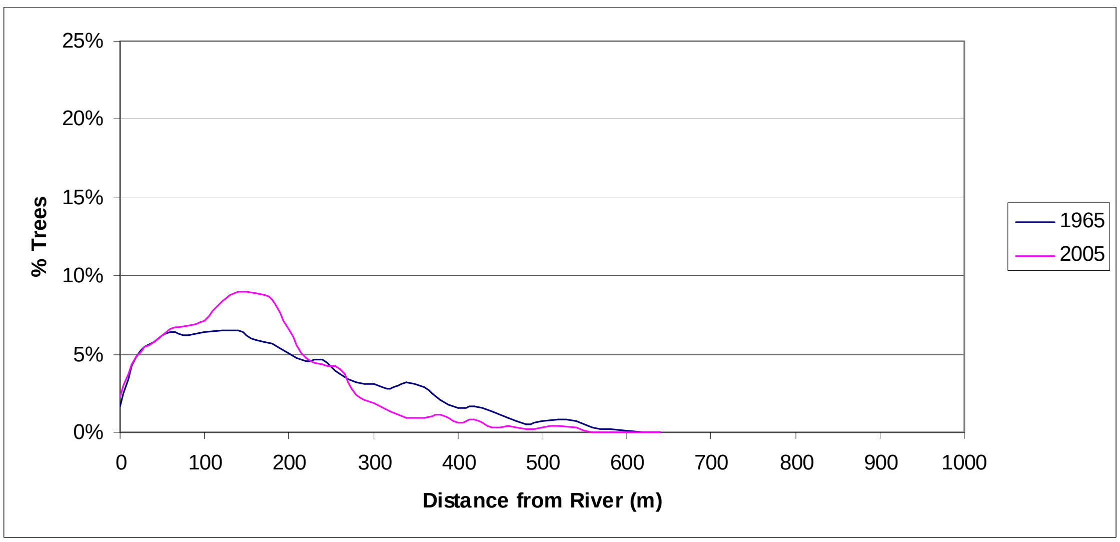
Weighted mean and standard deviation, as well as a 95% confidence interval for tree distance to the river at study sites 1-6, pre- and post-development are shown in Table 6. Histograms showing the distance from the river of all trees at each study area are shown in Fig. 21. This data shows that in study areas 2-4, the trees have moved closer to the river since development. Trees have moved further away from the river in study areas 1, 5, and 6 since development.

Table 6: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Tree Distance to Stream or River for Study Sites 1-6, Pre- and Post-Development.

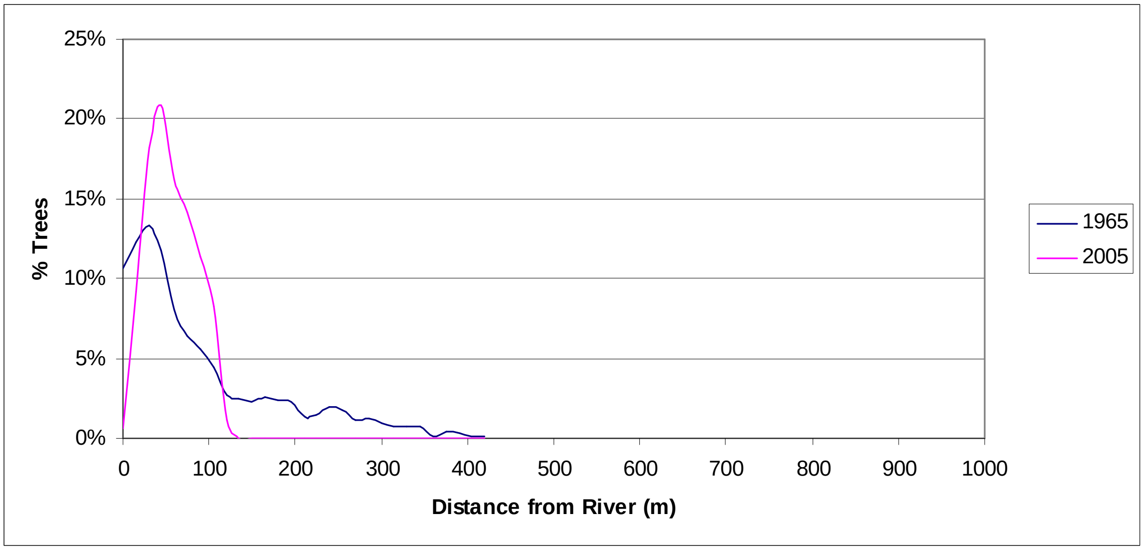
Study Area	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
1 Predevelopment	110 m	75 m	0-260 m
1 Post-Development	170 m	91 m	0-350 m
2 Predevelopment	190 m	130 m	0-450 m
2 Post-Development	140 m	96 m	0-330 m
3 Predevelopment	81 m	83 m	0-250 m
3 Post-Development	48 m	26 m	0-99 m
4 Predevelopment	280 m	170 m	0-620 m
4 Post-Development	250 m	180 m	0-600 m
5 Predevelopment	190 m	120 m	0-430 m
5 Post-Development	200 m	120 m	0-440 m
6 Predevelopment	160 m	120 m	0-400 m
6 Post-Development	180 m	130 m	0-440 m


0.25
0.2
0.15
0.1
0.05
0
% Tree Cover
0
100
200
300
400
500
600
700
800
900
1000
Distance from River (m)
1965
2005

a

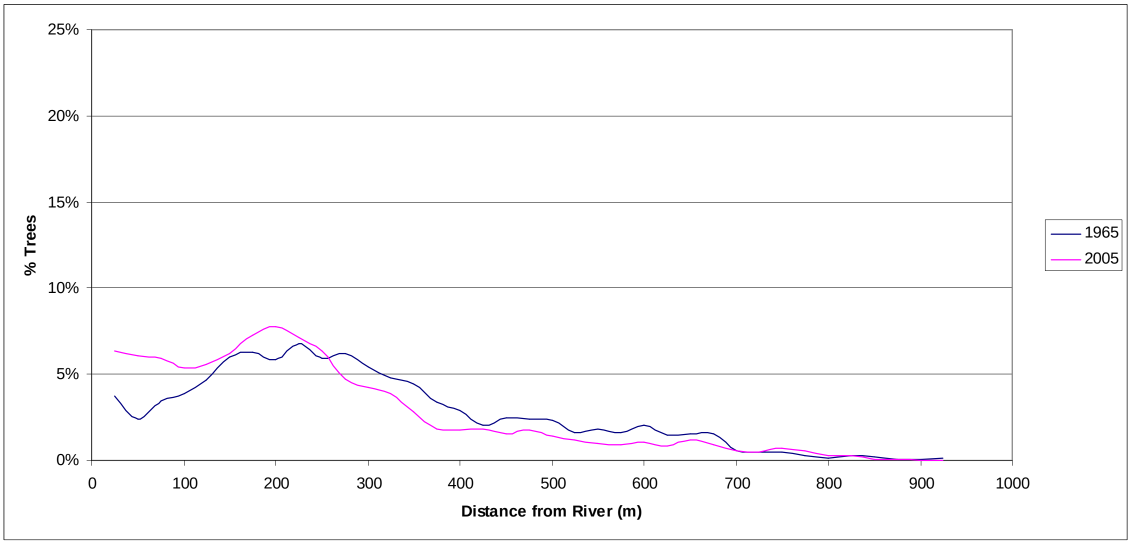

25%
20%
15%
10%
5%
0%
% Trees
0
100
200
300
400
500
600
700
800
900
1000
Distance from River (m)
1965
2005

b



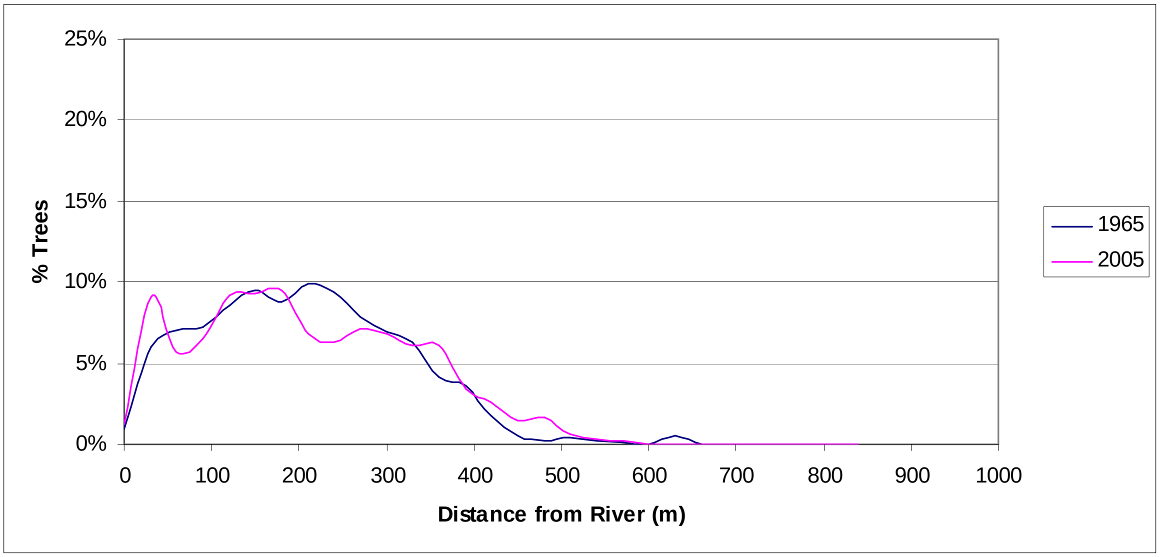
25%
20%
15%
10%
5%
0%
% Trees
0
100
200
300
400
500
600
700
800
900
1000
Distance from River (m)
1965
2005

c

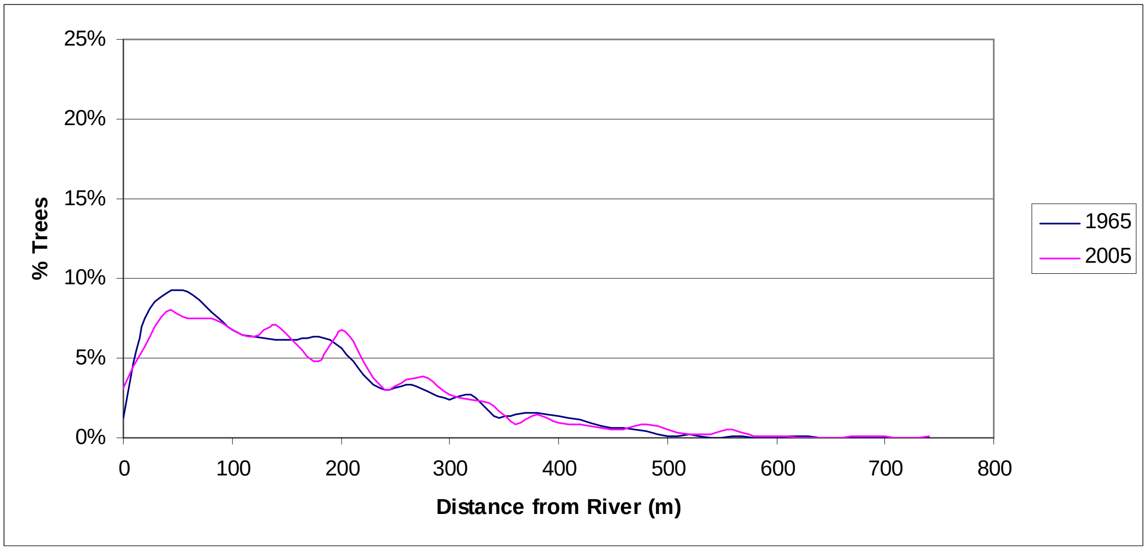


25%
20%
15%
10%
5%
0%
% Trees
0
100
200
300
400
500
600
700
800
900
1000
Distance from River (m)
1965
2005

d



e



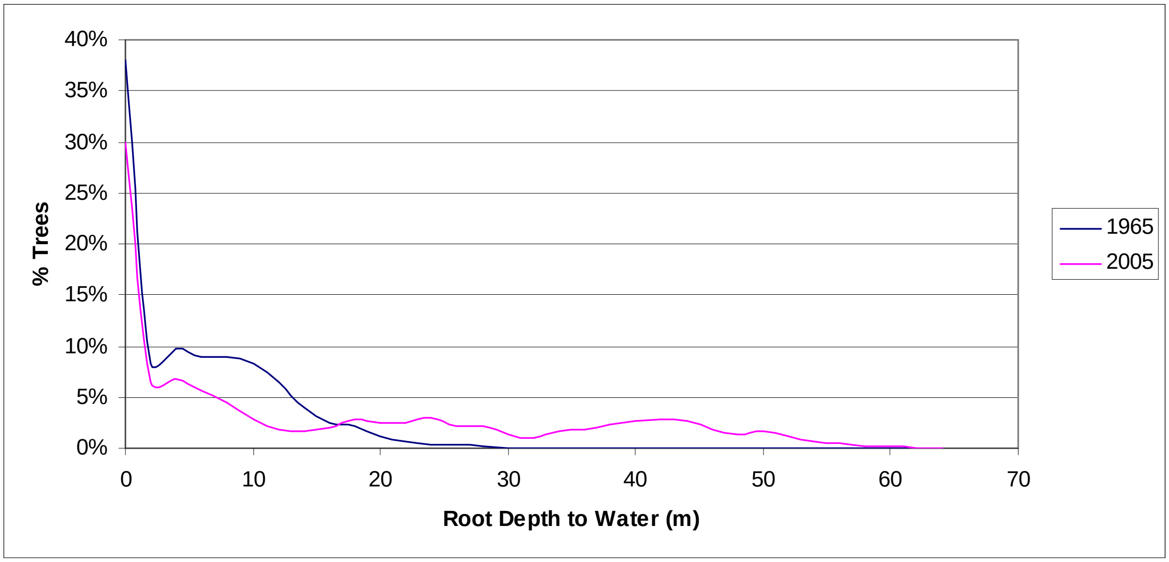
f

Figure 21: Distribution of Distance from the River for Trees at (a) Study Area 1, (b) Study Area 2, (c) Study Area 3, (d) Study Area 4, (e) Study Area 5, (f) Study Area 6.

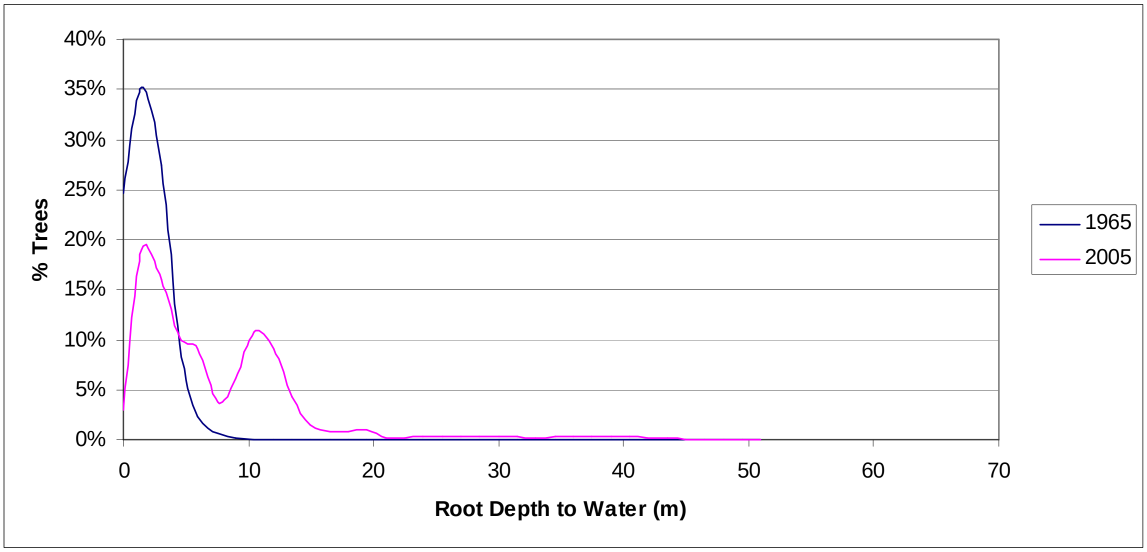
Table 7 shows the weighted means and standard deviations, as well as a 95% confidence interval, for depth to water along the Cimarron and Arkansas River corridors, both pre- and post-development. Fig. 22 shows histograms detailing the distribution of root depth to water along the Cimarron and Arkansas River corridors. This data shows that along the Cimarron River, both the average depth to water and 95% confidence interval have decreased over time. The opposite is true for the Arkansas River, where the average depth to water has increased by over 2 m and the 95% confidence interval has increased as well.

Table 7: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Root Depth to Water along the Cimarron and Arkansas River Corridors, Pre- and Post-Development.

Study Site	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
Predevelopment Cimarron	3.5 m	4.9 m	0-13 m
Predevelopment Arkansas	1.6 m	1.4 m	0-4.4 m
Post-Development Cimarron	8.8 m	14 m	0-37 m
Post-Development Arkansas	6.0 m	6.3 m	0-18 m



a



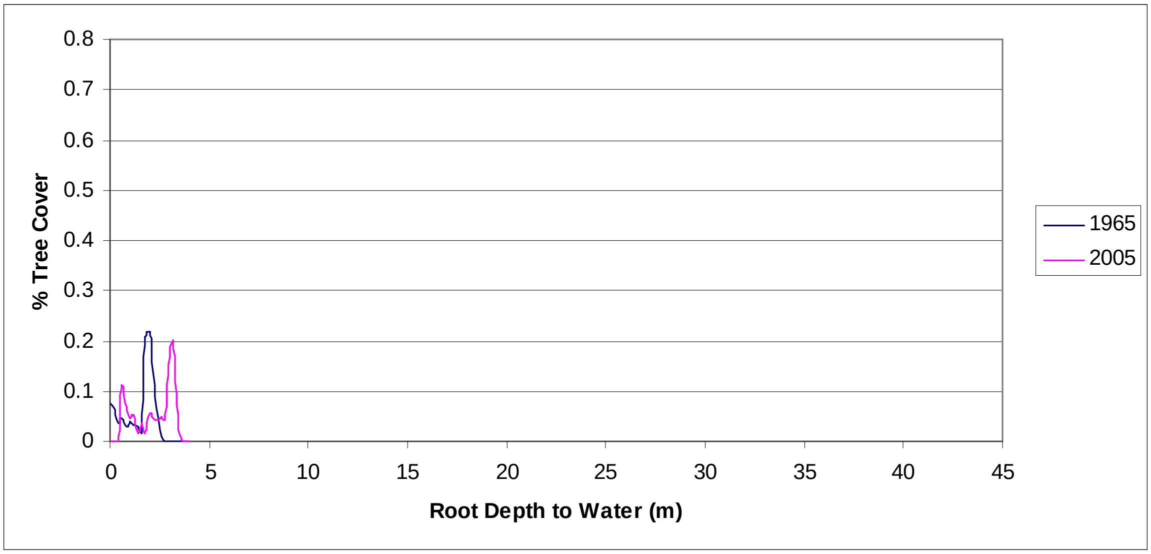
b

Figure 22: Distribution of Root Depth to Water for Trees along (a) the Cimarron River and (b) the Arkansas River.

Table 8 shows the weighted means, standard deviations, and 95% confidence intervals for depth to water under tree canopy at study areas 1-6, pre- and post-development. Fig. 23 shows histograms detailing the distribution of root depth to water for trees at study areas 1-6, pre- and post-development. At every study area except for Study Area 4, the mean depth to water increased after development.

Table 8: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Root Depth to Water at Study Sites 1-6, Pre- and Post-Development

Study Area	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
1 – Predevelopment	1.4 m	0.78 m	0-2.9 m
1 – Post-Development	2.1 m	0.97 m	0.18-4.0 m
2 – Predevelopment	1.1 m	0.90 m	0-2.8 m
2 – Post-Development	12 m	1.1 m	9.8-14 m
3 – Predevelopment	0.96 m	0.55 m	0-2.0 m
3 – Post-Development	19 m	0.35 m	18-20 m
4 – Predevelopment	0.90 m	1.2 m	0-3.3 m
4 – Post-Development	0.24 m	0.63 m	0-1.5 m
5 – Predevelopment	11 m	2.1 m	6.8-15.2 m
5 – Post-Development	21 m	2.6 m	16-26 m
6 – Predevelopment	7.1 m	2.2 m	2.7-11 m
6 – Post-Development	28 m	3.3 m	21-35 m



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
% Tree Cover
0
5
10
15
20
25
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Root Depth to Water (m)
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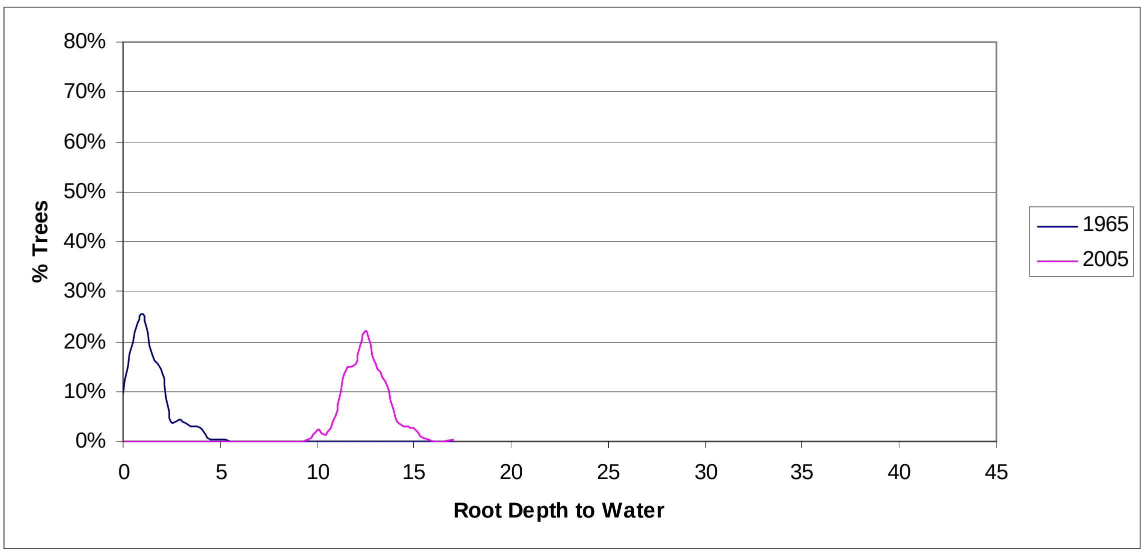
2005

a



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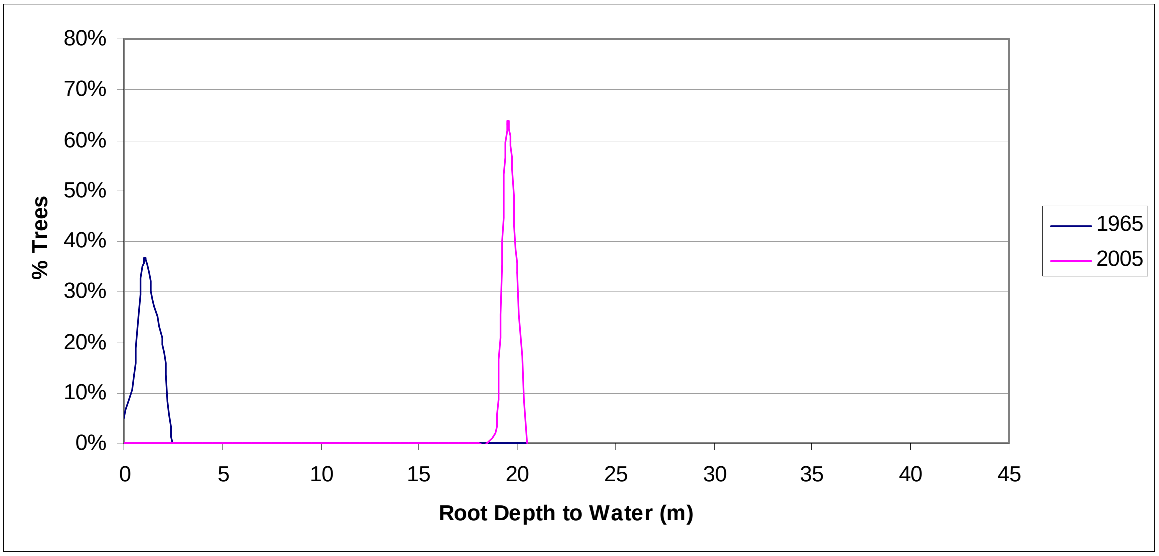
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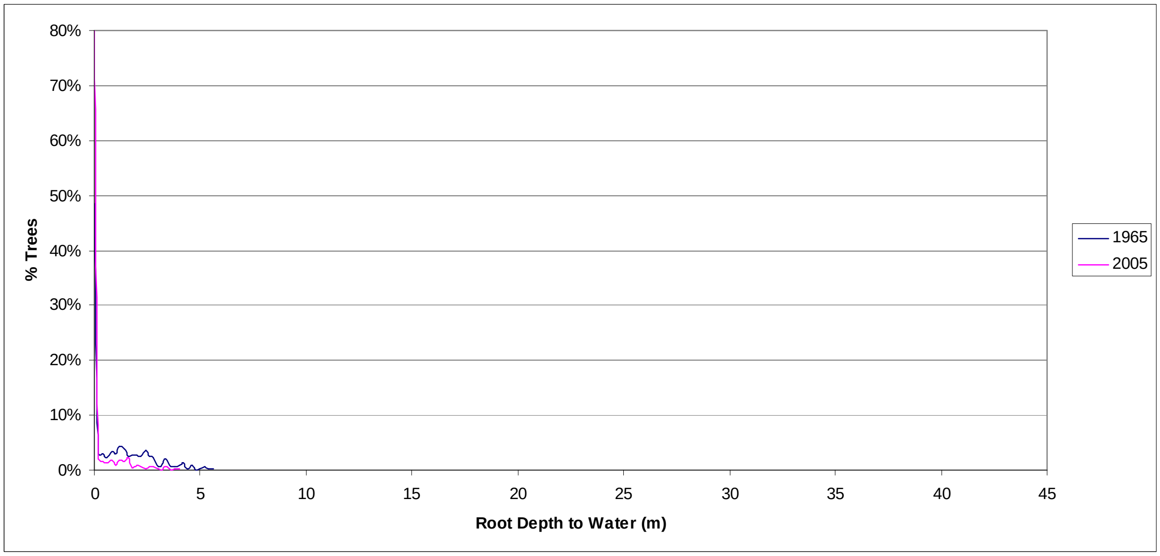
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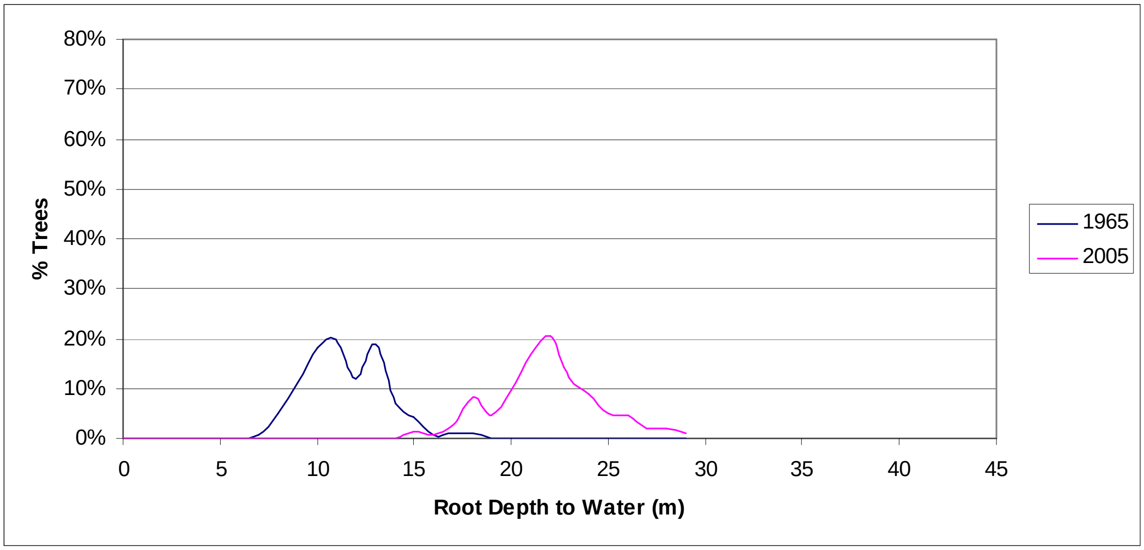

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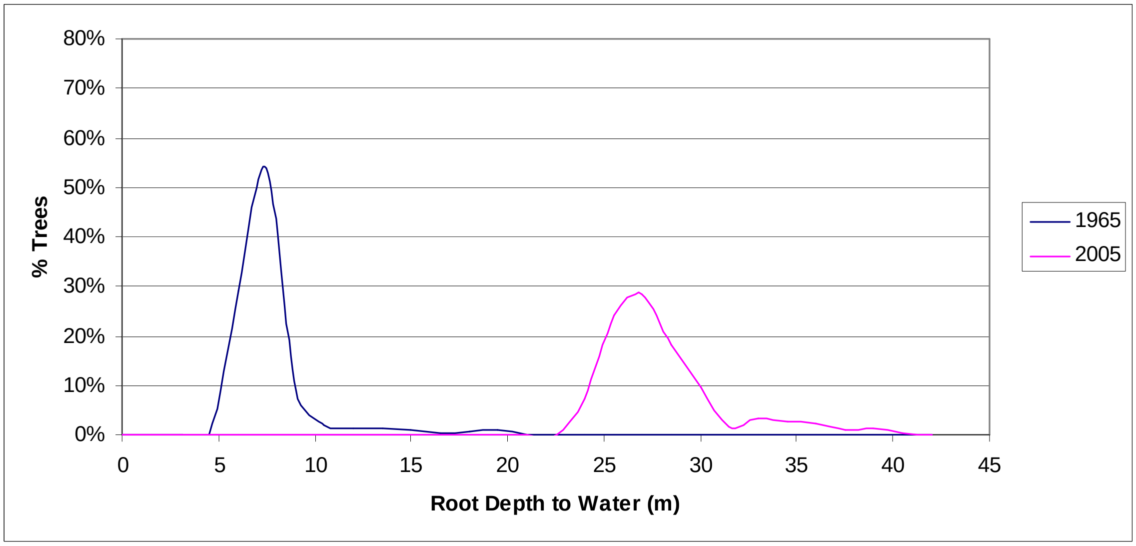

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Figure 23: Distribution of Root Depth to Water for Trees at (a) Study Site 1, (b) Study Site 2, (c) Study Site 3, (d) Study Site 4, (e) Study Site 5, and (f) Study Site 6.

Table 9 shows the weighted means and standard deviations, as well as a 95% confidence interval for increase in depth to water along the Cimarron and Arkansas River corridors. This data shows that trees along the Cimarron River corridor are located in areas where the water table rose by an average of 7.6 m, while trees along the Arkansas River are located in areas where the water table rose by an average of 1.6 m. The confidence intervals for each corridor are inclusive of both rising and declining water tables, but the Cimarron River trees show a definite skew toward rising water tables, while the Arkansas River trees show a skew toward declining water tables.

Table 9: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Increase in Tree Depth to Water along the Cimarron and Arkansas River Corridors.

Study Area	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
Cimarron River	-7.6 m	9.7 m	-27-12 m
Arkansas River	2.8 m	4.4 m	-5.9-12 m

The weighted means, standard deviations, and 95% confidence intervals for increase in depth to water under tree canopy for study areas 1-6 are reported in Table 10. Study Area 1 had no change in depth to water, so all values for it are zero. The average depth to water beneath tree canopy decreased at Study Area 4.

Table 10: Weighted Mean, Standard Deviation, and 95% Confidence Interval for Increase in Depth to Water Under Tree Canopy Areas at Study Sites 1-6.

Study Area	Weighted Mean	Weighted Standard Deviation	95% Confidence Interval
1	0	0	0
2	11 m	0.74 m	9.5-12.5 m
3	19 m	0.13 m	19 m
4	(-)2.2 m	0.60 m	(-)3.4-(-)1.012 m
5	11 m	1.2 m	8.6-13 m
6	19 m	0.91 m	17-21 m

Areas of each hydrologic soil group within 700 m of the Cimarron and Arkansas Rivers are shown in Table x. These data show that within 700 m of the Cimarron River, soil groups A, B, C, and D consist of 52%, 41%, 3.5%, and 4.2%, respectively, of the total land area. For the space within 700 m of the Arkansas River, soil groups A, B, C, and D make up 20%, 14%, 50%, and 16%, respectively. It should be noted that the areas in Table 11 do not always agree with Table 4 because a hydrologic soil group is not assigned when the value in the "muname" field of the SSURGO database is "River".

Table 11: Total Areas of Hydrologic Soil Groups A, B, C, and D within 700 m of the Cimarron and Arkansas Rivers

Study Site	Soil Group A	Soil Group B	Soil Group C	Soil Group D
Cimarron River	38 000 acres	30 000 acres	2600 acres	3100 acres
Arkansas River	10 000 acres	7000 acres	25 000 acres	8000 acres

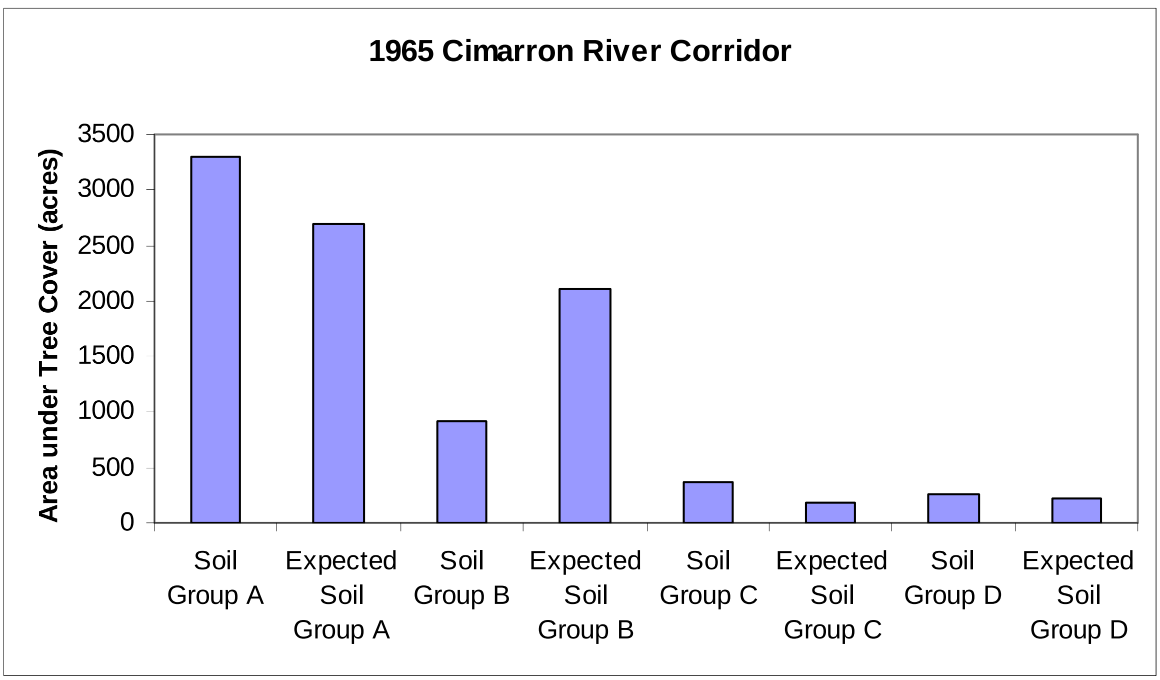
Table 12 shows expected tree canopy areas over hydrologic soil groups A, B, C, and D along both the Cimarron and Arkansas River corridors for pre- and post-development. Expected areas of soil groups A, B, C, and D were calculated based on the percentage of each soil group within 700 m of the river. Actual tree canopy areas, as well as their percent difference from the expected area, are shown in Table 13. Figs. 24 and 25 show the information in Tables 12 and 13 graphically.

Table 12: Expected Tree Canopy Areas over Hydrologic Soil Groups A, B, C, and D for Pre- and Post-Development Cimarron and Arkansas River Corridors Assuming Tree Location is Independent of Soil Type.

Study Site	Soil Group A Area	Soil Group B Area	Soil Group C Area	Soil Group D Area
Predevelopment Cimarron	2700 acres	2100 acres	180 acres	220 acres
Predevelopment Arkansas	800 acres	560 acres	2000 acres	640 acres
Post-Development Cimarron	1700 acres	1300 acres	120 acres	140 acres
Post-Development Arkansas	740 acres	520 acres	1900 acres	590 acres

Table 13: Actual Tree Canopy Areas over Soil Groups A, B, C, and D (and Percent Difference) for Pre- and Post-Development Cimarron and Arkansas River Corridors.

Study Site	Soil Group A Area	Soil Group B Area	Soil Group C Area	Soil Group D Area
Predevelopment Cimarron	3300 acres (+22%)	920 acres (-56%)	360 acres (+100%)	250 acres (+14%)
Predevelopment Arkansas	1400 acres (+75%)	79 acres (-86%)	1600 acres (-20%)	440 acres (-31%)
Post-Development Cimarron	2300 acres (+35%)	510 acres (-61%)	150 acres (+25%)	170 acres (+21%)
Post-Development Arkansas	1700 acres (+130%)	190 acres (-63%)	1200 acres (-37%)	620 acres (+5.1%)



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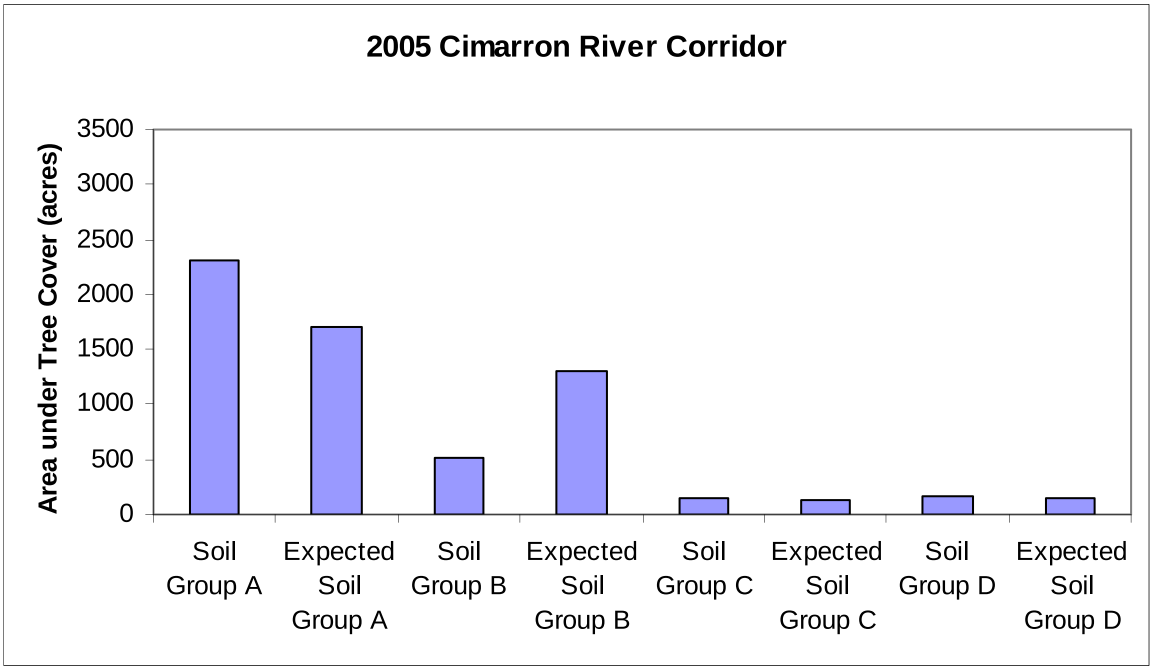

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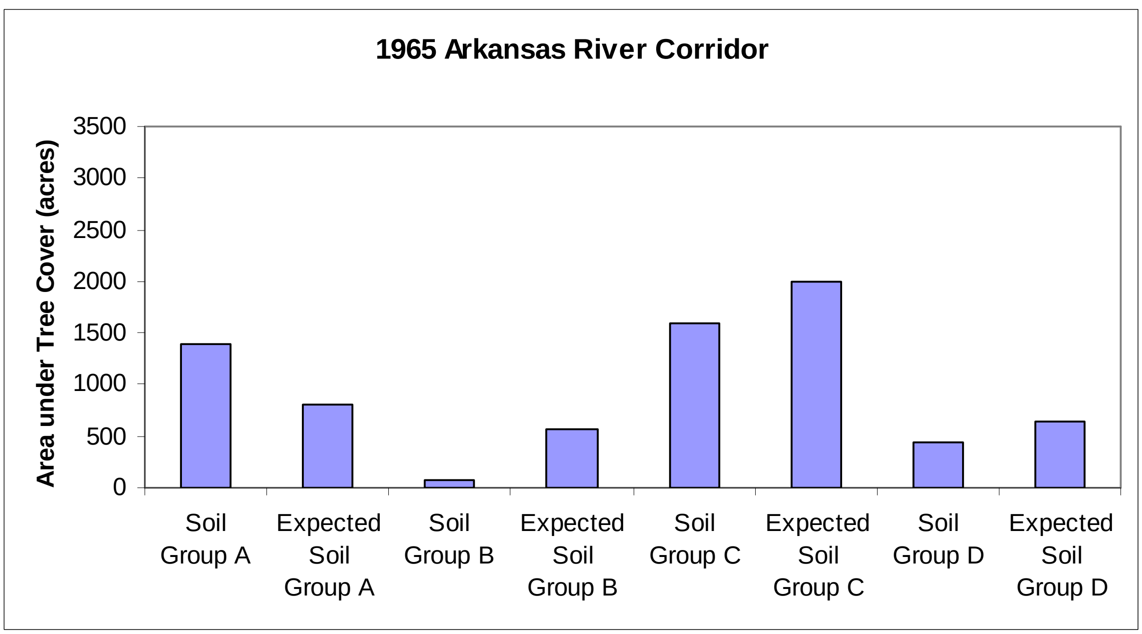
Figure 24: Actual and Expected Total Areas of Soil Groups A-D under Tree Cover along the Cimarron River Corridor (a) in 1965 and (b) in 2005.



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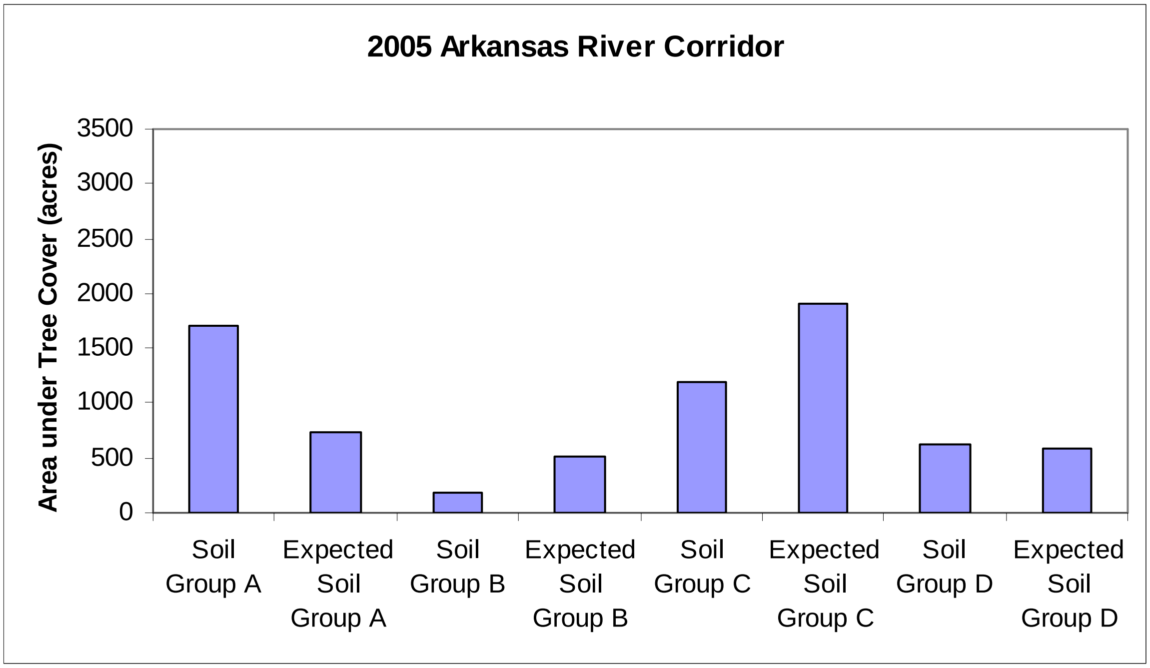


b

Figure 25: Actual and Expected Total Areas of Soil Groups A-D under Tree Cover along the Arkansas River (a) in 1965 and (b) in 2005.

Table 14 shows the total areas of the six study areas, pre- and post-development, and Table 15 shows pre- and post-development tree canopy areas in the six study areas. Table 16 gives pre- and post-development percentage of land area under tree canopy for each study area. This data shows that the amount of tree cover has increased since development in study areas 1 and 4, and has decreased in all other study areas.

Table 14: Areas of Study Sites 1-6.

Study Area	Area
1	650 acres
2	4300 acres
3	310 acres
4	3300 acres
5	1300 acres
6	4900 acres

Table 15: Pre- and Post-Development Tree Canopy Areas in Study Sites 1-6.

Study Area	Predevelopment Canopy Area	Post-Development Canopy Area
1	65 acres	96 acres
2	178 acres	100 acres
3	52 acres	23 acres
4	170 acres	240 acres
5	46 acres	25 acres
6	120 acres	50 acres

Table 16: Percentage of Land Area within 620 m of the River under Tree Canopy Cover, Pre- and Post-Development, in Study Sites 1-6.

Study Area	Predevelopment %	Post-Development %
1	14 %	20%
2	6.6%	3.7%
3	17%	7.7%
4	6.5%	9.2%
5	1.8%	1.0%
6	2.8%	1.2%

Table 17: Total Areas of Hydrologic Soil Groups A, B, C, and D in Study Sites 1-6.

Study Area	Soil Group A	Soil Group B	Soil Group C	Soil Group D
1	42 acres	1.8 acres	330 acres	100 acres
2	840 acres	180 acres	1400 acres	280 acres
3	48 acres	8.2 acres	170 acres	74 acres
4	1500 acres	1100 acres	0 acres	0 acres
5	2600 acres	2.2 acres	0 acres	0 acres
6	2800 acres	1500 acres	25 acres	0 acres

Expected tree canopy areas, assuming tree location is independent of soil type, are given in Table 18. These values were calculated based upon the total areas of soil groups in each study area presented in Table 17 and the total areas of tree canopy cover presented in Table 15. The actual area of each soil group in each study area, pre- and post-development, as well as the percent difference from the expected values, are presented in Table 19.

Table 18: Expected Areas of Tree Canopy over Hydrologic Soil Groups A, B, C, and D assuming that Tree Location is Independent of Soil Type.

Study Area	Soil Group A	Soil Group B	Soil Group C	Soil Group D
1 Predevelopment	5.8 acres	0.25 acres	45 acres	14 acres
1 Post-Development	8.5 acres	0.36 acres	67 acres	20 acres
2 Predevelopment	55 acres	12 acres	92 acres	18 acres
2 Post-Development	31 acres	6.7 acres	52 acres	10 acres
3 Predevelopment	8.3 acres	1.4 acres	29 acres	13 acres
3 Post-Development	3.7 acres	0.62 acres	13 acres	5.7 acres
4 Predevelopment	98 acres	72 acres	0 acres	0 acres
4 Post-Development	140 acres	100 acres	0 acres	0 acres
5 Predevelopment	46 acres	0.039 acres	0 acres	0 acres
5 Post-Development	25 acres	0.021 acres	0 acres	0 acres
6 Predevelopment	78 acres	42 acres	0.69 acres	0 acres
6 Post-Development	32 acres	17 acres	0.29 acres	0 acres

Table 19: Actual Areas of Tree Canopy over Hydrologic Soil Groups A, B, C, and D (and Percent Difference from Expected) at Study Sites 1-6, Pre- and Post-Development.

Study Area	Soil Group A	Soil Group B	Soil Group C	Soil Group D
1 Predevelopment	6.6 acres (+14%)	0 acres (-100%)	53 acres (+18%)	1.7 acres (-88%)
1 Post-Development	5.3 acres (-38%)	0 acres (-100%)	60 acres (-10%)	14 acres (-30%)
2 Predevelopment	92 acres (+67%)	0 acres (-100%)	65 acres (-29%)	7.2 acres (-60%)
2 Post-Development	52 acres (+67%)	0.32 acres (-95%)	42 acres (-19%)	0.82 acres (-92%)
3 Predevelopment	14 acres (+69%)	0 acres (-100%)	31 acres (+6.9%)	0 acres (-100%)
3 Post-Development	0.031 acres (-99%)	0 acres (-100%)	23 acres (+1.8%)	0 acres (-100%)
4 Predevelopment	160 acres (+63%)	12 acres (-83%)	0 acres (+0%)	0 acres (+0%)
4 Post-Development	220 acres (+57%)	19 acres (-81%)	0 acres (+0%)	0 acres (+0%)
5 Predevelopment	46 acres (+0%)	0 acres (-100%)	0 acres (+0%)	0 acres (+0%)
5 Post-Development	25 acres (+0%)	0 acres (-100%)	0 acres (+0%)	0 acres (+0%)
6 Predevelopment	110 acres (+41%)	18 acres (-57%)	0 acres (-100%)	0 acres (+0%)
6 Post-Development	32 acres (+0%)	18 acres (+5.8%)	0 acres (-100%)	0 acres (-100%)

4. Discussion

Groundwater from the Ogallala is important for municipal water supplies for western Kansas communities, and also as a source of water for irrigation for local agriculture. The results of this study were analyzed to determine common properties regarding hydrologic soil group, depth to groundwater, increase in depth to groundwater, and distance from the river. These results were analyzed both at a large scale, stretching over the entire lengths of the Arkansas and Cimarron Rivers over the extent of Ogallala Aquifer in Kansas, and also at small scales, using study sites 1-6. The following is an interpretation of the results, as well as an analysis of how these results could be useful to expand current and future research projects and to help guide installation of future monitoring networks.

The modeling results, shown in Figs. 8-19, indicate that the river is a losing stream in every case. However, the post-development head gradient is much steeper than the predevelopment gradient, so the river is losing water to infiltration at a faster rate now than it was prior to development. This increased infiltration helps explain why streamflow at the gauging stations shown in Fig. 3 have decreased over time. The results also show that for every case, the source of water for the trees is the river. This shows that under most conditions, phreatophytes uptake water that is infiltrated through streamflow.

Due to the large variations in hydrologic conditions along the Arkansas and Cimarron River corridors from west to east, it is best to view the statistical analysis for the corridors alongside the results for the study sites to gain perspective on the distribution of the results. This allows the study site results to be used as an interpolating factor, in a way.

The average distance between trees and the river decreased after development along the Arkansas River corridor, but the standard deviation of distance increased, allowing for a greater range of distances in the 95% confidence interval. Based on the results from study areas 1-6, this increase in standard deviation is likely caused by the average distance to the river increasing at the far western part of the corridor, where the depth to groundwater did not decrease. This contrasts with a decrease in average distance to the river along the rest of the corridor, where depth to groundwater increased. The results are then further skewed because the tree densities in the west are much greater than those in the east.

The same is true along the Cimarron River, so it is easy to presume that if Morton County were discounted, the decrease in average distance to the river would be much more profound. However, the average distance to the river increased at study areas 5 and 6, while decreasing at study area 4. This is the case because even though the water table has risen at study area 4, streamflow has greatly decreased, allowing new trees to grow in areas that the river used to flow, which decreases the average distance to the river. At study sites 5 and 6, the trees did not redistribute closer to the river because the distance to groundwater beneath the river is greater than 20 m, so there is no significant advantage for a phreatophyte to grow there. It is presumed that the average distance to the river increased at these sites because a lot of cottonwood trees that were living close to the river prior to development, when the depth to groundwater was about 10 m, died off when the depth to groundwater increased after development.

When looking at the average depth to water along the entire Arkansas and Cimarron River corridors, it appears that as depth to water increases, the number of trees decreases. However, this is not always the case, as evidenced by study site 1. As long as the water table remains at a level that is easily accessed by the roots of the trees, the trees will not die off with a decline in the water table, and the number of trees can increase. Canadell et al (1996) found the maximum rooting depth of cottonwood trees in a forest to be 2.6 m. The average depth to water beneath tree canopy at Study Site 1 is less than 2.6 m both prior to and post-development, so it seems that 2.6 m is probably close to the threshold where trees will start to die off with an increase in depth to water. This die-off trend is certainly not linear, and the introduction of tamarix further complicates the prediction of tree die-off because studies have shown that water table depths have little to no effect on tamarix, even at depths below 10 m (Cleverly 2006).

The average depths to water along the Arkansas and Cimarron River corridors seem counter-intuitive when looked at alongside the average increase in depth to water. This is because the average depth to groundwater beneath trees in both areas increased, but the average increase in depth to water for trees along the Cimarron River is a negative value. This is because along much of the Cimarron River corridor, the depth to groundwater has increased greatly, while the far western part of the corridor has experienced recharge. Most of the trees in the region where the water table has lowered have died off, so almost all of the trees along the Cimarron River corridor are clustered in the zones of recharge. There is an increase in average depth to water because some trees still exist at locations where the water table is very deep, and many new trees are located in areas that have experienced recharge, but have a depth to water that is greater than what was beneath the entire Cimarron River prior to development. See Figs B11, B14, and B17 for depth to water at study sites 4-6.

The soil analysis showed that in every case, more trees were located on hydrologic soil group A than would be expected if tree location were independent of soil type, and less trees were located on soil group B. In some cases, trees were more likely to be on soil groups C and D than expected, and in other cases, fewer trees were on those soils than expected. However, trees along both the Cimarron and Arkansas Rivers were more likely to be located on soil group D post-development than prior to development. It is not apparent what would cause this shift to soil group D because it has a low hydraulic conductivity, but one could speculate that this soil group might be more conducive to tamarix, which has increased in population since development and does not get water from the vadose zone (Busch 1992). It might be helpful to look at the shift to soil group D at a smaller scale, but almost none of these soils exist at the study sites along the Cimarron River.

Phreatophyte distributions can be used as indicators for soil type, hydraulic connectivity, and depth to groundwater. In western Kansas, areas with good hydraulic connectivity are of interest because it is not economically feasible to create artificial recharge projects that use injection due to treatment costs. It would be feasible, however, to route ditches over land with good hydraulic connectivity to increase natural recharge. It is possible that phreatophyte locations could be used to indicate locations with good surface water/groundwater connectivity because of the likelihood of phreatophytes to be located on hydrologic soil group A. Phreatophyte locations cannot be used as the only means for this task, however, because they exist on all soil types. More research should be completed to determine if cottonwood trees and saltcedar trees tend to populate different soil types. It seems that phreatophyte distributions are a better indicator of depth to groundwater than anything else, as a dense distribution of trees indicates a shallow water table, while a sparse distribution indicates a deep water table.

5. Conclusions

The Ogallala Aquifer has been pumped for irrigation since the 1950's. Since this time, some regions of western Kansas have experienced a water table decline of more than 40 m. In southwest Kansas, a sustainable groundwater supply is important for municipal water and the long-term viability of irrigation. The decline of the water table, as well as a change in overall land use, has caused a redistribution of riparian phreatophytes along the Cimarron and Arkansas Rivers. This thesis studies the impact that this redistribution has had on the hydrologic balance, and identifies characteristics that make phreatophytes more likely to exist at a location. This will allow for a better understanding of groundwater movement both prior to and post-development.

To study the impact of phreatophytes on local hydrology, six study areas were chosen, and tree distributions were mapped using remote sensing on aerial photography. A map of these study areas can be seen in Fig. 1. ArcAEM was used to model the water table, as well as the point source for water from phreatophytes. These models, shown in Figs. 8-19, show that at every study site, the river is injecting water into the ground, i.e. is a losing stream. The head contour gradient at every site gets steeper post-development, showing that the river loses water faster than it did prior to development. This helps explain the declining flows that both rivers have experienced (see Fig. 3). These models also show that in every case but Pre-Development Study Site 1, the phreatophytes get their water from the river. At Study Site 1, they get water from the aquifer.

Tree locations at each study area and also along the entire Arkansas and Cimarron River Corridors were analyzed based on hydrologic soil group, depth to groundwater, increase in depth to groundwater, and distance from a stream or river. The results of this analysis can be seen in Tables 5-10. All results were calculated based on Eqns. 7 and 9.

The results for average depth to water vary spatially. In areas with a dense tree population (>10% tree cover), the average depth to water ranged from 0.24-1.4 m. In areas with moderate tree density (5-10% tree cover), the average depth to water ranged from 2.1-19 m. In areas with low tree density (<5% tree cover), the average depth to water ranged from 11-28 m. The large ranges of values are most likely due to the differences in rooting depths of cottonwood trees and saltcedars.

The results for the increase in depth to water indicate that, in genereal, the amount of trees will decrease as depth to groundwater increases, but phreatopytes can still exist at depths up to, and possibly exceeding, 35 m. Conversely, the amount of trees increased in areas where the depth to groundwater decreased or stayed the same. The results for distance to a stream or river indicate that as the water table declines, trees will be redistributed closer to the river, as long as the water table near the river is shallow enough to be ideal for phreatophyte growth.

Hydrologic soil group results along the entire river corridors were determined to be better for analysis than the results for the six study areas because there was a very low amount of soil belonging to groups C and D at the study sites along the Cimarron River. From the results pertaining to hydrologic soil group over the entire Arkansas and Cimarron River corridors, it seems that a disproportionately large amount of phreatophytes were located on hydrologic soil group A. Soils in group B seemed to not be conducive to phreatophyte growth, as a disproportionately low amount of trees were located on these soils in most cases. The results indicate that trees were more likely to be located on soil group and D post-development than they were prior to development, and the same is true for soil group A. Trees are not likely to be located on soil group B in any case.

Phreatophyte locations could possibly be used as an indicator for areas with good surface water/groundwater connectivity because they are more likely to be located on hydrologic soil group A than any other group. This soil group has a high hydraulic conductivity, which is one of the most important factors in determining the permeability of the hyporheic zone (Soil Survey Division Staff 1993, Brunke 1997). Tree locations cannot be used as the only means of determining surface water/groundwater connectivity, however, because they can exist on soil from any hydrologic group.

Phreatophyte distributions have been altered over time with the pumping of the Ogallala Aquifer. This study analyzed possible causes for this redistribution, and through this analysis, developed a set of conditions under which phreatophytes are likely to exist. From this set of conditions, tree distributions can be used as a predictor for depth to water, soil type, and groundwater/surface water connectivity. The information learned in this study can be used to help guide the installation of future monitoring networks and expand current research projects from central Kansas to western Kansas.

Similar research should be conducted on the distribution of different species of phreatophytes in order to increase the accuracy of these predictions. Some regions, such as the city of Wichita, KS, are using artificial recharge as a means of maintaining its water supply. Because treatment of water for artificial recharge is not an economically viable option is western Kansas, further research should also be conducted to determine if phreatophytes are an indicator of water quality, and methods should be developed to make naturally infiltrated water cleaner without treatment.

Bibliography

Ahmad, M., W. G. M. Bastiaanssen, and R. A. Feddes: 2004, 'A New Technique to Estimate Net Groundwater Use across Large Irrigated Areas by Combining Remote Sensing and Water Balance Approaches, Rechna Doab, Pakistan'. *Hydrogeology Journal* **13**, 653-654.

Akita, T., K. Sakai, Y. Iwabuchi, Y. Hoshino, and XJ Ye: 2008, 'Spatial Autocorrelation in Masting Phenomena of Quercus Serrata Detected by Multi-Spectral Imaging'. *Ecological Modelling* **215**(1-3), 217-224.

Becker, M. W.: 2006, 'Potential for Satellite Remote Sensing of Groundwater'. *Ground Water* **44**(2), 306-318.

Brunke, M. and T. Gonser: 1997, 'The Ecological Significance of Exchange Processes between Rivers and Groundwater'. *Freshwater Biology* **37**, 1-33.

Busch, D. E., N. L. Ingraham, and S. D. Smith: 1992, 'Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A Stable Isotope Study'. *Ecological Applications* **2**(4), 450-459.

Butler Jr., J. J., G. J. Kluitenberg, D. O. Whittemore, S. P. Loheide II, W. Jin, M. A. Billinger, and X. Zhan: 2007, 'A Field Investigation of Phreatophyte-Induced Fluctuations in the Water Table'. *Water Resources Research* **43**(2).

Canadell, J., R. B. Jackson, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze: 1996, 'Maximum Rooting Depth of Vegetation Types at the Global Scale'. *Oecologia* **108**, 583-595.

Cleverly, J. R., C. N. Dahm, J. R. Thibault, D. E. McDonnell, and J. E. Allred Coonrod: 2006, 'Riparian Ecohydrology: Regulation of Water Flux from the Ground to the Atmosphere in the Middle Rio Grande, New Mexico'. *Hydrological Processes* **20**, 3207-3225.

Cooper, D. J., D. R. D'Amico, and M. L. Scott: 2003, 'Physiological and Morphological Response Patterns of Populus Deltoides to Alluvial Groundwater Pumping'. *Environmental Management* **31**(2), 215-226.

Devlin, J. F.: 2004, 'The Persistence of the Water Budget Myth and its Relationship to Sustainability'. *Hydrogeology Journal* **13**, 549-554.

Gutentag, E. D., F. J. Heimes, N. C. Krothe, R. R. Luckey, and J. B. Weeks: 1984, 'Geohydrology of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming'. USGS Report 1400-B.

Hansen, C. V.: 1991, 'Estimates of Freshwater Storage and Potential Natural Recharge for Principal Aquifers in Kansas'. USGS Water-Resources Investigations Report 87-4230.

Holdenbach, G: 1987, 'Tamarix Control'. *In*: M. R. Kunzmann, R. R. Johnson, and P. Bennett [eds.]. 'Tamarix Control in the United States. Tucson, AZ: University of Arizona. p. 116-123.

Jensen, J. R.: 2005, *Introductory Digital Image Processing*, 3rd Ed., Upper Saddle River, NJ: Prentice Hall, 526 pages.

Jiang, Y., C. Zhang, D. Yuan, G. Zhang, and R. He: 2008, 'Impact of Land Use Change on Groundwater Quality in a Typical Karst Watershed of Southwest China: a Case Study of the Xiaojiang Watershed, Yunnan Province'. *Hydrogeology Journal* **16**, 727-735.

Kansas Geological Survey (KGS): 2006, Water Information Storage and Retrieval Database (WIZARD).

Keller, J. M., M. R. Gray, and J. A. Givens: 1985, 'A Fuzzy K-Nearest Neighbor Algorithm'. *IEEE Transactions on Systems Man and Cybernetics* **15**(4), 580-585.

Law, D. J., C. B. Marlow, J. C. Mosley, S. Custer, P. Hook, and B. Leinard: 2000, 'Water Table Dynamics and Soil Texture of Three Riparian Plant Communities'. *Northwest Science* **74**(3), 234-241.

Münch, Z., and J. Conrad: 2007, 'Remote Sensing and GIS Based Determination of Groundwater Dependent Ecosystems in the Western Cape, South Africa'. *Hydrogeology Journal* **15**, 19-28.

Nagler, P. L., O. Hinojosa-Huerta, E. P. Glenn, J. Garcia-Hernandez, R. Romo, C. Curtis, A. R. Huete, and S. G. Nelson: 2005, 'Regeneration of Native Trees in the Presence of Invasive Saltcedar in the Colorado River Delta, Mexico'. *Conservation Biology* **19**(6), 1842-1852.

Owens, M. K. and G. W. Moore: 2007, 'Saltcedar Water Use: Realistic and Unrealistic Expectations'. *Rangeland Ecology and Management* **60**(5), 553-557.

Rodell, M., J. Chen, H. Kato, J. Famiglietti, J. Nigro, and C. R. Wilson: 2006, 'Estimating Groundwater Storage Changes in the Mississippi River Basin (USA) Using GRACE'. *Hydrogeology Journal* **15**, 159-166.

Shafroth, P. B., J. R. Cleverly, T. L. Dudley, J. P. Taylor, C. Van Riper III, E. P. Weeks, and J. N. Stuart: 2005, 'Control of Tamarix in the Western United States: Implications for Water Salvage, Wildlife Use, and Riparian Restoration'. *Environmental Management* **35**(3) 231-246.

Soil Survey Division Staff: 1993, Soil Survey Manual. Soil Conservation Service. U. S. Department of Agriculture Handbook 18.

Sophocleous, M.: 2005, 'Groundwater Recharge and Sustainability in the High Plains Aquifer in Kansas, USA'. *Hydrogeology Journal* **13**(2), 351-365.

Steward, D. R. and T. S. Ahring: 2009, 'An Analytic Solution for Groundwater Uptake by Phreatophytes Spanning Spatial Scales from Plant to Field to Regional'. *Journal of Engineering Mathematics* **64**(2), 85-103.

Suarez, J. C., C. Ontiveros, S. Smith, and S. Snape: 2005, 'Use of Airborne LiDAR and Aerial Photography in the Estimation of Individual Tree Heights in Forestry'. *Computers and Geosciences* **31**(2), 253-262.

United States Department of Agriculture (USDA) Agricultural Stabilization and Conservation Service: 1965, Aerial Photography Flown by Park Aerial Surveys, Inc., Louisville, KY.

USDA Agricultural Stabilization and Conservation Service: 1967, Aerial Photography Flown by Park Aerial Surveys, Inc., Louisville, KY.

USDA Commodity Stabilization Service: 1957, Aerial Photography Flown by Park Aerial Surveys, Inc., Louisville, KY.

USDA-Farm Services Agency (FSA) Aerial Photography Field Office: 2006, 'FSA National Agriculture Imagery Program (NAIP) 2006'. USDA FSA Aerial Photography Field Office, Salt Lake City, UT.

United States Geological Survey (USGS): 2008, National Water Information System: Web Interface. http://waterdata.usgs.gov/nwis

Appendix A: Calculations for the K_{hat} Coefficient

	Predevelopment Study Site 1 Test Information					
	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
Remote Sensing Classification	Bare Ground	94	4	4	0	102
	Sand Bar	2	33	0	2	37
	Tree	7	0	37	0	44
	Water	6	10	0	5	21
	Column Total	109	47	41	7	204

a

K_{hat} = 73.4%

	Predevelopment Study Site 1 Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	37	7	44
	Not Tree	4	156	160
	Column Total	41	163	204

b

K_{hat} = 83.7%

Figure A1: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 1 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees.

	Post-Development Study Site 1 Test Information				
	Class	Cropland/Ground	Tree	Water	Row Total
Remote Sensing Classification	Cropland/Ground	57	16	32	105
	Tree	1	86	9	96
	Water	1	0	2	3
	Column Total	59	102	43	204

a

K_{hat} = 52.8%

	Post-Development Study Site 1 Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	86	10	96
	Not Tree	16	92	108
	Column Total	102	102	204

b

K_{hat} = 74.5%

Figure A2: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 1 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Study Site 2 Test Information					
Remote Sensing Classification	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
	Bare Ground	70	2	3	29	104
	Sand Bar	13	27	0	11	51
	Tree	8	0	33	4	45
	Water	1	0	1	2	4
	Column Total	92	29	37	46	204

a

K_{hat} = 48.9%

	Predevelopment Study Site 2 Test Information			
Remote Sensing Classification	Class	Tree	Not Tree	Row Total
	Tree	33	12	45
	Not Tree	4	155	159
	Column Total	37	167	204

b

K_{hat} = 75.6%

Figure A3: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 2 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Study Site 2 Test Information					
Remote Sensing Classification	Class	Grass	Ground	Tree	Water	Row Total
	Grass	14	3	3	0	20
	Ground	21	98	2	5	126
	Tree	8	4	37	0	49
	Water	2	0	0	7	9
	Column Total	45	105	42	12	204

a

K_{hat} = 61.3%

	Post-Development Study Site 2 Test Information			
Remote Sensing Classification	Class	Tree	Not Tree	Row Total
	Tree	37	12	49
	Not Tree	5	150	155
	Column Total	42	162	204

b

K_{hat} = 76.0%

Figure A4: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 2 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

Remote Sensing Classification	Predevelopment Study Site 3 Test Information					
	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
	Bare Ground	95	23	7	5	130
	Sand Bar	13	24	1	8	46
	Tree	1	1	23	0	25
	Water	0	1	1	1	3
	Column Total	109	49	32	14	204

a

K_{hat} = 48.8%

Remote Sensing Classification	Predevelopment Study Site 3 Test Information			
	Class	Tree	Not Tree	Row Total
	Tree	23	2	25
	Not Tree	9	170	179
	Column Total	32	172	204

b

K_{hat} = 77.6%

Figure A5: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 3 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

Remote Sensing Classification	Post-Development Study Site 3 Test Information				
	Class	Cropland/Ground	Tree	Water	Row Total
	Cropland/Ground	116	4	4	124
	Tree	10	44	0	54
	Water	9	1	16	26
	Column Total	135	49	20	204

a

K_{hat} = 73.7%

Remote Sensing Classification	Post-Development Study Site 3 Test Information			
	Class	Tree	Not Tree	Row Total
	Tree	44	10	54
	Not Tree	5	145	150
	Column Total	49	155	204

b

K_{hat} = 80.5%

Figure A6: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 3 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Study Site 4 Test Information					
	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
Remote Sensing Classification	Bare Ground	95	3	4	0	102
	Sand Bar	5	29	0	3	37
	Tree	5	0	40	0	45
	Water	5	10	1	4	20
	Column Total	110	42	45	7	204

a

K_{hat} = 72.5%

	Predevelopment Study Site 4 Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	40	5	45
	Not Tree	5	154	159
	Column Total	45	159	204

b

K_{hat} = 85.7%

Figure A7: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 4 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Study Site 4 Test Information				
	Class	Cropland/Ground	Tree	Water	Row Total
Remote Sensing Classification	Cropland/Ground	129	9	1	139
	Tree	9	49	0	58
	Water	4	1	2	7
	Column Total	142	59	3	204

a

K_{hat} = 73.4%

	Post-Development Study Site 4 Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	49	9	58
	Not Tree	10	136	146
	Column Total	59	145	204

b

K_{hat} = 77.2%

Figure A8: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 4 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Study Site 5 Test Information					
	Class	**Bare Ground**	**Sand Bar**	**Tree**	**Water**	**Row Total**
Remote Sensing Classification	**Bare Ground**	104	0	4	30	138
	Sand Bar	2	16	0	8	26
	Tree	1	0	17	0	18
	Water	2	0	0	20	22
	Column Total	109	16	21	58	204

a

K_{hat} = 60.8%

	Predevelopment Study Site 5 Test Information			
	Class	**Tree**	**Not Tree**	**Row Total**
Remote Sensing Classification	**Tree**	17	1	18
	Not Tree	4	182	186
	Column Total	21	183	204

b

K_{hat} = 85.8%

Figure A9: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 5 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Study Site 5 Test Information				
	Class	**Cropland/Ground**	**Tree**	**Water**	**Row Total**
Remote Sensing Classification	**Cropland/Ground**	160	4	22	186
	Tree	1	9	0	10
	Water	3	0	5	8
	Column Total	164	13	27	204

a

K_{hat} = 43.2%

	Post-Development Study Site 5 Test Information			
	Class	**Tree**	**Not Tree**	**Row Total**
Remote Sensing Classification	**Tree**	9	1	10
	Not Tree	4	190	194
	Column Total	13	191	204

b

K_{hat} = 77.0%

Figure A10: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 5 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Study Site 6 Test Information					
	Class	**Bare Ground**	**Sand Bar**	**Tree**	**Water**	**Row Total**
Remote Sensing Classification	**Bare Ground**	100	3	4	28	138
	Sand Bar	4	10	0	8	26
	Tree	2	0	20	0	18
	Water	2	2	0	21	22
	Column Total	109	16	21	58	204

a

K_{hat} = 55.9%

	Predevelopment Study Site 6 Test Information			
	Class	**Tree**	**Not Tree**	**Row Total**
Remote Sensing Classification	**Tree**	20	2	22
	Not Tree	4	178	182
	Column Total	24	180	204

b

K_{hat} = 85.3%

Figure A11: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Predevelopment Study Site 6 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Study Site 6 Test Information				
	Class	**Cropland/Ground**	**Tree**	**Water**	**Row Total**
Remote Sensing Classification	**Cropland/Ground**	161	4	25	190
	Tree	1	8	0	9
	Water	2	0	3	11
	Column Total	164	12	28	204

a

K_{hat} = 35.0%

	Predevelopment Study Site 6 Test Information			
	Class	**Tree**	**Not Tree**	**Row Total**
Remote Sensing Classification	**Tree**	8	1	9
	Not Tree	4	191	195
	Column Total	12	192	204

b

K_{hat} = 74.9%

Figure A12: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy at Post-Development Study Site 6 (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Arkansas River Corridor Test Information					
	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
Remote Sensing Classification	Bare Ground	95	3	4	40	142
	Sand Bar	2	8	1	6	17
	Tree	5	0	16	0	21
	Water	5	6	0	13	24
	Column Total	107	17	21	59	204

a

K_{hat} = 39.5%

	Predevelopment Arkansas River Corridor Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	16	5	21
	Not Tree	5	178	183
	Column Total	21	183	204

b

K_{hat} = 73.5%

Figure A13: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy along the Predevelopment Arkansas River Corridor (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Arkansas River Corridor Test Information				
	Class	Cropland/Ground	Tree	Water	Row Total
Remote Sensing Classification	Cropland/Ground	118	5	31	154
	Tree	10	33	2	45
	Water	2	1	2	5
	Column Total	130	39	35	204

a

K_{hat} = 47.1%

	Post-Development Arkansas River Corridor Test Information			
	Class	Tree	Not Tree	Row Total
Remote Sensing Classification	Tree	33	12	45
	Not Tree	6	153	159
	Column Total	39	165	204

b

K_{hat} = 73.1%

Figure A14: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy along the Post-Development Arkansas River Corridor (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Predevelopment Cimarron River Corridor Test Information					
Remote Sensing Classification	Class	Bare Ground	Sand Bar	Tree	Water	Row Total
	Bare Ground	100	0	4	30	134
	Sand Bar	2	16	0	8	26
	Tree	1	0	21	0	22
	Water	2	0	0	20	22
	Column Total	105	16	25	58	204

a

K_{hat} = 62.4%

	Post-Development Cimarron River Corridor Test Information			
Remote Sensing Classification	Class	Tree	Not Tree	Row Total
	Tree	21	1	22
	Not Tree	4	178	182
	Column Total	25	179	204

b

K_{hat} = 88.0%

Figure A15: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy along the Predevelopment Cimarron River Corridor (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

	Post-Development Cimarron River Corridor Test Information				
Remote Sensing Classification	Class	Cropland/Ground	Tree	Water	Row Total
	Cropland/Ground	148	6	20	174
	Tree	3	17	2	22
	Water	7	1	0	8
	Column Total	158	24	22	204

a

K_{hat} = 40.7%

	Post-Development Cimarron River Corridor Test Information			
Remote Sensing Classification	Class	Tree	Not Tree	Row Total
	Tree	17	5	22
	Not Tree	7	175	182
	Column Total	24	180	204

b

K_{hat} = 70.6%

Figure A16: Calculations for K_{hat} Coefficient of Remote Sensing Accuracy along the Post-Development Cimarron River Corridor (a) Using the Entire Dataset and (b) Using only Trees and Not Trees

Appendix B: Water Table Depth, Soil Type, and Remote Sensing Results

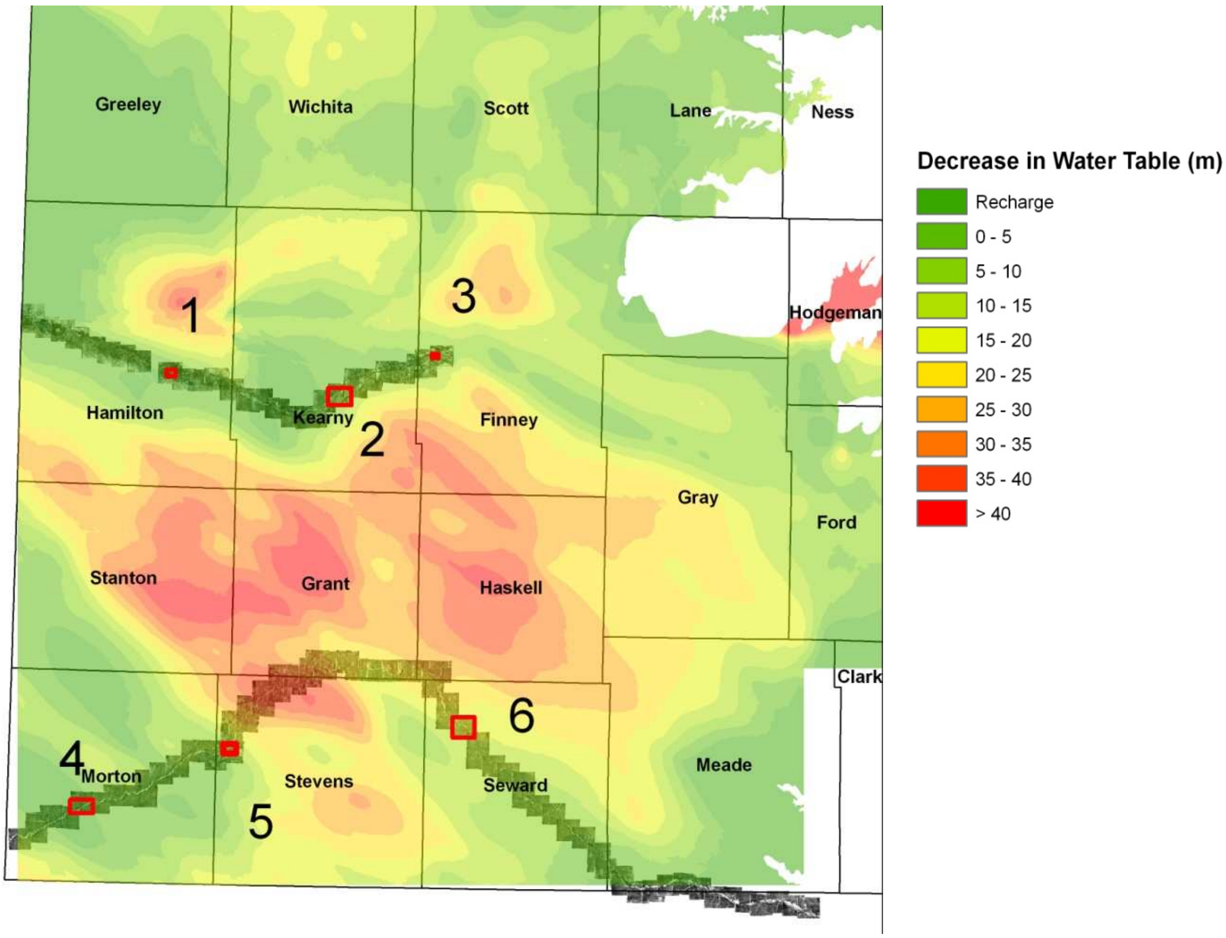
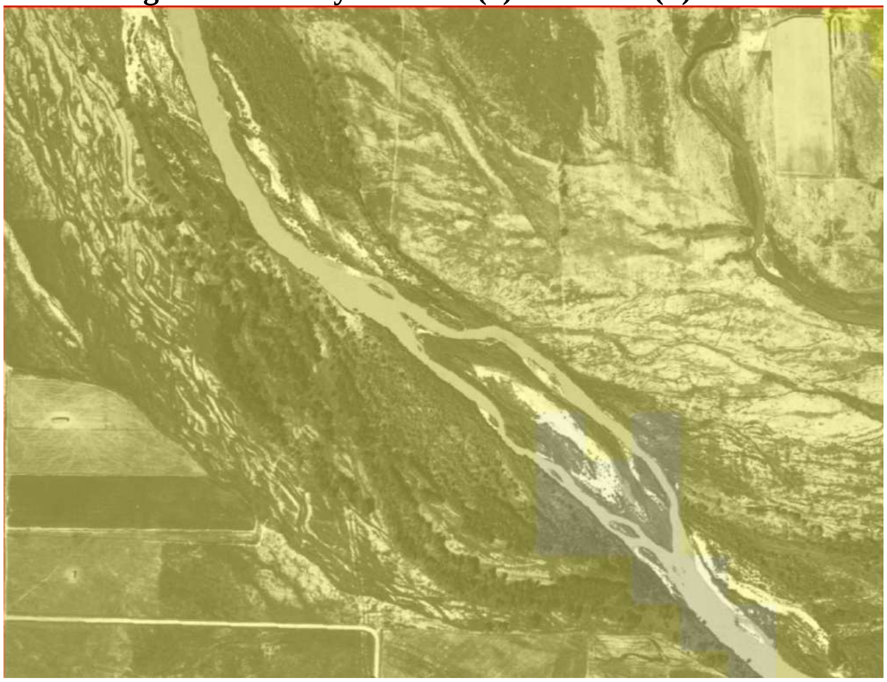


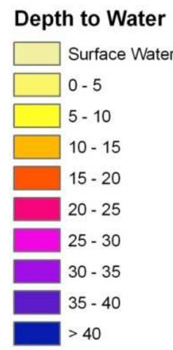
Figure B1: Decrease in the Water Table in Western Kansas between 1965 and 2005.

a

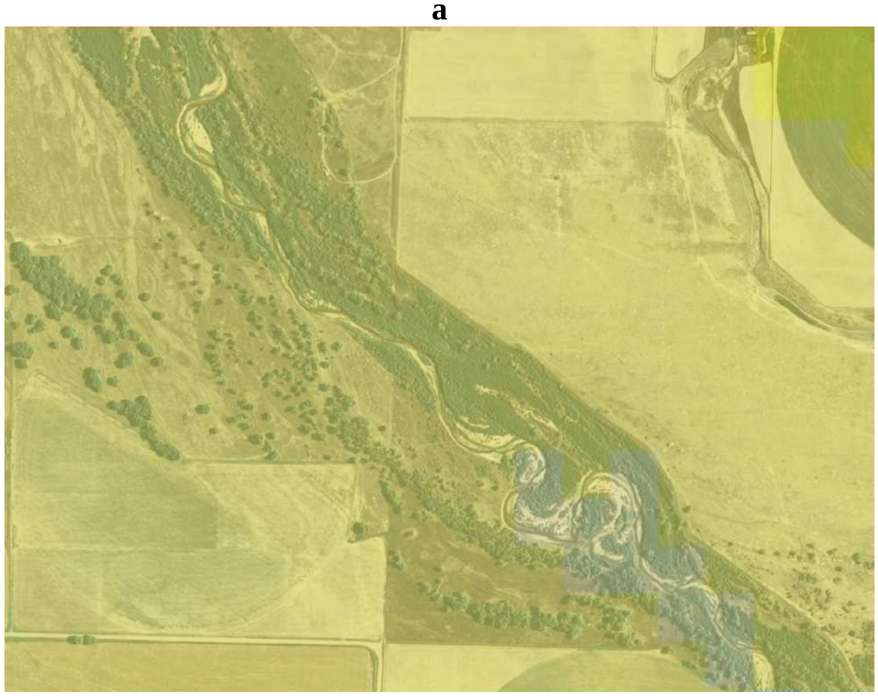
b

Figure B2: Study Site 1 in (a) 1957 and (b) 2006.



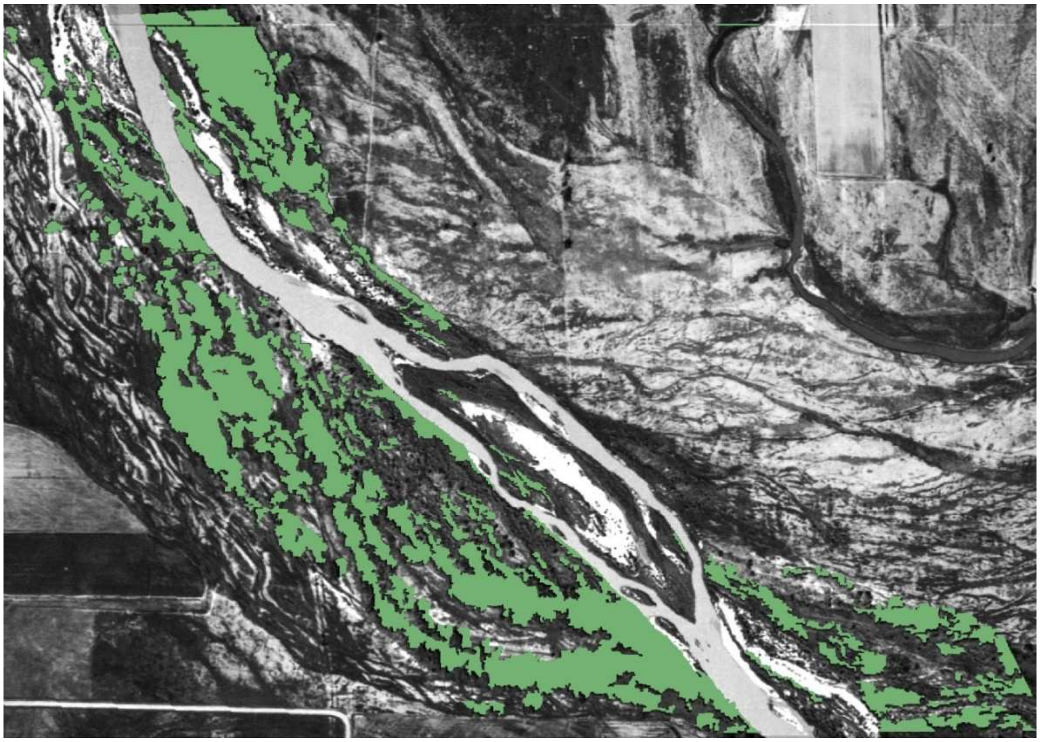


a



b

Figure B3: Depth to Groundwater, in m, at Study Site 1 in (a) 1965 and (b) 2005.



a

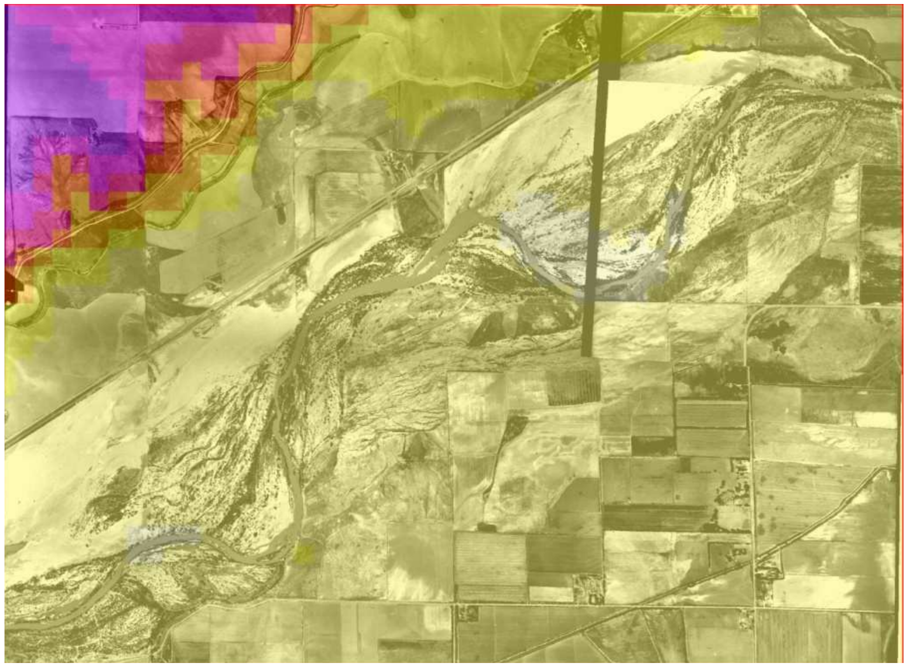
b

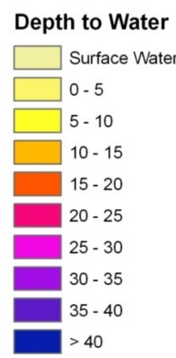
Figure B4: Remote Sensing Tree Locations at Study Site 1 in (a) 1957 and (b) 2006.

a

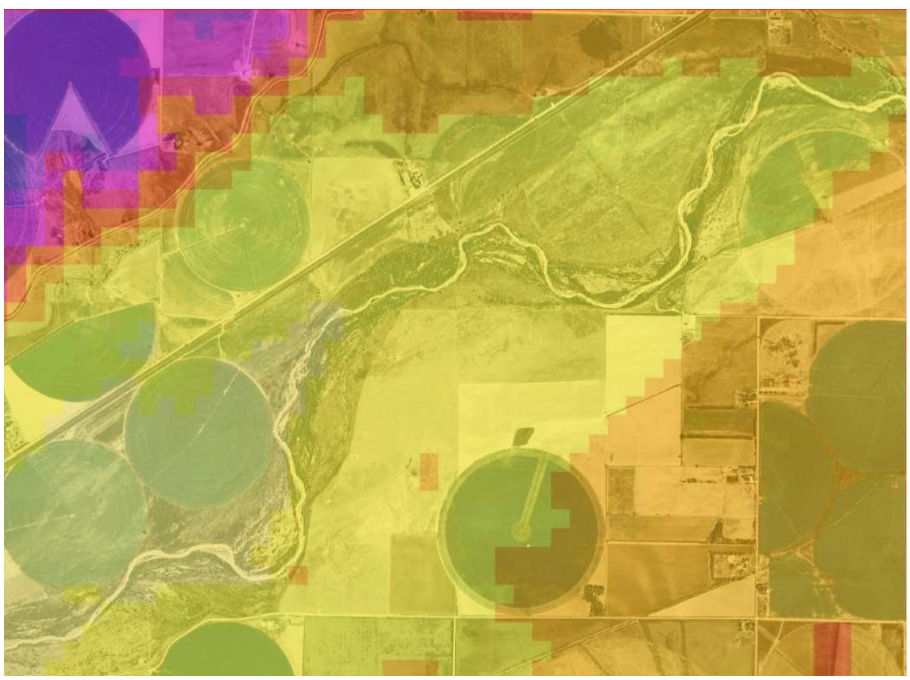
b

Figure B5: Study Site 2 in (a) 1965 and (b) 2006.



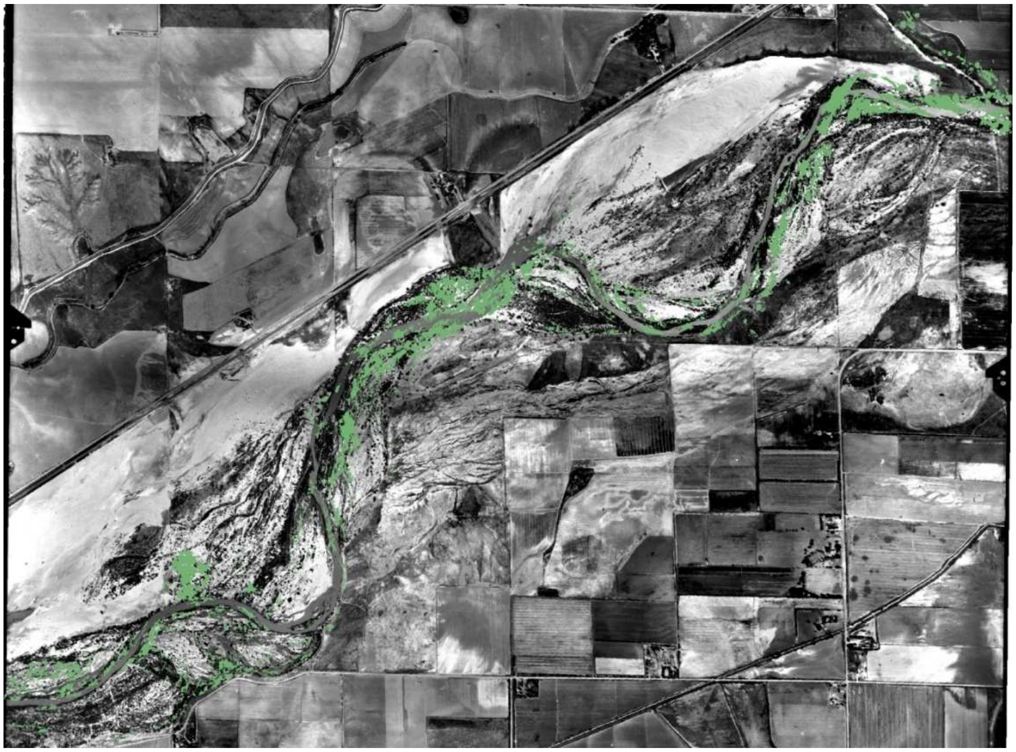


a

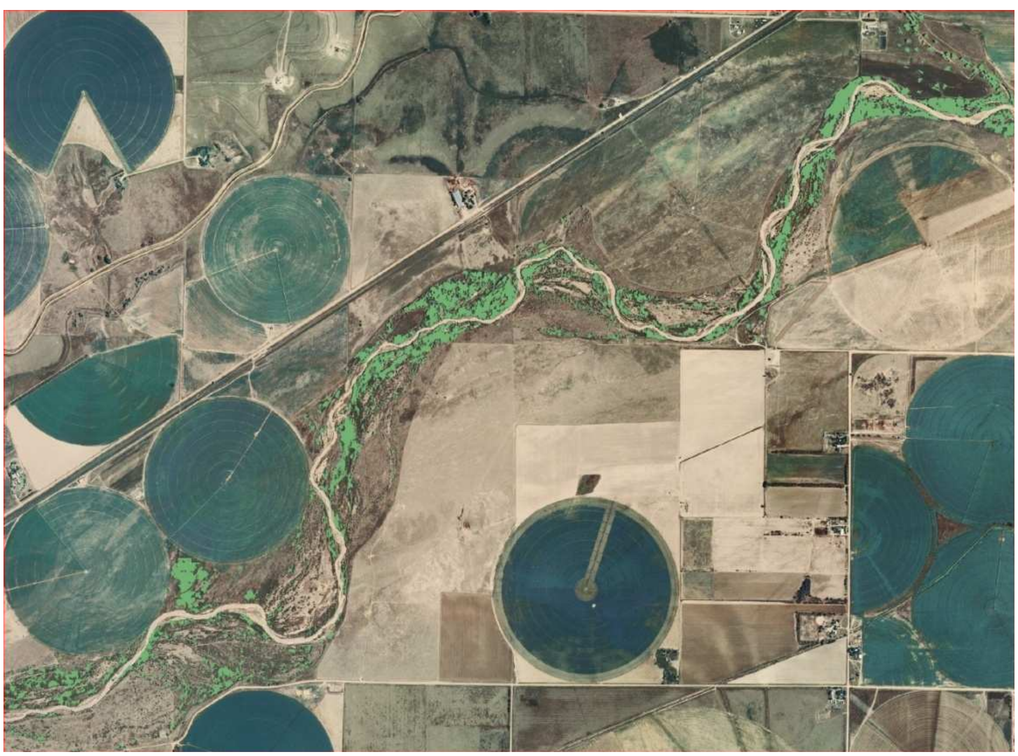


b

Figure B6: Depth to Groundwater, in m, at Study Site 2 (a) in 1965 and (b) in 2005.

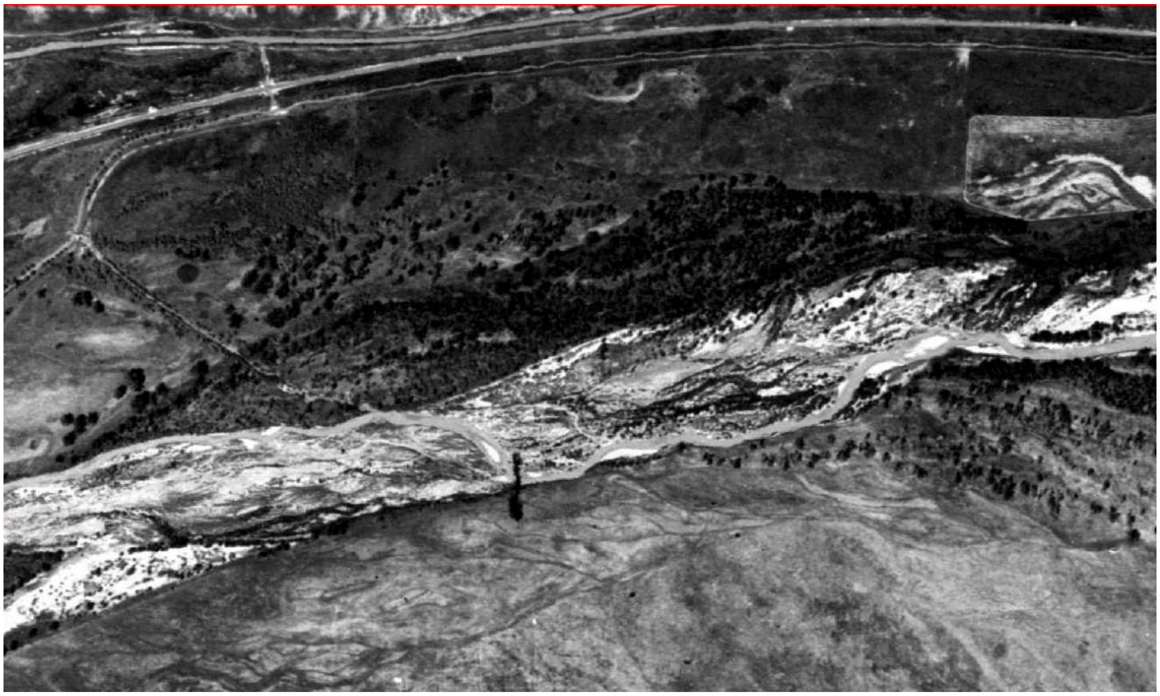


a

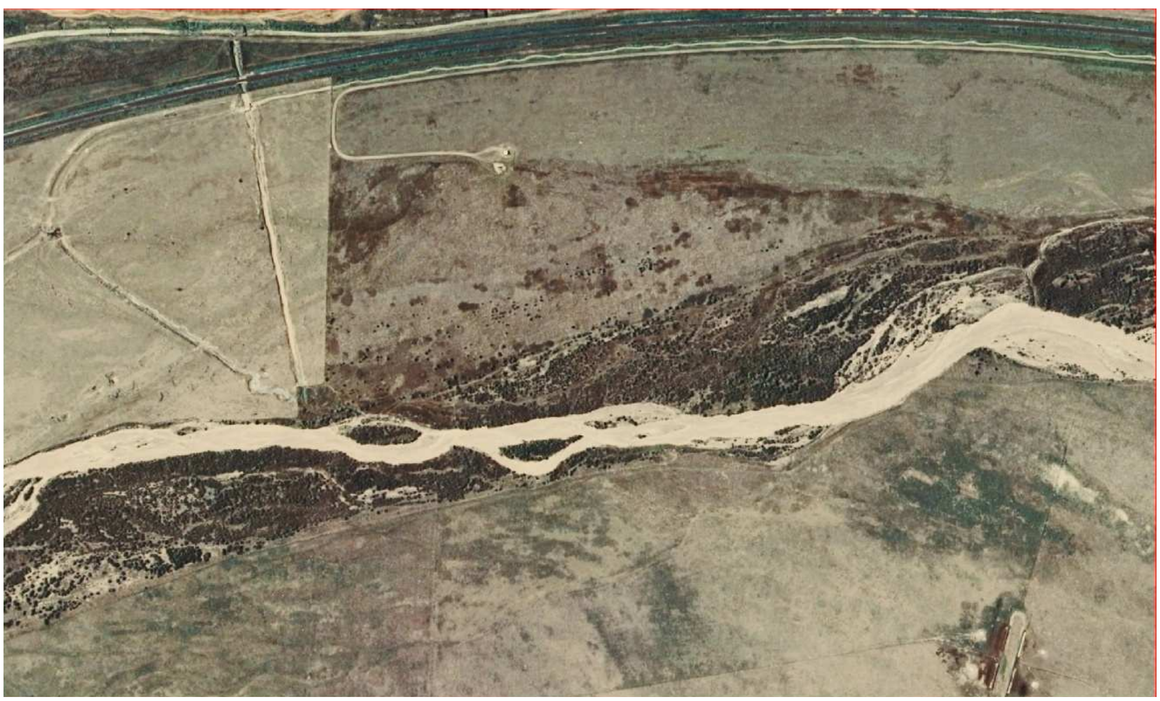


b

Figure B7: Remote Sensing Tree Locations at Study Site 2 in (a) 1965 and (b) 2006.



a



b

Figure B8: Study Site 3 in (a) 1957 and (b) 2006.

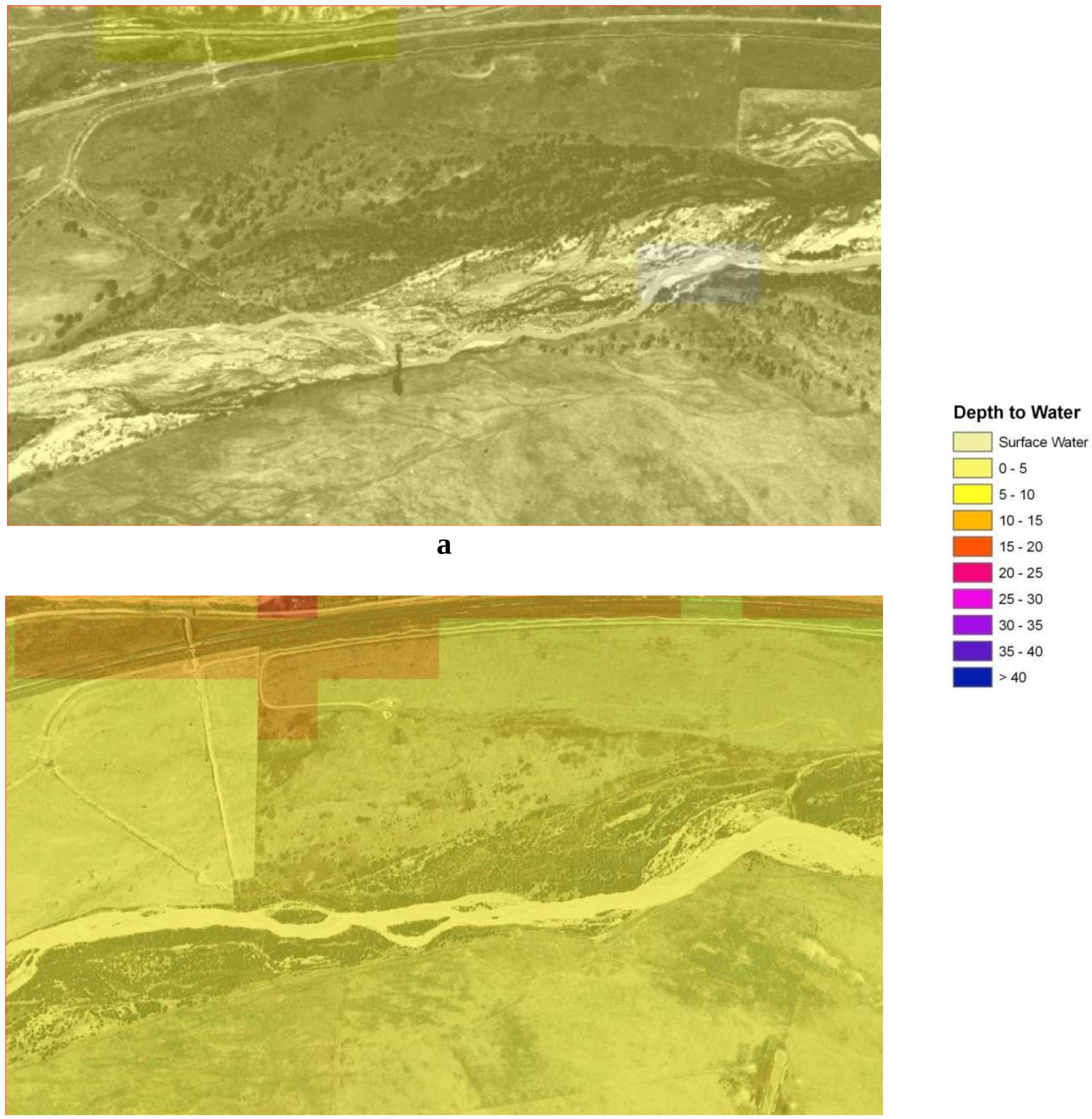
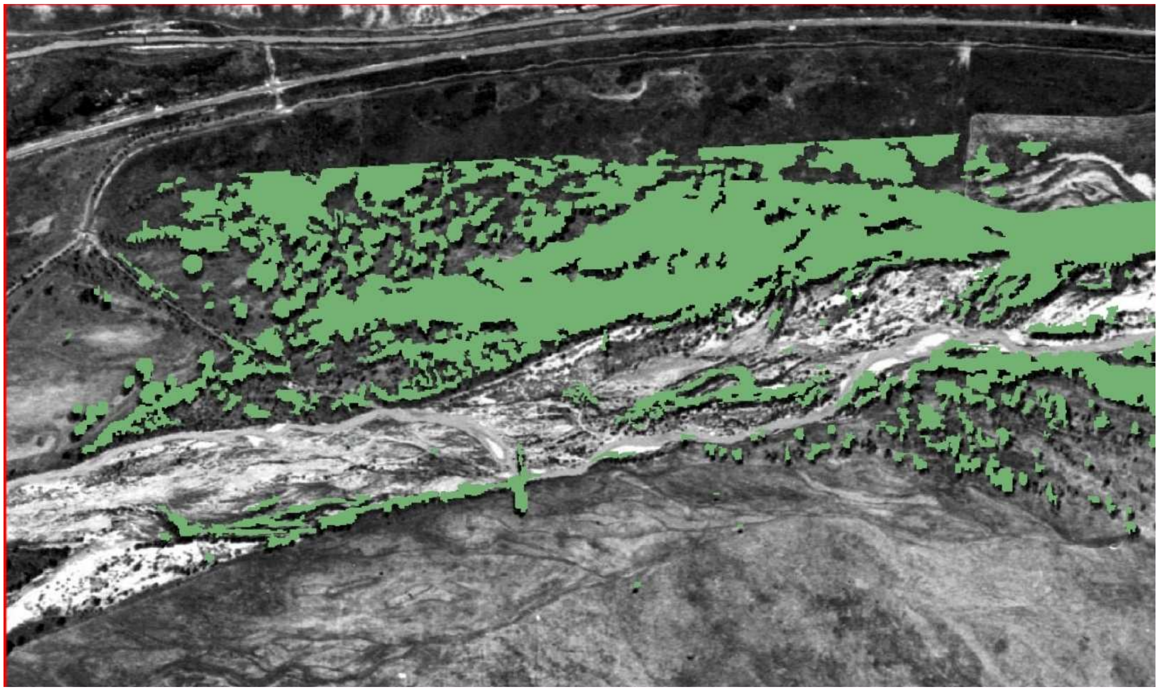


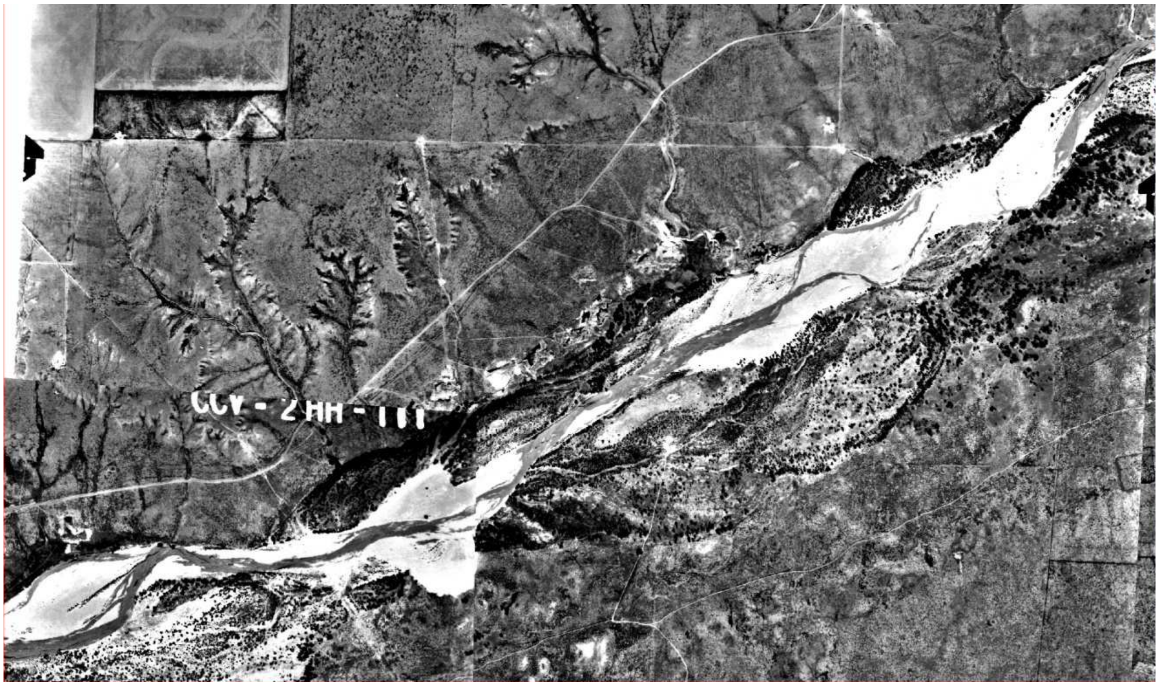
Figure B9: Depth to Groundwater, in m, at Study Site 3 in (a) 1965 and (b) 2006.



a

b

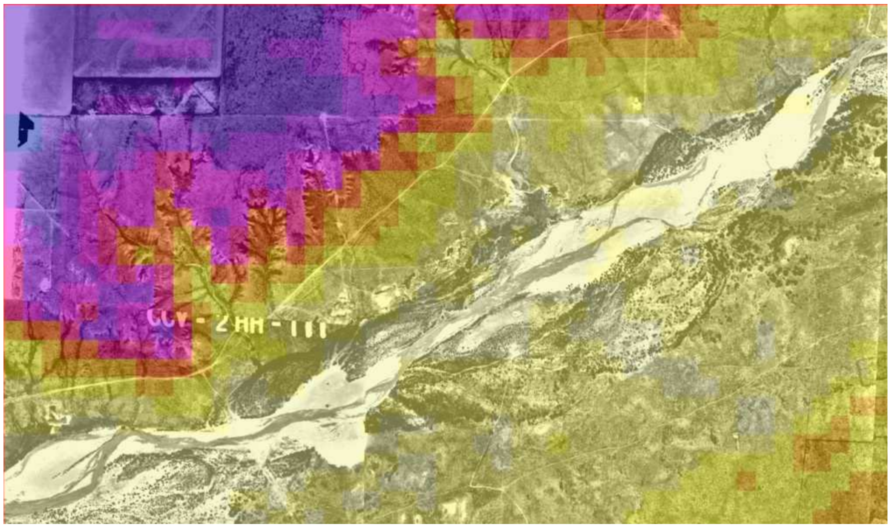
Figure B10: Remote Sensing Tree Locations for Study Site 3 in (a) 1953 and (b) 2006.

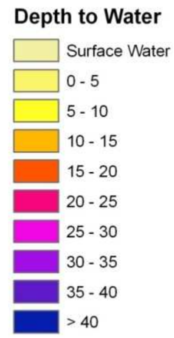


a

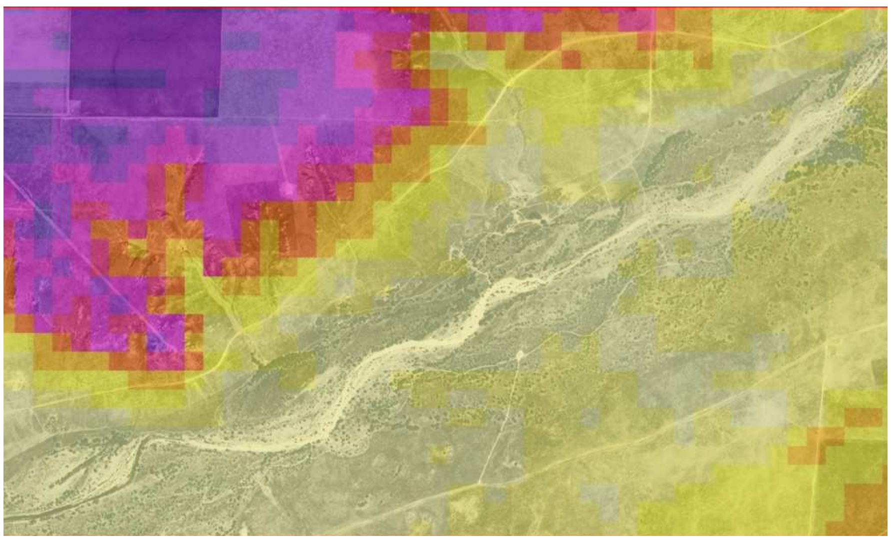
b

Figure B11: Study Site 4 in (a) 1967 and (b) 2006.



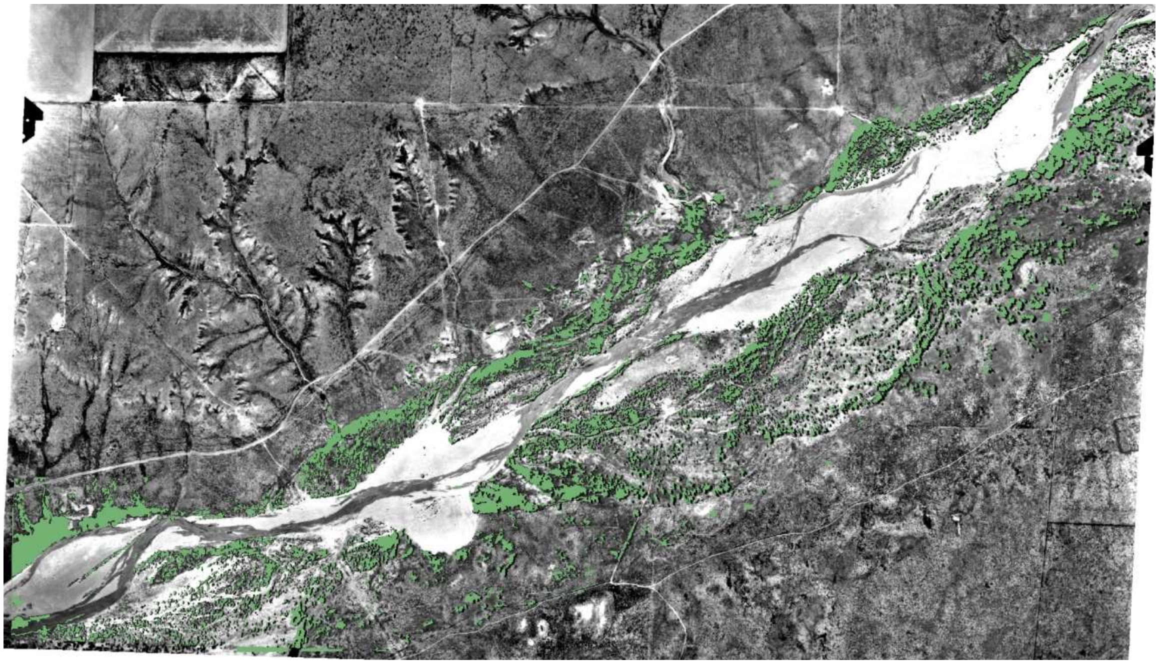


a

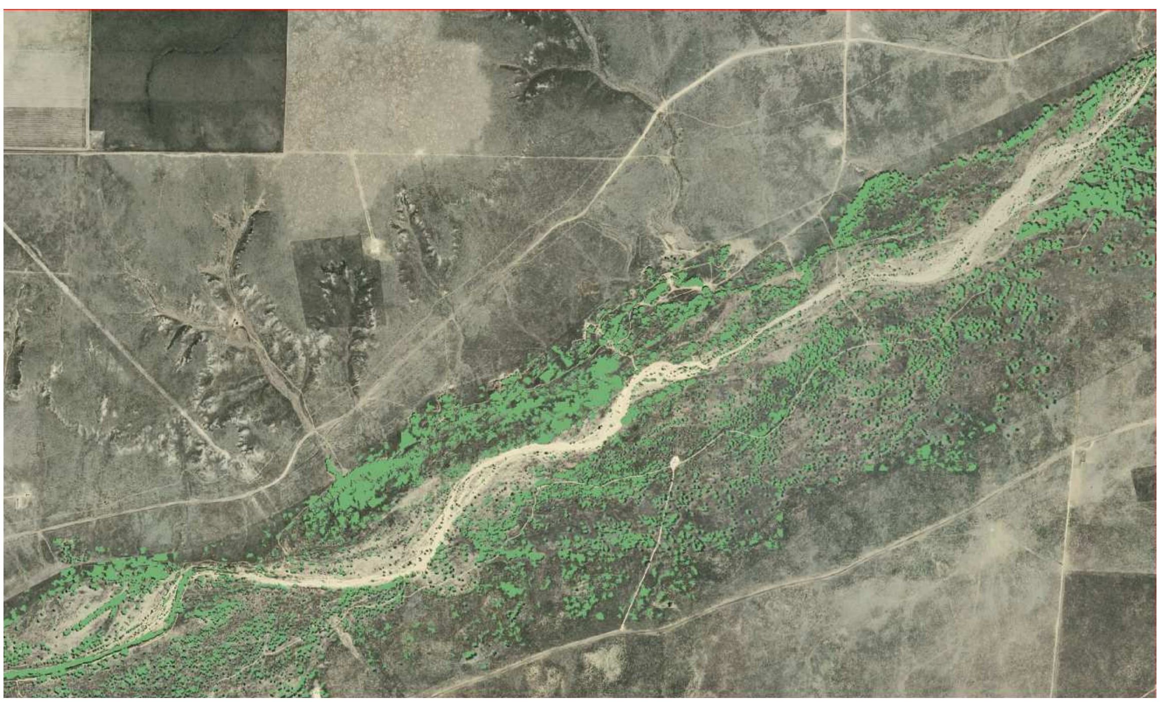


b

Figure B12: Depth to Groundwater, in m, at Study Site 4 in (a) 1965 and (b) 2005.

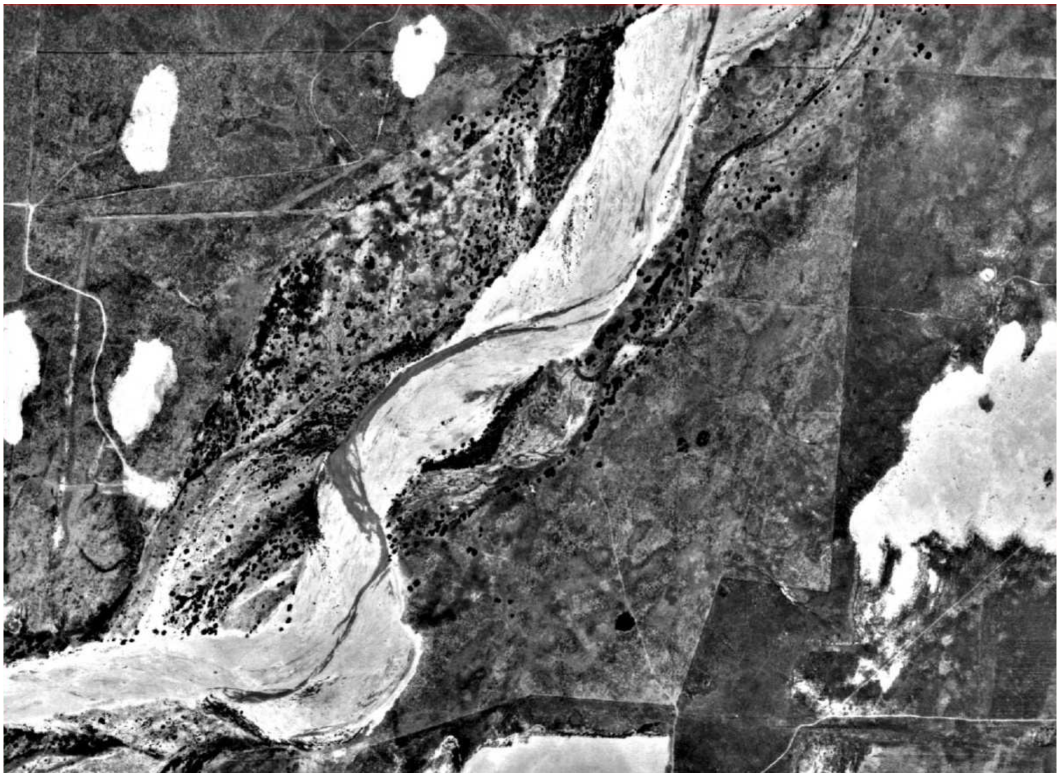


a



b

Figure B13: Remote Sensing Tree Locations at Study Site 4 in (a) 1967 and (b) 2006.



a

b

Figure B14: Study Site 5 in (a) 1967 and (b) 2006.

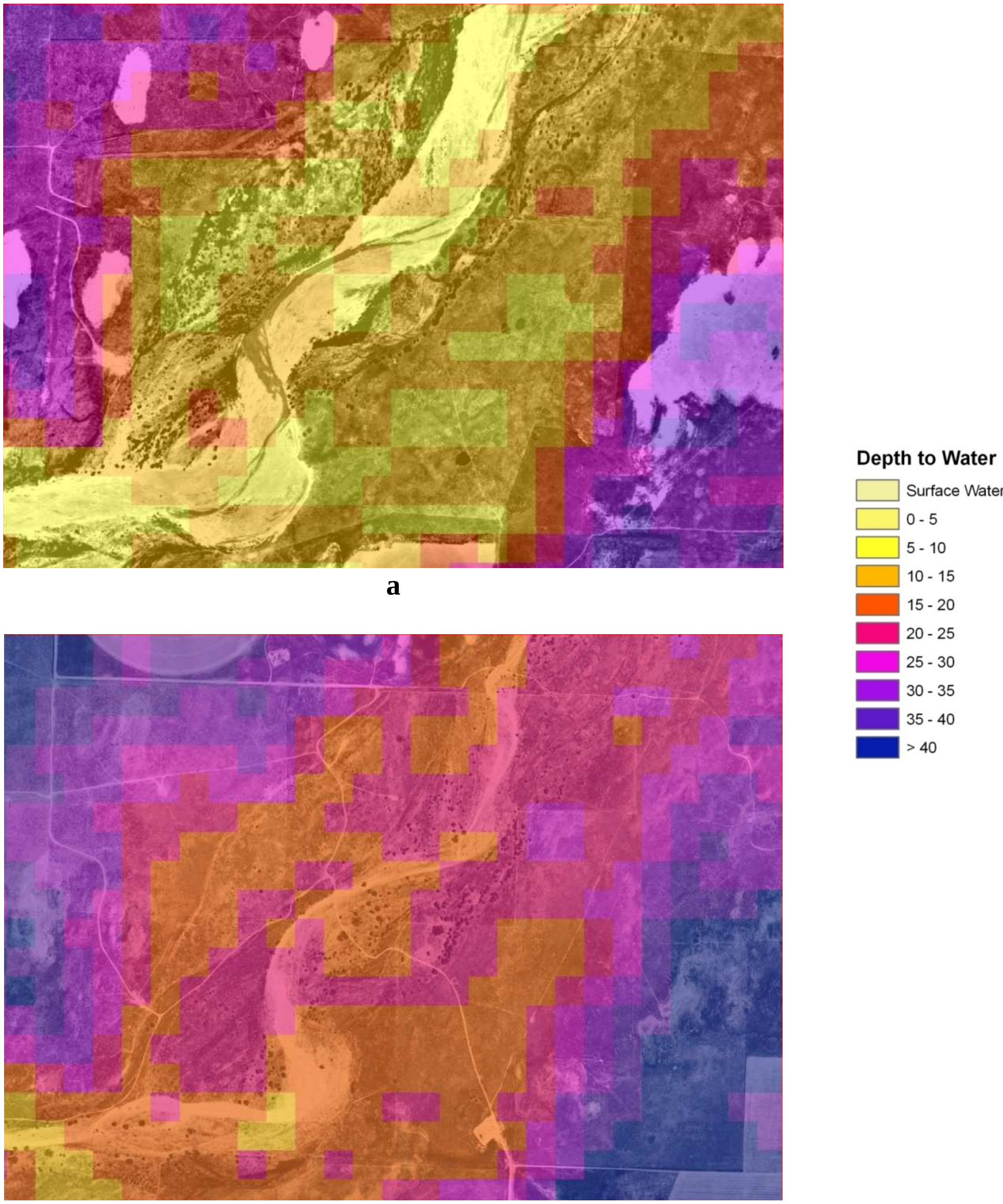
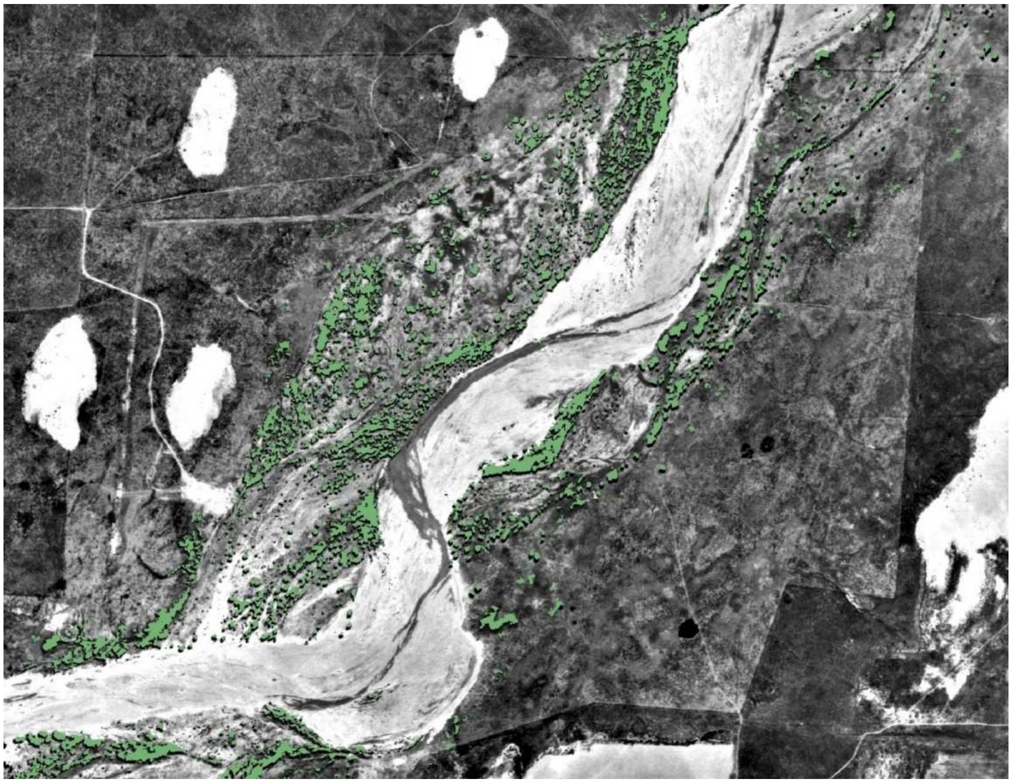
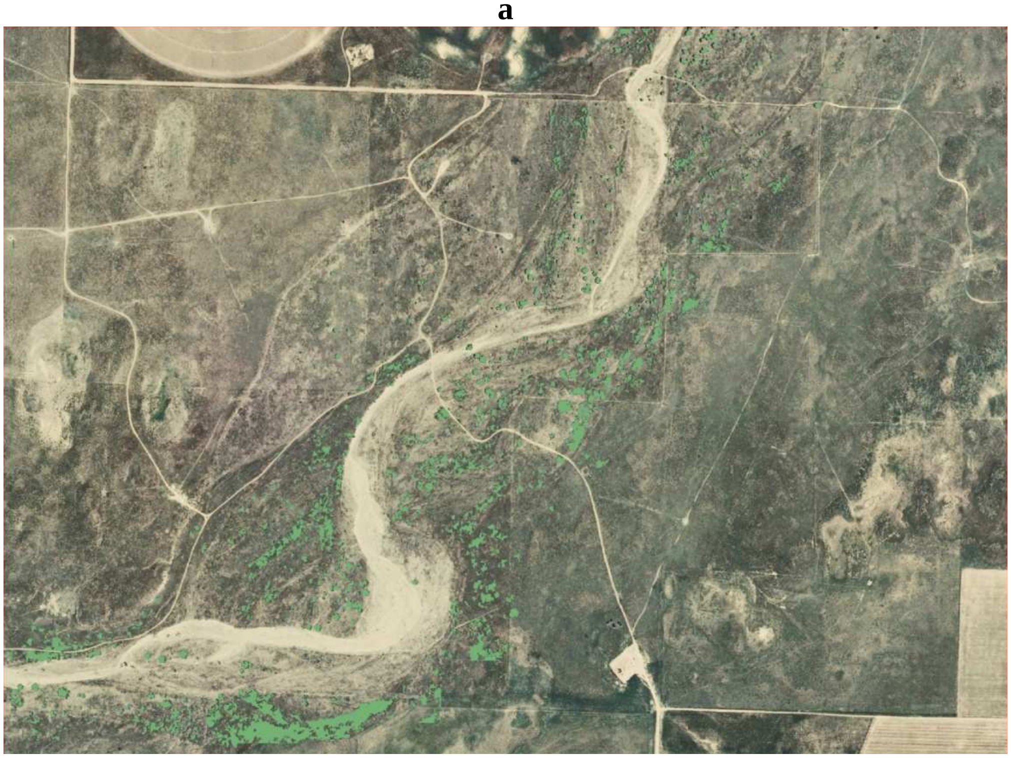


Figure B15: Depth to Groundwater, in m, at Study Site 5 in (a) 1965 and (b) 2005.

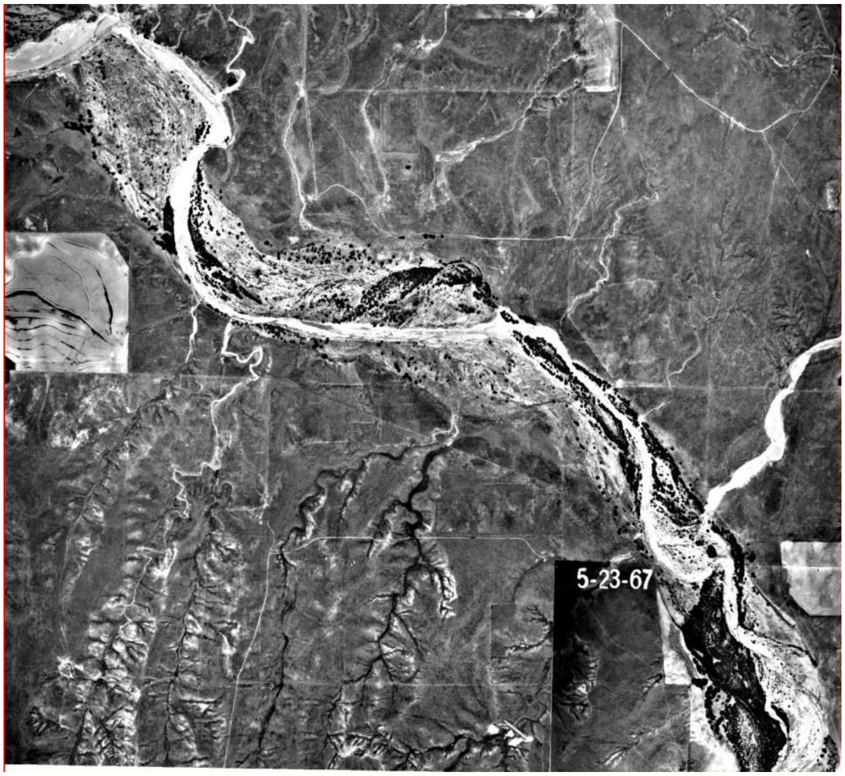


a



b

Figure B16: Remote Sensing Tree Locations at Study Site 5 in (a) 1967 and (b) 2006.



a

b

Figure B17: Study Site 6 in (a) 1967 and (b) 2006.

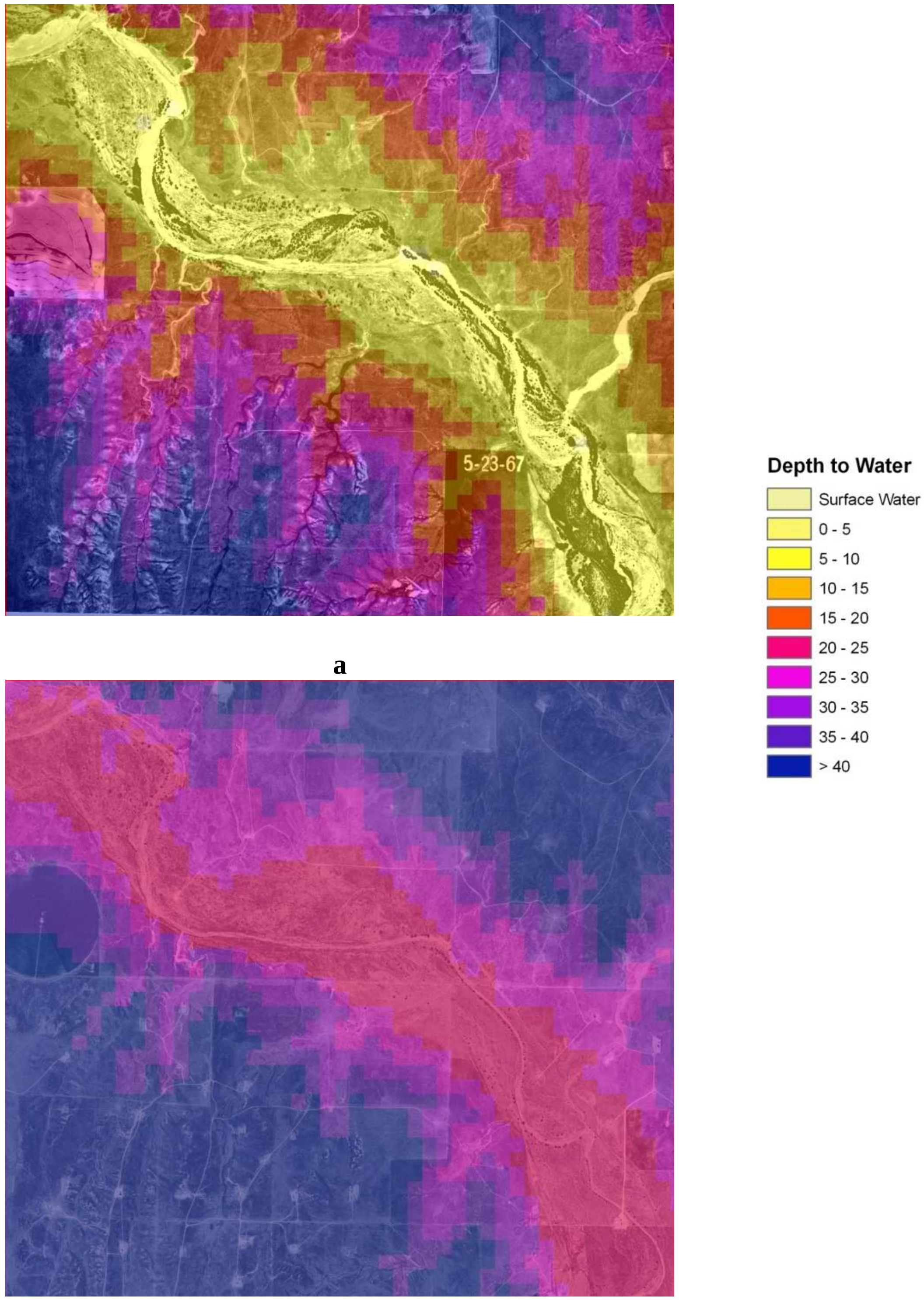
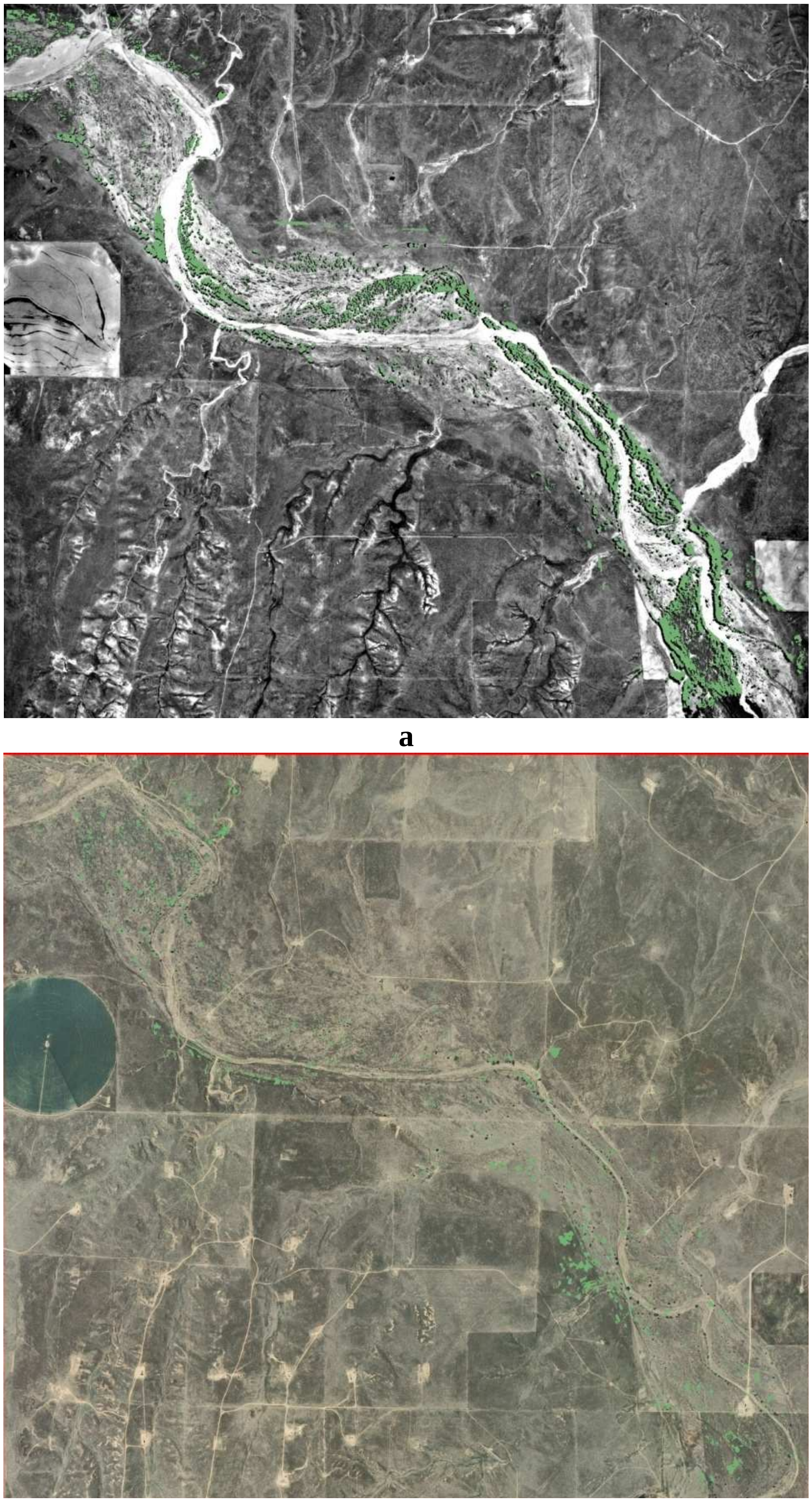


Figure B18: Depth to Groundwater, in m, at Study Site 6 in (a) 1965 and (b) 2005.



a

b

Figure B19: Remote Sensing Tree Locations at Study Site 6 in (a) 1967 and (b) 2006.