

GIS-BASED COUPLED CELLULAR AUTOMATON MODEL TO ALLOCATE IRRIGATED
AGRICULTURE LAND USE IN THE HIGH PLAINS AQUIFER REGION

by

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Abstract

The Kansas High Plains region is a key global agricultural production center (U.S. G.S, 2009). The High Plains physiography is ideal agricultural production landscape except for the semi-arid climate. Consequently, farmers mine vast groundwater resources from the High Plains Ogallala Aquifer formations to augment precipitation for crop production. Growing global population, current policy and subsidy programs, declining aquifer levels coupled with regional climatic changes call into question both short-term and long-term resilience of this agrarian landscape and food and water security.

This project proposes a means to simulate future irrigated agriculture land use and crop cover patterns in the Kansas High Plains Aquifer region based on coupled modeling results from ongoing research at Kansas State University. A Cellular Automata (CA) modeling framework is used to simulate potential land use distribution, based on coupled modeling results from groundwater, economic, and crop models. The CA approach considers existing infrastructure resources, industrial and commercial systems, existing land use patterns, and suitability modeling results for agricultural production. The results of the distribution of irrigated land produced from the CA model provide necessary variable inputs for the next temporal coupled modeling iteration. For example, the groundwater model estimates water availability in saturated thickness and depth to water. The economic model projects which crops will be grown based on water availability and commodity prices at a county scale. The crop model estimates potential yield of a crop under specific soil, climate and growing conditions which further informs the economic model providing an estimate of profit, which informs regional economic and population models. Integrating the CA model into the coupled modeling system provides a key linkage to simulate spatial patterns of irrigated land use and crop type land cover based on coupled model results. Implementing the CA model in GIS offers visualization of coupled model components and results as well as the CA model land use and land cover. The project outcome hopes to afford decision-makers, including farmers, the ability to use the actual landscape data and the developed coupled modeling framework to strategically inform decisions with long-term resiliency.

Table of Contents

List of Figures	v
List of Tables	vii
Acknowledgements	viii
Chapter 1 - Introduction.....	1
Chapter 2 - High Plains/Ogallala Aquifer Landscape.....	4
History of Aquifer Water Use.....	16
Literature Review	22
Development of Land Use Model.....	23
Central Places and Concentric Land Use Model	24
Concentric Urban Land Use.....	25
Sector Urban Land Use	26
Multiple Nuclei Urban Land Use.....	27
Hybrid Land Use	28
Land Use Market.....	29
Cellular Automata	30
Cellular Automaton Model	31
Von Neumann Neighborhood	31
Conway's Game of Life	34
Land Use Model Simulation Applications.....	37
Coupled Model Approach.....	41
Chapter 3 - Research Method	44
Study Area and Dataset.....	46
Defining Transition Rules.....	58
CA Model Simulation Results	60
Chapter 4 - Conclusions.....	66
Work Cited.....	68

List of Figures

Figure 2.1	Extent of the High Plains/Ogallala aquifer System.....	5
Figure 2.2	Map of High Plains Aquifer Average Depth to Water for 2007-2009	6
Figure 2.3	Average saturated thickness 2007-2009 of the High Plains aquifer region	7
Figure 2.4	Percentage of State Land Underlain by Aquifer Formations	8
Figure 2.5	State Land Area Underlain by Aquifer Formation and Average Weight Saturated Thickness	8
Figure 2.6	Rivers across High Plains Aquifer region	9
Figure 2.7	Estimated Annual Minimum Temperature in Kansas	10
Figure 2.8	Estimated Annual Maximum Temperature in Kansas.....	11
Figure 2.9	Estimated Annual Precipitation in Kansas	12
Figure 2.10	Estimate Natural Recharge for the High Plains Aquifer Region.....	13
Figure 2.11	Diagram of Cone of Depress Caused by Rapid Pumping	14
Figure 2.12	Estimated Usable lifetime for the High Plains Aquifer in Kansas 1999-2009.....	15
Figure 2.13	Surface vs. Ground water use in Kansas	18
Figure 2.14	Reported Water Use by Type in Kansas.....	19
Figure 2.15	Projected concentrated irrigated farmland on the High Plains aquifer region	20
Figure 2.16	Estimated irrigated farmland in the High Plains aquifer counties.....	21
Figure 2.17	Von Thunen's Regional Land Use Model	24
Figure 2.18	Burgess Urban Land Use Model	25
Figure 2.19	Sector Urban Land Use	26
Figure 2.20	Nuclei Urban Land Use	27
Figure 2.21	Hybrid Land Use	28
Figure 2.22	Land Use Market	29
Figure 2.23	Cellular Automata Land Use Model.....	30
Figure 2.24	Von Neumann Neighborhood.....	32
Figure 2.25	Iteration of Von Neumann Neighborhood from Original Cell.....	32
Figure 2.26	Moore Neighborhood	33
Figure 2.27	Iteration of Moore Neighborhood from Original Cell.....	33

Figure 2.28 Illustration of Conway’s Game of Life	34
Figure 2.29 Diagram shows concept of transition rule in CA model Moore neighborhood	35
Figure 2.30 Diagram shows transition rules in the CA model.....	36
Figure 2.32 Coupled Models Integration Using OpenMI, GIS and ODM	41
Figure 2.33 Interactions and data exchange between multidisciplinary models	42
Figure 3.1 Driving Factor for the CA model	45
Figure 3.4 Finney County Cropland Data Layer 2006, before reclassify	48
Figure 3.5 Finney County Cropland Data Layer 2006, after reclassify	49
Figure 3.6 CAFOs 30 and 50 Mile Radius Map	51
Figure 3.7 Biofuel Plants 30 and 50 Mile Radius Map.....	51
Figure 3.8 Grain Elevators 30 and 50 Mile Radius Map	52
Figure 3.9 Stafford County Kansas Prime Farmland Soil Coverage	53
Figure 3.10 Stafford County Prime Farmland Soil Coverage Overlay with Irrigated Cropland Data	54
Figure 3.11 Block statistics vs. Focal statistics in calculating cell neighborhood	55
Figure 3.12 Example of Extracted Irrigated Cropland Using Center Pivot Polygon Data	57
Figure 3.13 Diagram of CA Model Land Use Transition Rules.....	59
Figure 3.14 Map of Saturated Thickness that Met Minimum Required Threshold of 30 Feet....	61
Figure 3.15 Existing Irrigated Land Use by CDL Crop Type in 2006 in South Central Kansas	62
Figure 3.16 First CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes	63
Figure 3.17 Second CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes	63
Figure 3.18 Fifth CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes	64
Figure 3.19 Comparison of CA Model Cell Acreage from First, Second and Fifth Iterations....	65

List of Tables

Table 2.31 Table of Existing Urban Land Use Simulation Applications	38
Table 3.2 GIS Data Sources.....	46
Table 3.3 Cropland Data Layer Classes.....	47

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I would also like to thank my husband, for his support when I needed the most.

Chapter 1 - Introduction

Water is the primary support system for all living creatures on Earth. The availability of water has played an important role in determining where people can live and their ability to sustain living in a particular location. People all over the world use water for drinking, growing crops and industrial purposes. Today the balance between human demand and existing supplies is highly intricate. While the relationship of the availability of water largely determines where, and to what extent various land developments can occur, technology and elaborate water engineering projects have manipulated watersheds and hydrologic systems to increase water availability in certain areas.

Typically for any development in the world to happen, water must be available and easily accessible for the explicit development purpose and related, or value-added, purposes affiliated with the development. Water demand has focused on expanding or manipulating the exiting supply to meet the vast use need or desire of humans, flora and fauna locally, however increasingly natural and political system implications across scales from local to global are being considered. Ultimately land development practices impact the growth of population, water management policies, as well as short-term and long-term resilience of food and water security in a region and the world.

Cumulatively the growing global population, declining freshwater water resources, regional climatic changes, persistent drought and accelerated desertification, have caused scarcity of food and water supplies throughout the world. Farmers are facing challenges of declining supplies of irrigation water, loss of high quality cropland to urban development, rising fuel costs, and rapid growing needs for agriculture products for human consumption, livestock feeding, and crop-based fuel demands (Schaible & Aillery, 2013). In a global economy, decisions on what to plant often seem limited by policy or commodity pricing systems, or at odds with local growing conditions implicating the amount of water used. These issues and challenges are all present in the High Plains/Ogallala Aquifer Region of the United States.

Landscape architects have long been interested in understanding and designing sustainable land use and cover patterns. Landscape architecture is demonstrated through planning and design based upon a comprehensive understanding of the dynamic interactions of spatial and temporal

components within landscape systems. The disciplines' approach and philosophy make landscape architects key participants in understanding, communicating and solving complex issues like those in the High Plains/Ogallala Aquifer Region.

The ability to simulate current and future agriculture land use, and water availability and use, is critical for resiliency of agricultural communities like those in the High Plains/Ogallala aquifer region reliant upon a scarce water resource. Simulation can help people understand the region's complex landscape from a multiple perspectives and demonstrate short and long-term effects of land use and cover choices made to the overall natural/human systems, as well as local to global food supply.

To facilitate simulation, natural and social systems comprising the landscape must first be understood. Maps and animations created in a Geographic Information System (GIS) illustrate spatial and temporal landscape systems via abstractions of a landscape's thematic layers and attributes associated with objects in the layers. GIS generated maps are extremely useful as they provide critical thematic layer information from attributes characterizing spatial areas while visually communicating the relationship between layers of information (Arctur & Zeiler, 2004). When thematic layers are seen together, or overlaid, they not only illustrate thematic land use and cover patterns, but spark theories as to why the patterns exist.

The advent of the GIS geodatabase to not only store thematic layer information (point, line, polygon and raster data types), but to also create relationships between objects and layers allows GIS users to conceptualize and model dynamic landscape system interactions as opposed to static layer representations. Geodatabases are typically designed from a thematic data layer inventory and analysis aimed at conceptualizing the relationships of objects within and between layers of discrete landscape information like topography, geology, soils, watersheds, wells, population, transportation, etc.

Geodatabase models, called data models, are the abstract conceptualization of complex landscape system elements as relational digital database objects. Geodatabase data model templates and standards have been established, or are emerging for landscape systems such as land ownership, watersheds and groundwater, transportation systems, Homeland Security, etc. (Arctur & Zeiler, 2004). Storing objects in systematic and standardized ways in geodatabases for individual systems allows for more complex connections of multiple systems along with

statistical and mathematical analysis of the dynamics of and between the landscape systems (Zeiler & Murphy, 1999).

For the scope of this project, the High Plains/Ogallala Aquifer Region, land use and land cover patterns are the result of a complex agronomic system formed around the aquifer water resource thus requiring linking multiple dynamic landscape systems together. Here a model, or conceptualization of the system becomes important to mimic the real world conditions and input parameters of the dynamic landscape systems at play. Given the nature of this complex land use and land cover problem directly tied to the water resource system, a GIS and geodatabase models are valuable.

This project lies in the context of ongoing research projects attempting to help individual actors and policy makers make informed decisions about aquifer water use. At the outset of the projects beginning in 2001, the approach was to understand the complexity of the systems and the interactions within the systems from a multi-disciplinary perspective (Steward, 2006; Steward, 2007; Steward, 2009). Advances made through this understanding have led to a coupled modeling approach. At present, groundwater, crop and economic models (mathematical and statistical) are coupled resulting in outputs of groundwater elevation and saturated thickness, crop choice, crop yield, recharge. Given the coupled model results, the current question is where within a modeled area of the aquifer would the model results for certain percentages of irrigated crop choices be grown? This requires understanding first where irrigated crops can be grown as the aquifer declines, a land use model, and second which irrigated crop would be grown in a given irrigated area a land cover model.

There are a number of tools and applications used to simulate land use and cover patterns. Cellular Automata (CA) models enable users to examine a wide range of variables to determine the most important factors causing the change of land use pattern and the impacts they have on the availability of the existing natural resources, which ultimately influence land use and cover decisions. Herein lies the thesis, a GIS-based coupled modeling system can use a cellular automata model to allocate irrigated agriculture land use and crop choices spatially in the High Plains/Ogallala Aquifer Region.

Chapter 2 - High Plains/Ogallala Aquifer Landscape

The High Plains/Ogallala Aquifer is considered the “largest underground reservoir” in the United States (Peck, 2007). It is often referred to as the Ogallala Aquifer the name of one of the two geologic formations holding the groundwater. The other formation, which largely coincides with the Ogallala formation spatially, is the High Plains formation. Together these formations underlie approximately 174,000 square miles of the High Plains region—a higher elevation of land between the Rocky Mountains and the Central Lowlands—of the Great Plains physiographic province. The High Plains physiography has been characterized by gentle slopes and smooth plains which makes the area ideal for agricultural activities (Billington & Ridge, 2001).

The aquifer area includes the panhandles of Texas and Oklahoma, eastern New Mexico and Colorado, Nebraska and small portions of South Dakota and Wyoming (Figure 2.1). It was estimated that the eight-state aquifer area contained 3,250 million acre-feet (U.S. Geological Survey, High Plains Aquifer Water-Level Monitoring Study Characteristics of the High Plains Aquifer, 2013). The aquifer predominately is fossil water formed by runoff and sediments from the Rocky Mountains more than 12 million years ago (Diffendal, 2004). The formation process began when gravel and sand from the Rocky Mountains was eroded by rain and deposited as sediments which made a sponge-like structure that caught most of the mountain runoff (Guru & Horne, 2000).

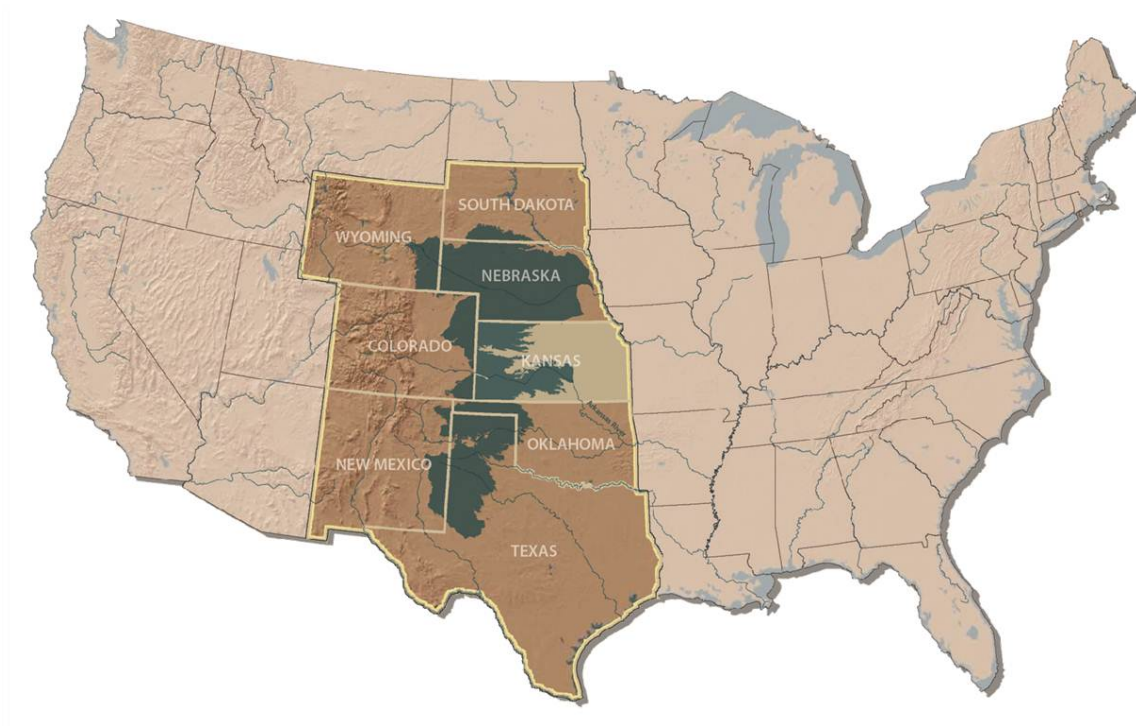


Figure 2.1 Extent of the High Plains/Ogallala aquifer System

Data Source: USGS, KS DASC & ESRI

Today, the High Plains/Ogallala Aquifer is described as an unconfined geologic formation which minimally recharges from precipitation and natural runoff (Long, Putnam, & Carter, 2003) due to a geologic movement which cut-off groundwater flow from the Rockies into the sand and gravel formations. Over time additional sediment was deposited atop the sponge like deposits and today the depth from the topographic surface down to water ranges from 0 to 500 feet, with an average depth of about 100 feet (Figure 2.2).

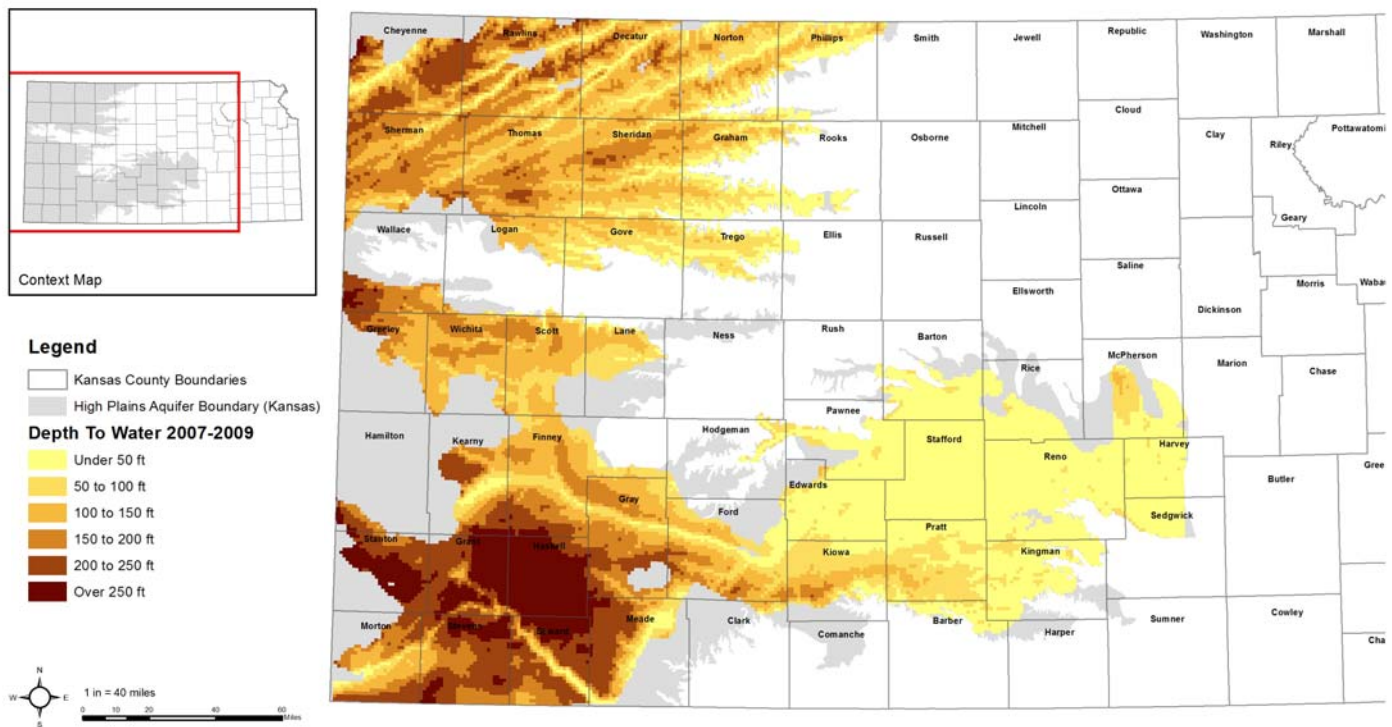


Figure 2.2 Map of High Plains Aquifer Average Depth to Water for 2007-2009

Data Source: USGS & KS DASC

The bottom of the aquifer formation is a bedrock formation which generally tips from west to east, or from Colorado's Rocky Mountains down toward the Missouri River Valley. Due to the sloping bedrock groundwater flows at a rate of about 1 foot per day from west to east (U. S. Geological Survey, 2012).

As indicated in Figure 2.3, the distribution of the saturated thickness is not consistent or homogeneous across the formations. Although saturated thickness is commonly measured in feet, one feet of saturated thickness does not equal one foot of actual water as the water in an aquifer is stored in the pore space between sand and gravel particles. In this aquifer, only about 10 to 25 percent of a volume is water which can be extracted from the aquifer pore spaces. For example if the aquifer had 17 percent pore space, pumping one (1) acre-foot of water would cause a water table drop of approximately six feet (Buchanan, Buddemeier, & Wilson , 2009). In some areas the aquifer consists of less than 50 feet of saturated thickness receiving little recharge. In other areas, such as Groundwater Management District (GMD) #3 in southwest

Kansas, the average aquifer formation is over 178 feet thick, compared to GMD #4 in central Kansas with an average thickness of about 73 feet. The following graphs illustrate the amount of water within each state as compared to the area of the state underlain by the High Plains and Ogallala formations.

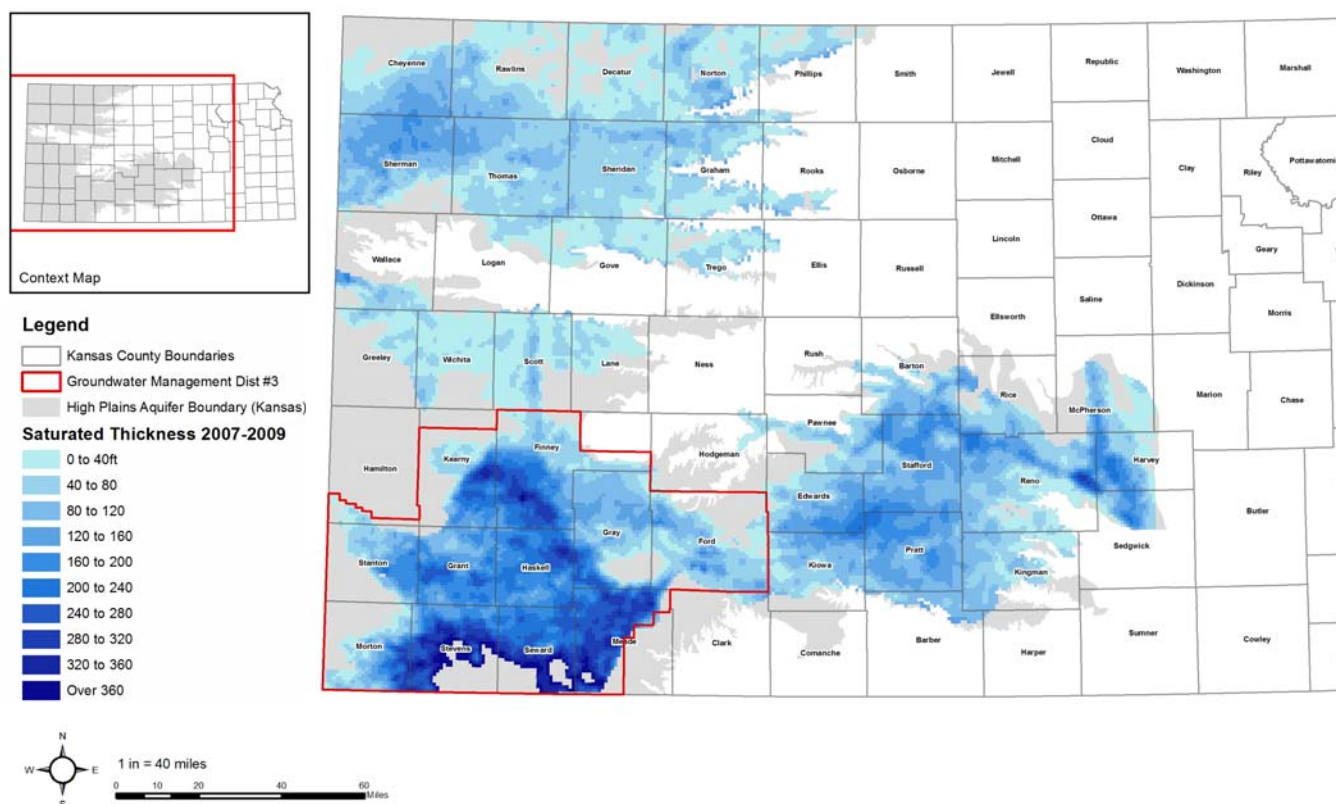


Figure 2.3 Average saturated thickness 2007-2009 of the High Plains aquifer region

Data Source: U.S. Geological Survey, KS DASC & ESRI

The Aquifer saturated thickness, or the portion of the unconfined sand and gravel formation which is holding water within its pore space today, ranges from 0 to more than 1,000 feet with an average depth about 200 feet (Figure 2.4 & 2.5). The thickest areas of the formation are in Nebraska (Diffendal, 2004). Approximately 36 percent of the water is located under Nebraska, 20 percent under Texas, 17 percent under Kansas, 8.6 percent under Colorado, 5.4 percent under New Mexico, 4.6 percent under Wyoming, 4.2 percent under Oklahoma (Guru & Horne, 2000).

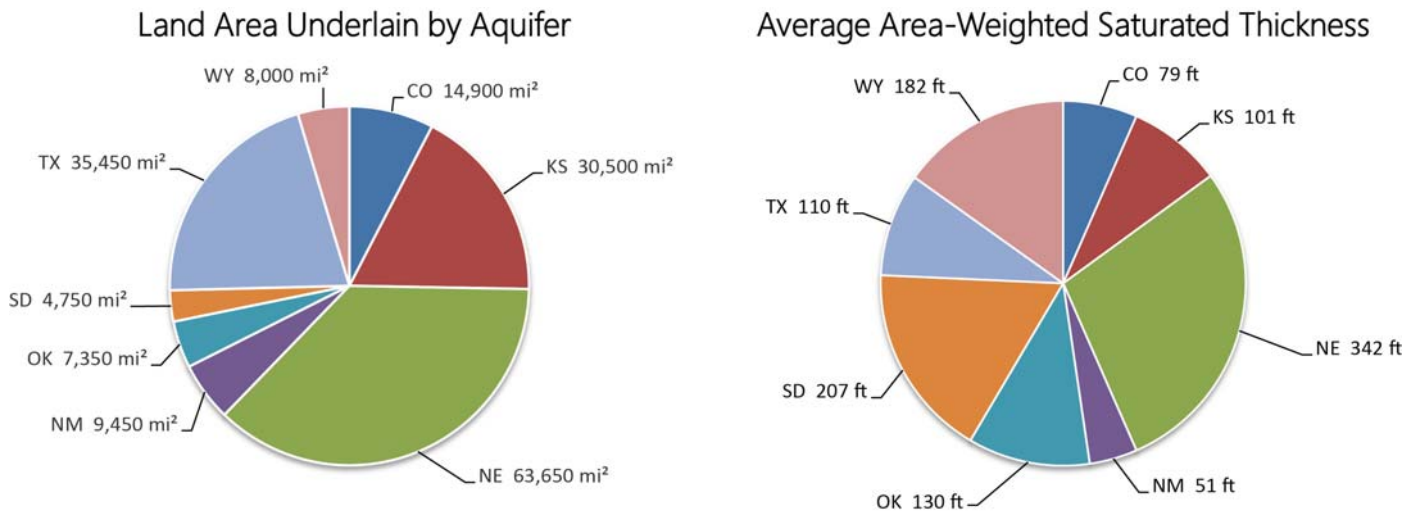


Figure 2.4 Percentage of State Land Underlain by Aquifer Formations

Data Source: U.S. Geological Survey

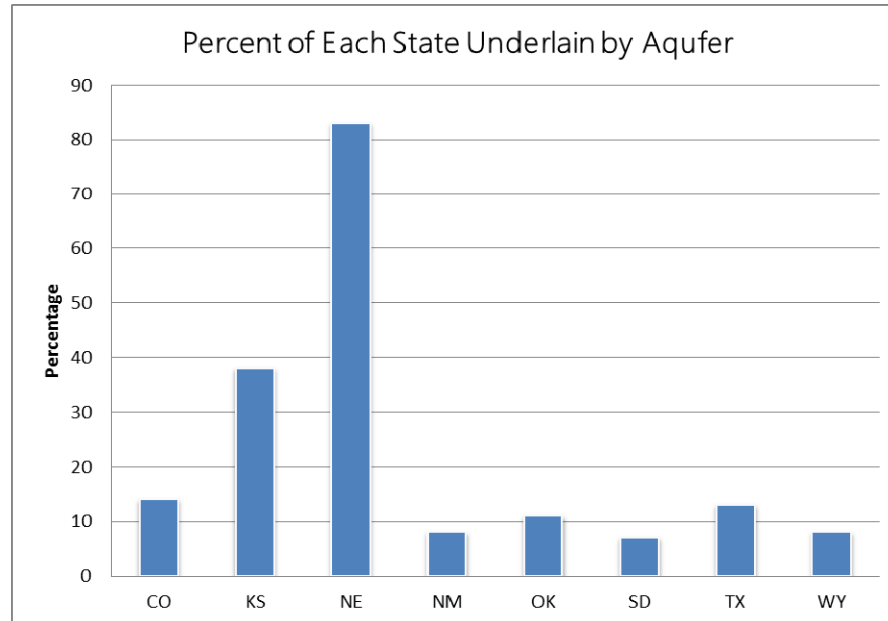


Figure 2.5 State Land Area Underlain by Aquifer Formation and Average Weight Saturated Thickness

Data Source: U.S. Geological Survey

On the surface there are several major river systems crossing the aquifer from west to east including the Platte, Republican, Arkansas, Cimarron and Canadian Rivers. According to a study conducted by the U. S. Geological Survey in the 1980's, the aquifer is hydraulically connected to the river systems. During dry periods, water in the river is entirely derived from groundwater discharge rather than supplying recharge to the aquifer (U. S. Geological Survey, 2012). Natural recharge to the aquifer occurs mostly through the percolation of precipitation through the soil or via stream seepage into the underground water holding formation (Figure 2.6).

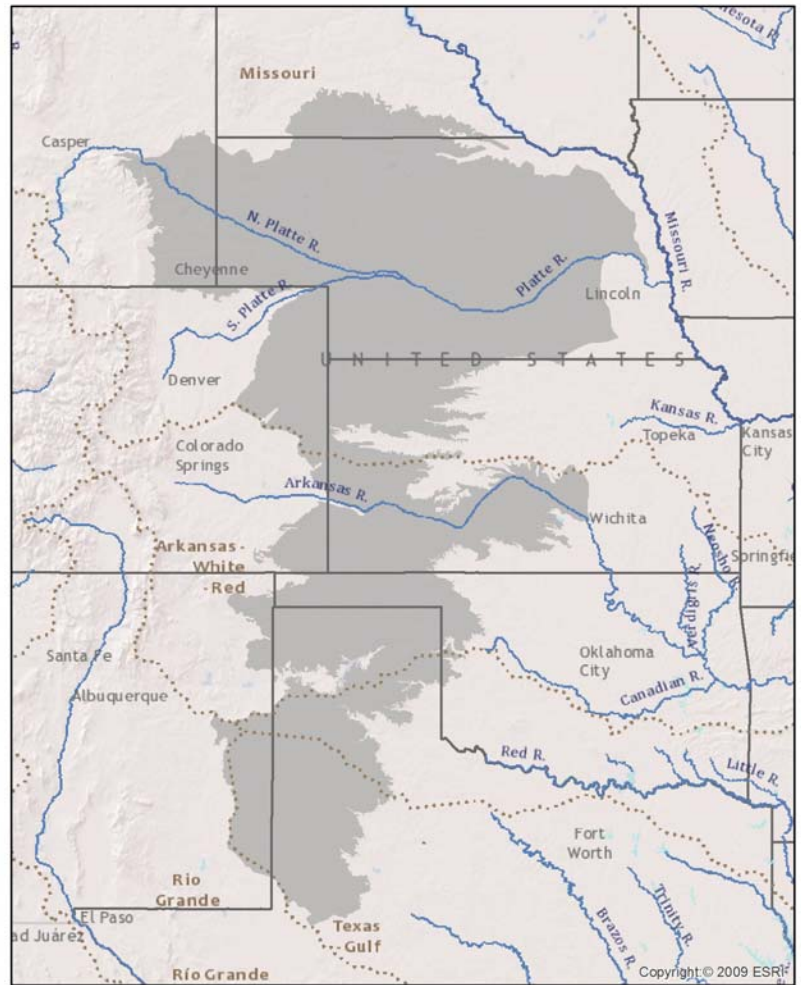


Figure 2.6 Rivers across High Plains Aquifer region

Data Source: USGS, KS DASC & ESRI

Climate in the area is usually hot in summer, cold in winter, and always dry (Ashworth, 2006). The High Plains area is considered a dry continental climate with abundant sunlight, low to moderate precipitation, low humidity and a high rate of evaporation. Figures 2.7 and 2.8 illustrate minimum annual temperature and maximum annual temperature. Mean annual precipitation ranges from less than 17 inches in western Kansas to over 41 inches in eastern Kansas as shown in Figure 2.9.

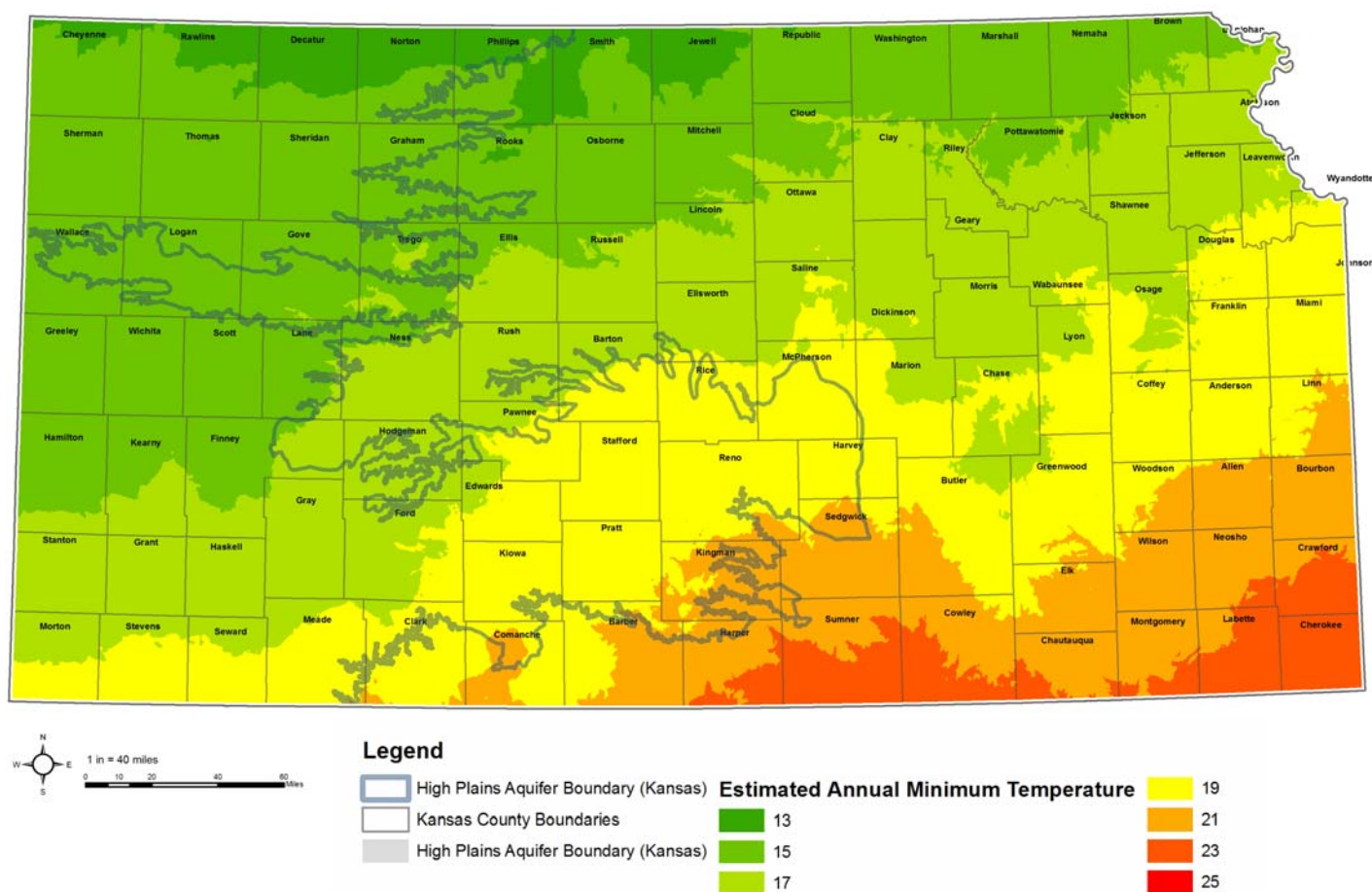


Figure 2.7 Estimated Annual Minimum Temperature in Kansas

Data Source: KS DASC

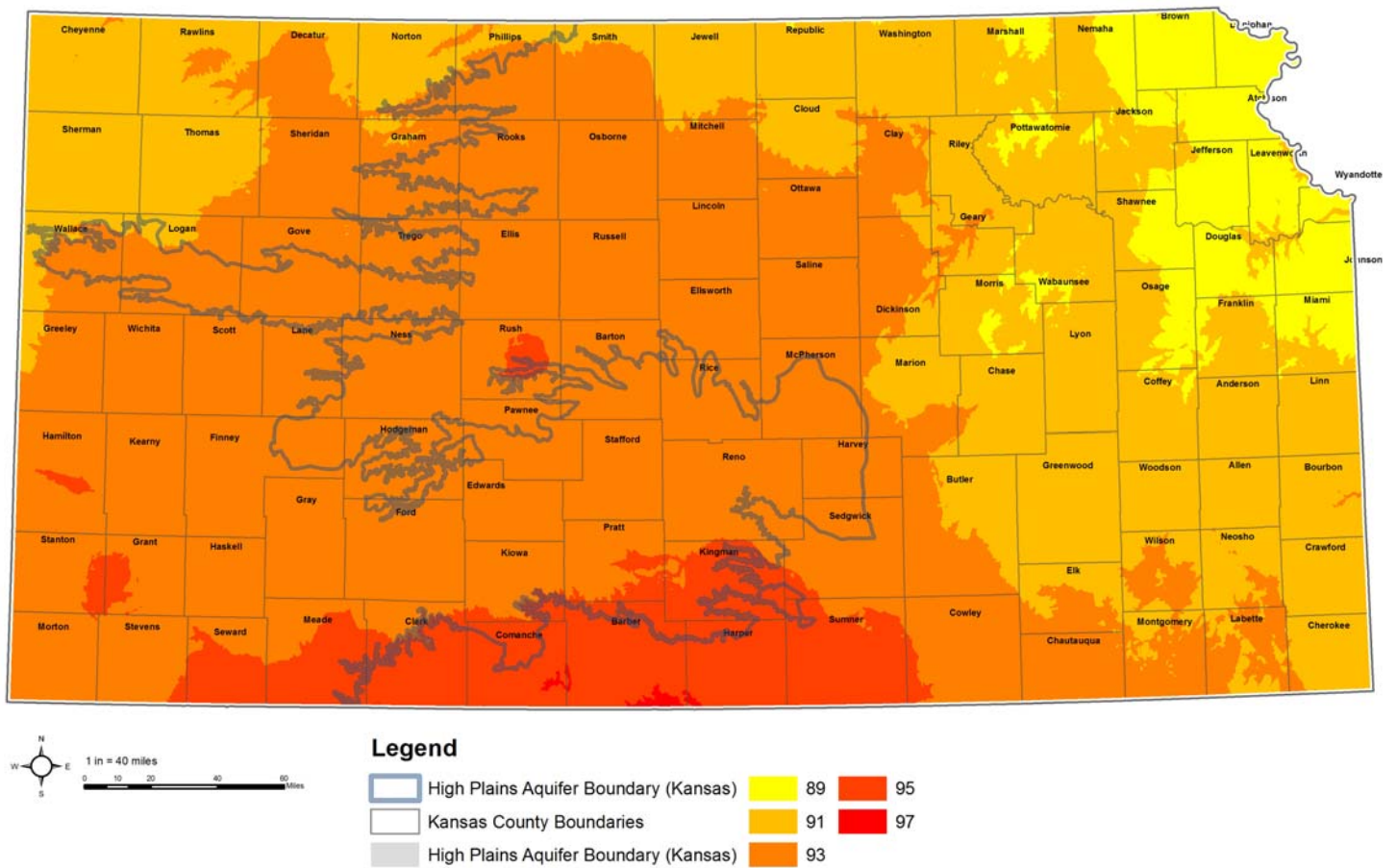


Figure 2.8 Estimated Annual Maximum Temperature in Kansas

Data Source: KS DASC

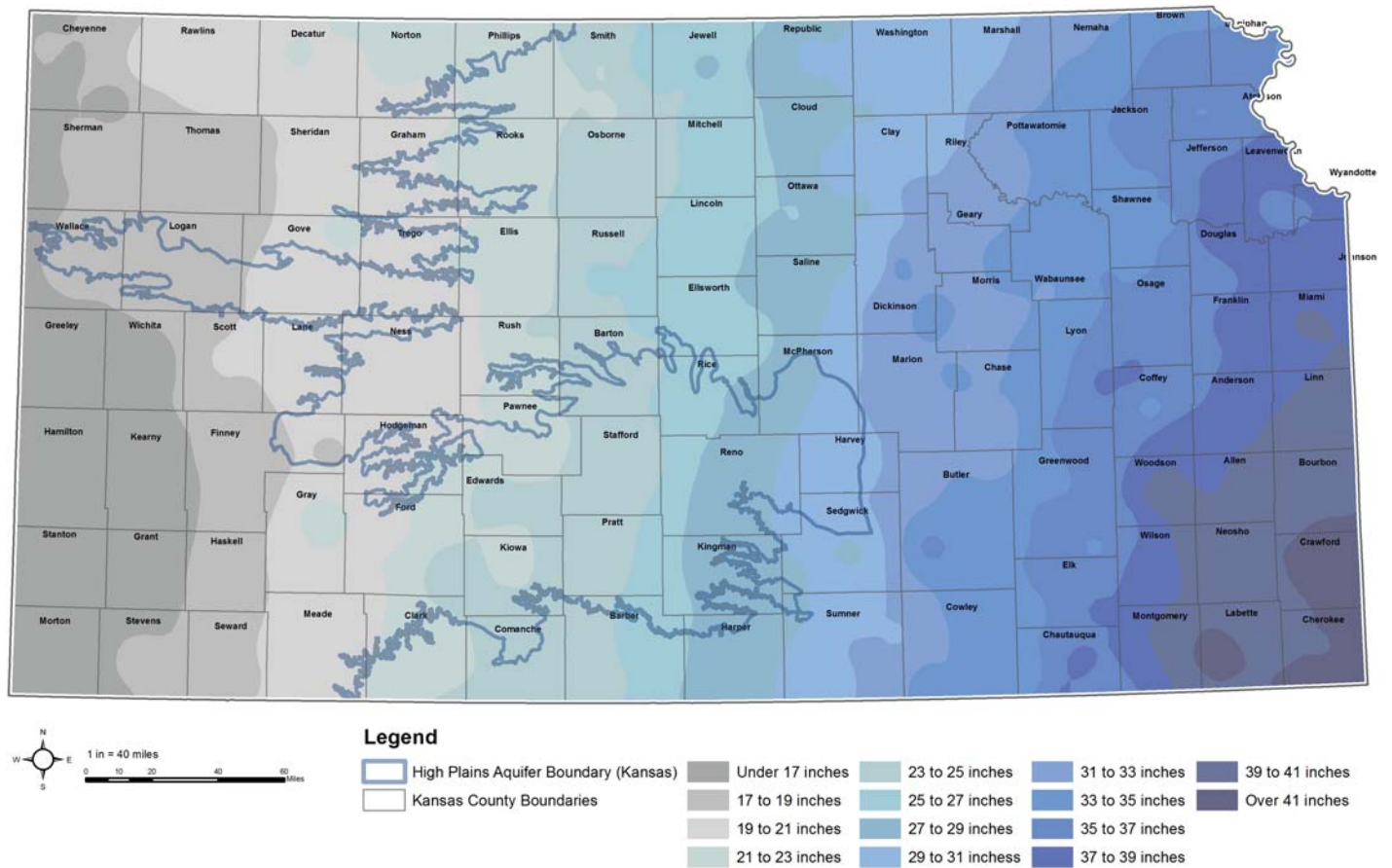


Figure 2.9 Estimated Annual Precipitation in Kansas

Data Source: USDA NRCS & KS DASC

Natural recharge to the aquifer from precipitation is minimal and very slow due to limited precipitation 12 inches annually and timing of rainfall coinciding with growing seasons meaning most precipitation is intercepted by plants. Figure 2.10 illustrates aquifer natural recharge estimates ranging from half inch in the western area to almost two inches eastward toward central Kansas. This trend is consistent throughout entire aquifer region (Kansas Department of Agriculture, 2010). Estimated average annual natural recharge to the aquifer is about 0.72 million acre-feet in Kansas (Buchanan, Buddemeier, & Wilson , 2009).

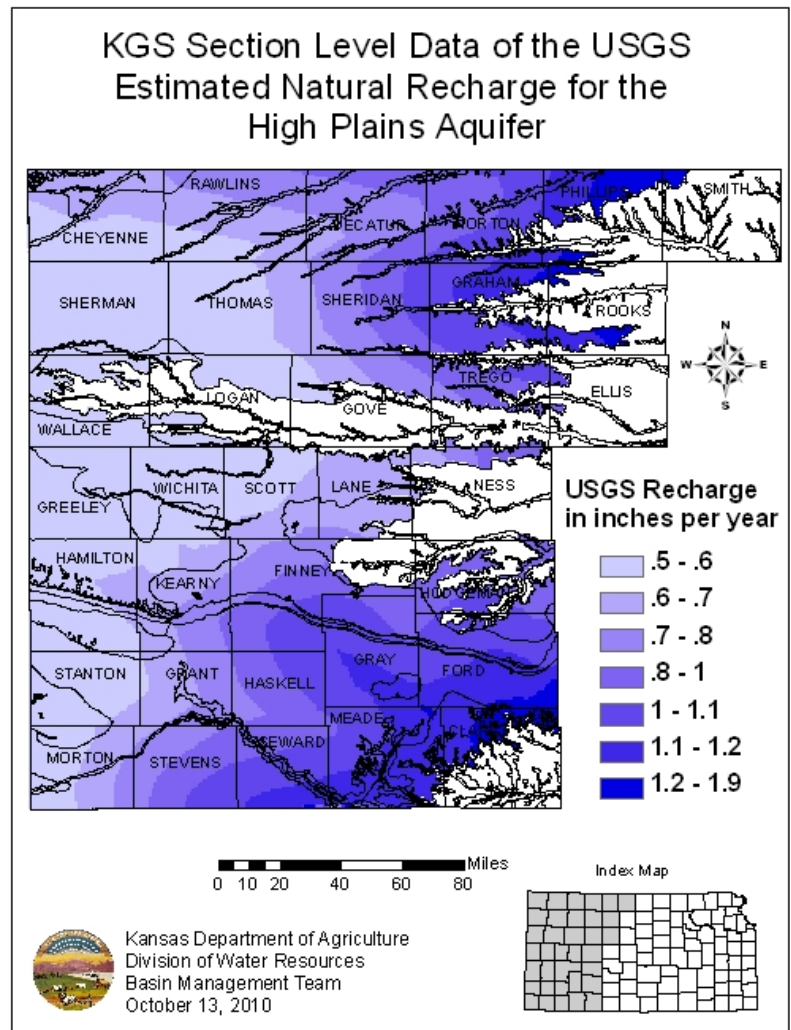


Figure 2.10 Estimate Natural Recharge for the High Plains Aquifer Region

Image Source: Kansas Department of Agriculture

When a well is built and pumped for any purpose it creates a diversion in water from the aquifer source. The diversion of water in an aquifer first appears as a cone of depression when the pump is operating. The area where the cone is formed is the zone of influence. This zone of influence can stretch more than a mile depending on the characteristics of the aquifer (Cowen, 2006). See Figure 2.11. When the amount of water diverted in the zone of influence is greater than the recharge, the result is a decline in saturated thickness and water level in the aquifer. The effect of rapid water pumping in an area by a well, or many wells, causes deviations in flow direction as gravity moves water to fill the cone of depression. Areas where there have been substantial water declines can also exhibit flows which deviate from natural water movements.

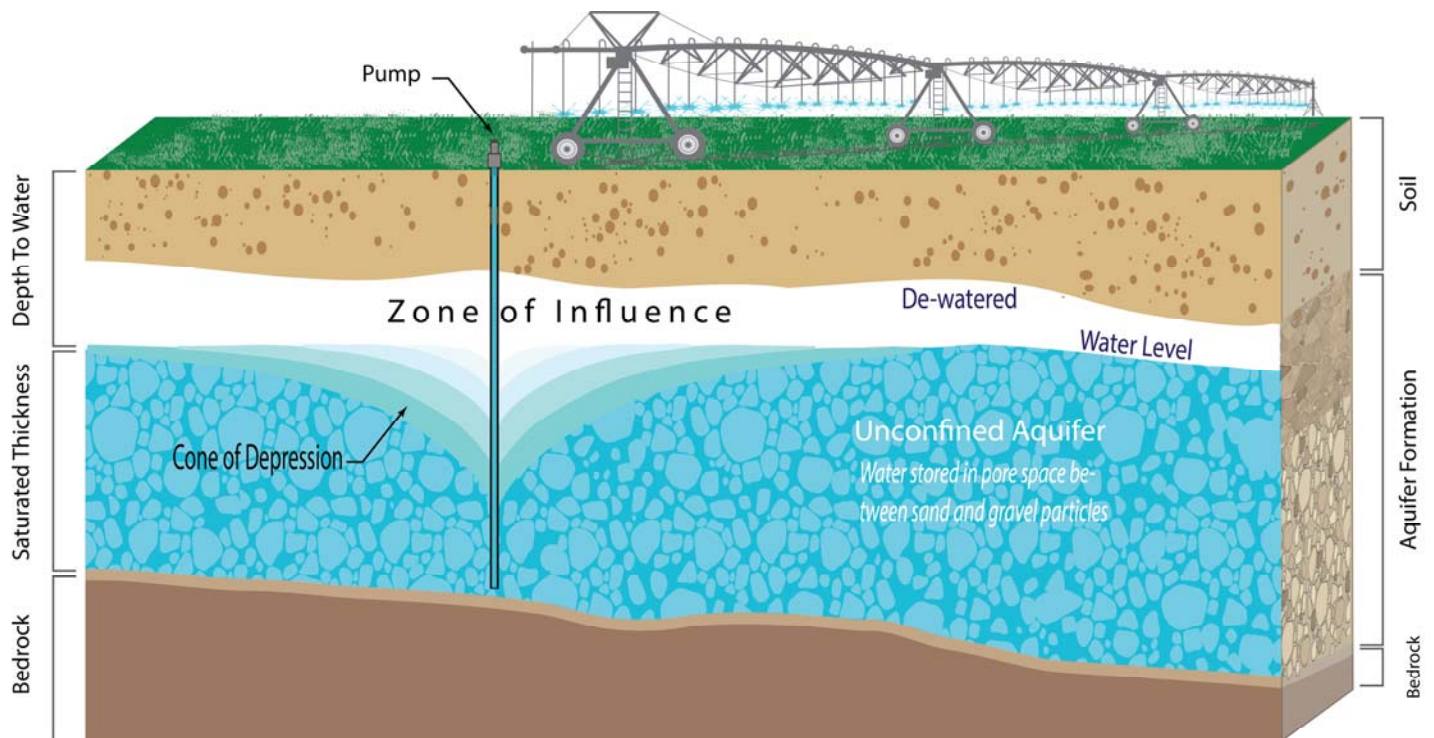


Figure 2.11 Diagram of Cone of Depress Cause by Rapid Pumping

Illustrated by Author

Based on recharge rate, typical withdrawal rate for irrigating a quarter section center pivot at a minimum of 400 gallons per minute (GPM) for 90 days, and current saturated thickness, Figure 2.12 illustrates an estimate of the aquifer's usable life time. As indicated, parts of western Kansas either has already reached or is near at the end of the usable lifetime for irrigated agricultural uses.

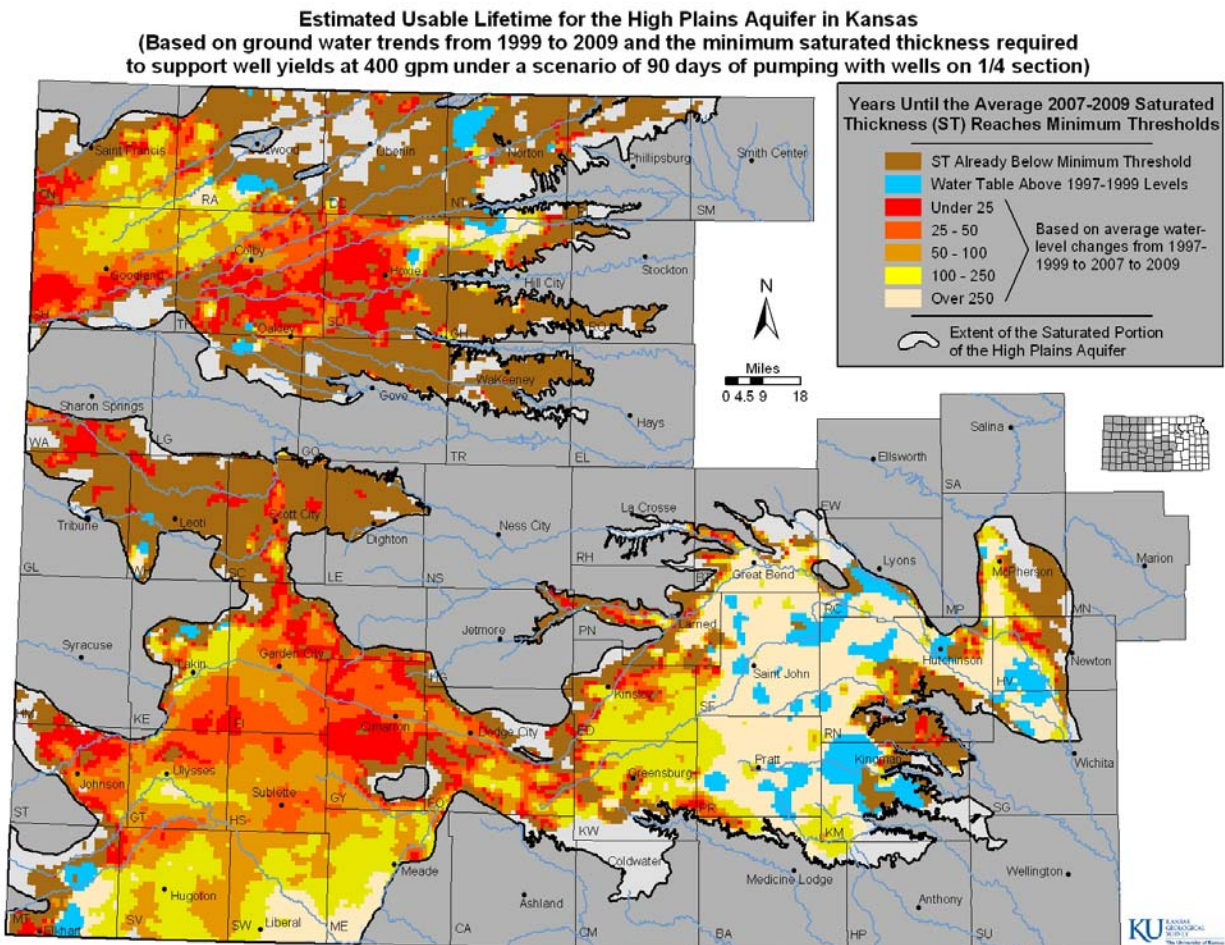


Figure 2.12 Estimated Usable lifetime for the High Plains Aquifer in Kansas 1999-2009

Image Source: Kansas Geological Survey

There are severe geological and economic consequences of over pumping groundwater. First, groundwater has to be pumped from deeper and deeper levels through time which increases the extraction cost per unit pumped and also requires more powerful pumps. As pumping proceeds, the cone of depression of a particular well may intersect with neighboring wells degrading a neighbor's water supply in quantity, quality, and increasing costs of water pumping

(U.S. Geological Survey, 2013). Additionally, over pumping can cause compaction in the underground sediments where the water is stored permanently lowering porosity and permeability and reducing the aquifer storage capacity while increasing the time for a cone of depression to recover from a pumping cycle. This has already begun to occur in many areas including western and south-central Kansas (Cowen, 2006).

History of Aquifer Water Use

The High Plains aquifer is the most important water source of western and central Kansas. The history of water use began when the early pioneers and settlers expanded westward, along with cattle ranching and farming industry to the region in the late 1800's. During the early periods, settlers acquired water mostly through digging of wells to survive the arid Kansas climate (Kansas Historical Society, 2011). Historically, the climate patterns on the High Plains have been an alternate of drought years, followed by a year with more precipitation. During wetter years, farmers could grow bumper crops just relaying on natural rainfall. However, much of local agricultural production and food security of the settlers were at the mercy of Mother Nature for their harvest and livelihood.

During dry years, surface water was also limited. Rivers such as Platte rivers, Arkansas river and Canadian river that flow across have cut their beds into the plains, which made it difficult to divert them for irrigation (Cowen, 2006). In the 1890's, the Ogallala Aquifer was discovered and by the United States Geological Survey, but it was considered to be of limited agricultural importance because of the aquifer depth and limitation in irrigation technology making it largely inaccessible for farmers on the High Plains (Hornbeck & Keskin, 2011).

After the World War II, the post-depression federal government started to subsidize irrigation projects to help solve water issues on the High Plains. This brought the improvement of center pivot irrigation technology which ultimately made the arid tall grass region a major agricultural producing region for the nation (Kansas Historical Society, 2011). By the 1950's there were approximately 80 wells a year were dug to the aquifer in the state of Colorado alone (Worm, 2004)

In the 1960's, groundwater was being pumped out of the wells at the rate of one thousand cubic feet a minute to irrigate quarter sections of wheat, alfalfa, grain sorghum and corn (Guru & Horne, 2000). By the 1970's, methods of center pivot irrigation were the most

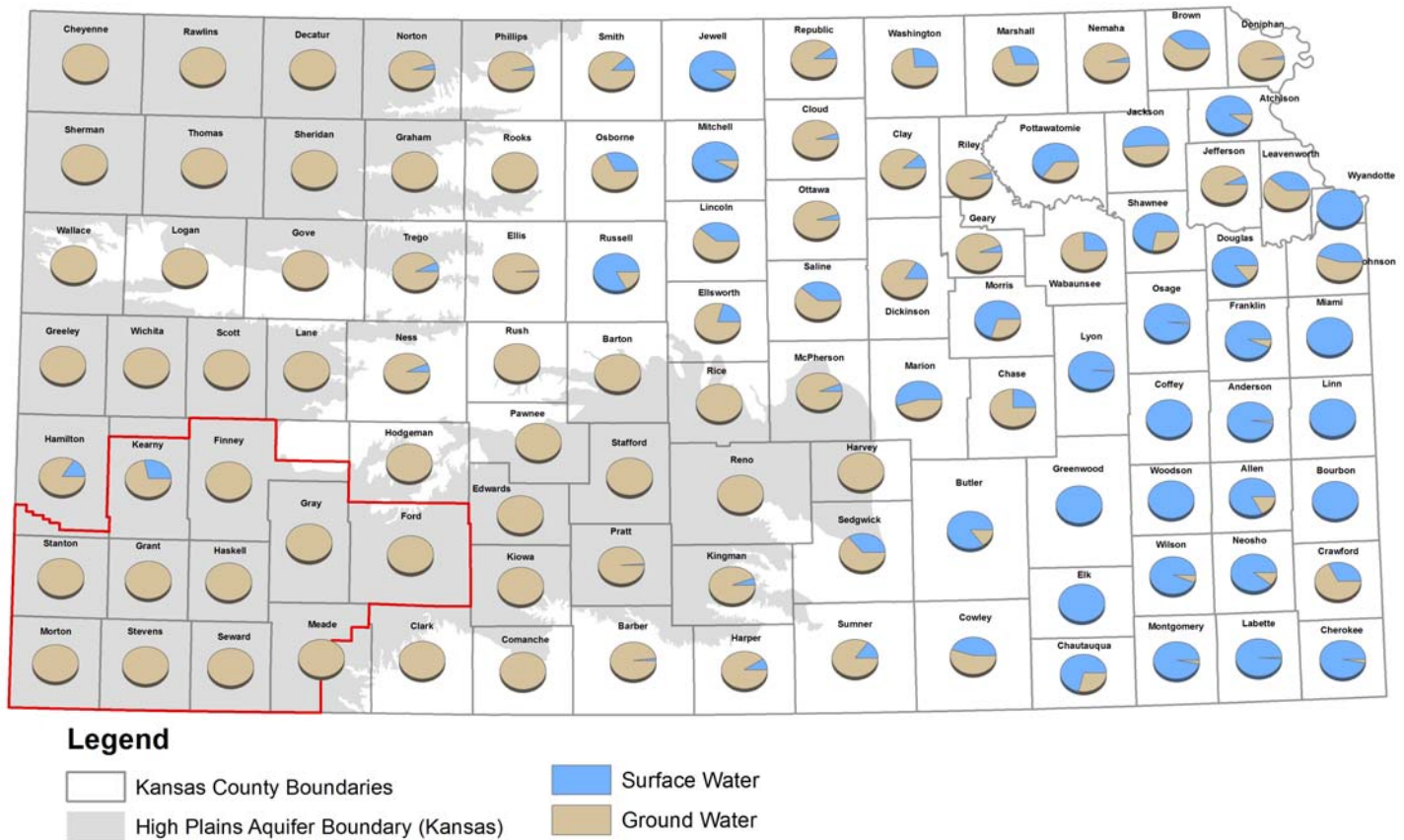
widely use irrigated methods on the High Plains (Miller & Appel , 1997). It is estimated approximately 95 percent of the water pumped from the Ogallala is for irrigation, which represents 65 percent of the total irrigated acreage in the United States (High Plains Underground Water Conservation District No. 1, 2012).

While inexpensive drilling technology for water wells and combination powerful electric pumps became widely available, the U. S. government also came out of the Great Depression into a wartime economy. The federal government began to provide farmers with low interest rate loans and strong crop prices to encourage farmers to maximize their agricultural production. For many farmers, deep drilling and center pivot irrigation systems with the groundwater became an economic opportunity and transformed the High Plains into a major agricultural center. In 1980 about 170,000 wells were pumping 18 million acre feet per year, which is more than flow of the Colorado River (U. S. Geological Survey, 2012).

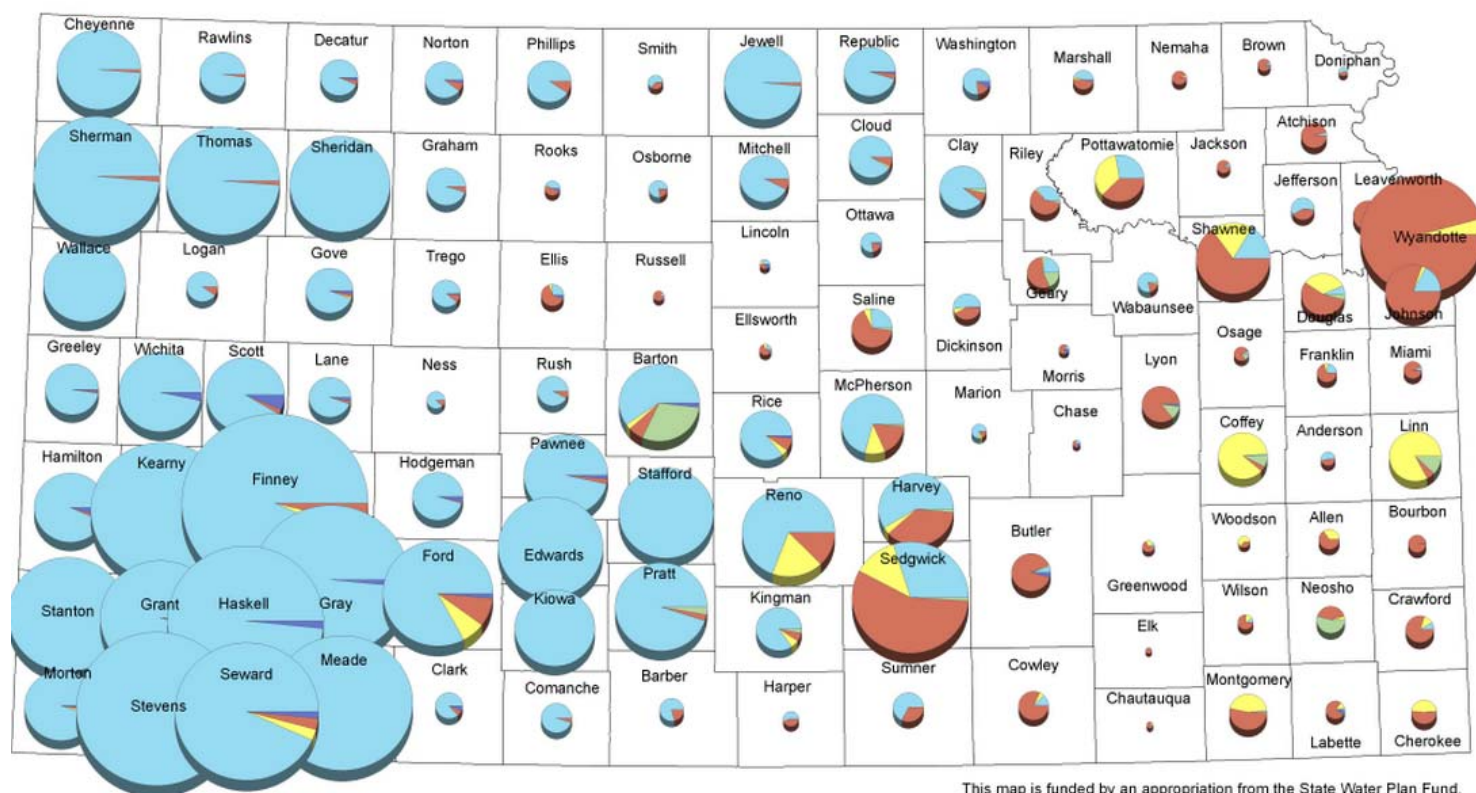
For many years, people believed the High Plains aquifer would never run dry. However, large scale irrigation caused a substantial decrease of aquifer water table. The water-level changes in the aquifer compiled by the U.S. Geological Survey indicate groundwater pumping has exceeded natural recharge. Total water storage in the aquifer has declined about eight percent since predevelopment overall, but as indicated in Kansas is not uniform. Approximately 5 percent of aquifer area had over 50 percent decrease. About one-fourth of the aquifer area had a saturated thickness decrease more than 25 percent since predevelopment (U.S. Geological Survey, 2012). In southwest Kansas the decline in the aquifer has been as much as 150 feet. The Sand Hills Region in Nebraska was uncultivated because lack of water for a long time, but now is one of the most intensive central pivot irrigation land use areas in the country.

Today, the High Plains/Ogallala Aquifer water diversions irrigate over 13 million acres of cropland, compared with 2 million acres in 1949, which is approximately 20 percent of the irrigated land in the United States. This irrigated area uses about 30 percent of the total U.S. groundwater used for irrigation. The aquifer supports a substantial amount of the nation's economy as crops grown in the High Plains region make up a large percentage of the total crop production for the United States annually. The area also produces about 40 percent of the grain-fed beef cattle in the U.S. with large feedlots and meat-packing centers built creating a major economic center on the Plains (Cowen, 2006). As Figure 2.13 shows almost 100 percent of water source in the High Plains aquifer region is from groundwater. Figure 2.14 indicates over

90 percent of water use in the southwest region of Kansas—Groundwater Management District #3—is used for agriculture irrigation purposes.



Reported Water Use, by Type of Use for Kansas Counties



Disclaimer: Features on this map represent conditions as of the date of the map and are subject to change. The user is referred to specific policies, regulations and/or orders of the Chief Engineer.

Percentages of 1.5% or less do not show up in the pie charts.

This map is intended for planning purposes only.



Pratt: 70,221 AF

McPherson: 32,240 AF

Lane: 14,386 AF



Kansas Department of Agriculture
Division of Water Resources
Water Use Unit
March 3, 2009

Use Made of Water



Figure 2.14 Reported Water Use by Type in Kansas

Image Source: Kansas Department of Agriculture

The economics of the High Plains aquifer region accounts for major part of national food supply and it is apparent in the spatial pattern of the region's irrigated agricultural land use. In the heat map analysis illustrated in Figure 2.15, most concentrated irrigated farmlands are generally located at the southwest corner of Kansas. Figure 2.16 indicates Finney County has the highest acreage of irrigated crops in Kansas as well as the highest acreage of irrigated corn. Finney County also has a high concentration of feeder cattle and covers a deep area of the aquifer formation.

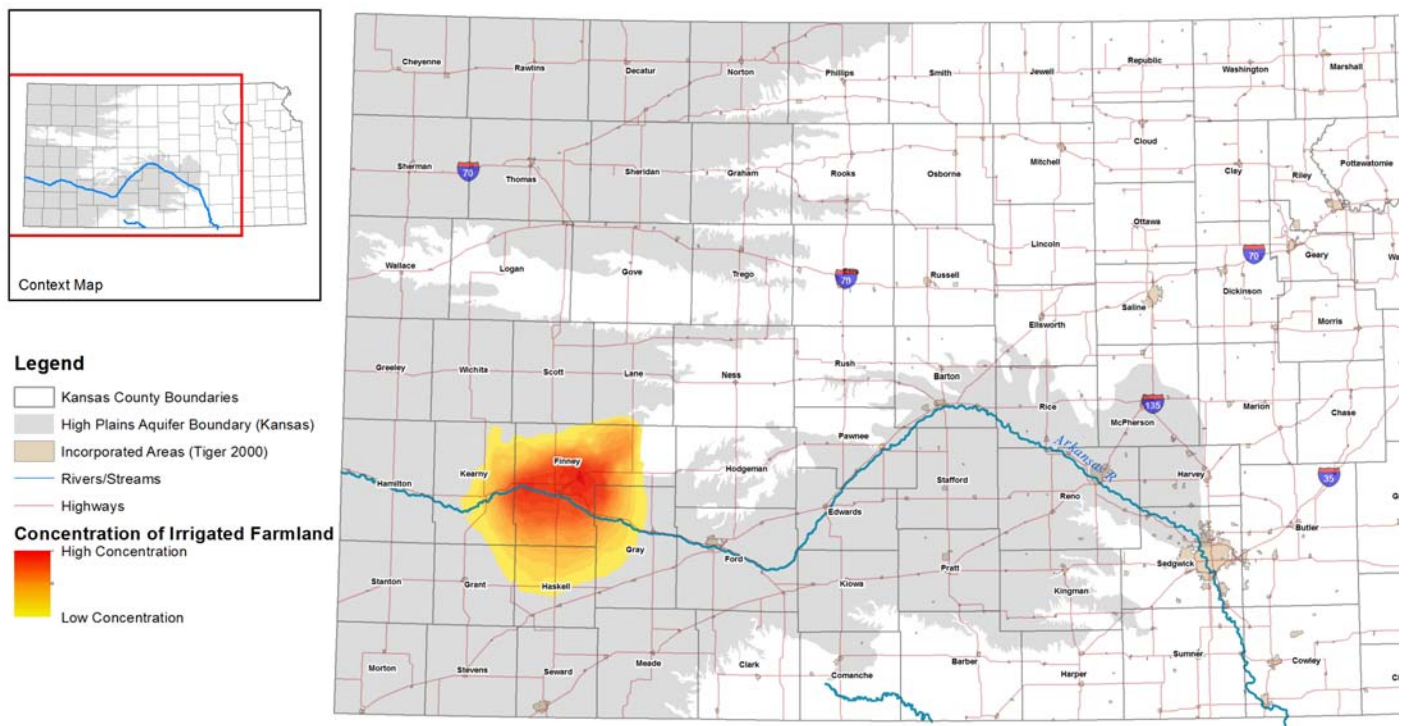


Figure 2.15 Projected concentrated irrigated farmland on the High Plains aquifer region

Data source: USGS & KS DASC

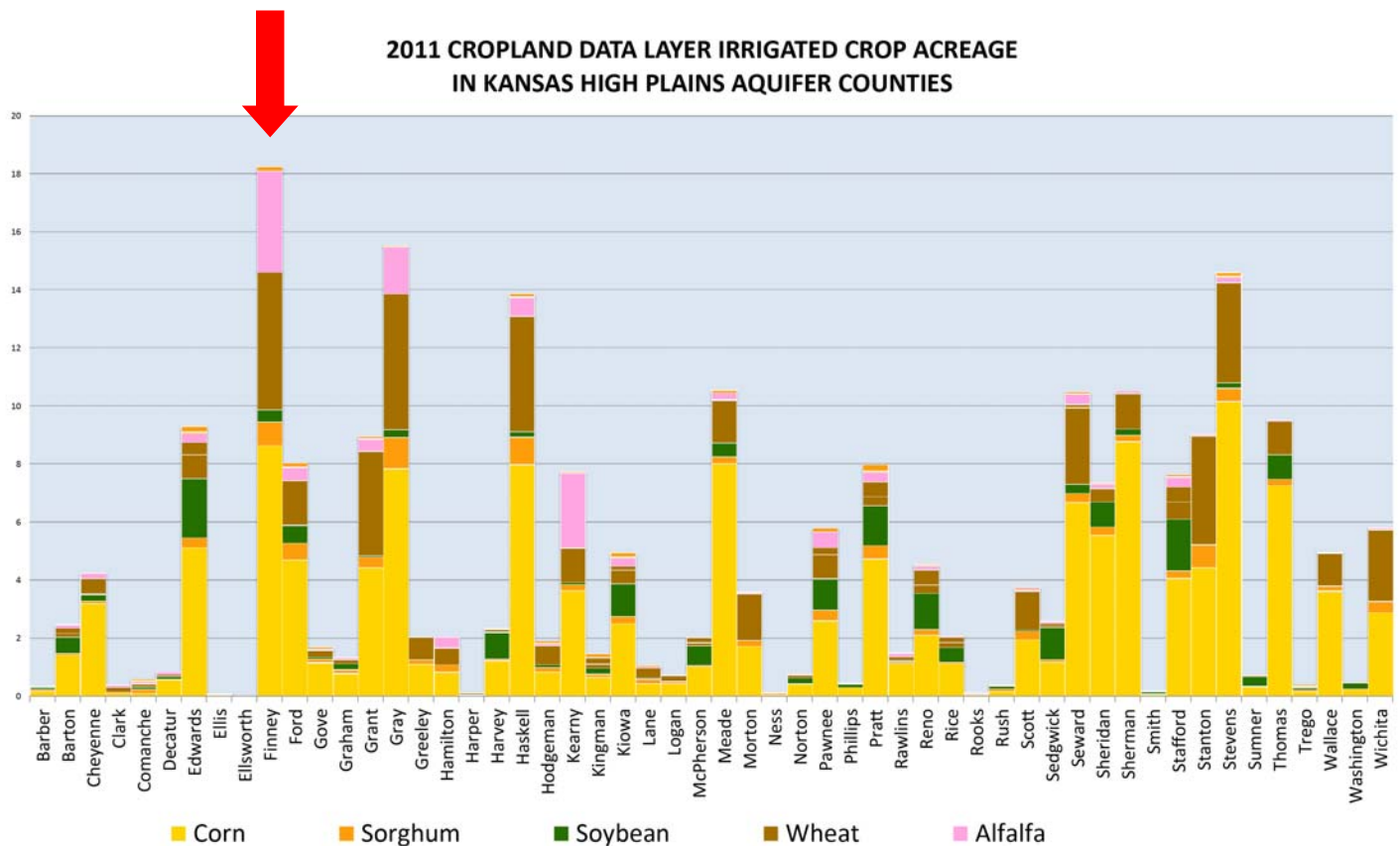


Figure 2.16 Estimated irrigated farmland in the High Plains aquifer counties

Data extracted from Cropland Data Layer 2011 from USDA NRCS

The spatial relationship between the High Plains/Ogallala Aquifer resource and the region's irrigated land use, combined with the low sloping, fertile soils have dramatically changed the short-grass prairie landscape into a key U.S. economic engine. The decline in the aquifer can also be an indication of reduction in the volume of economic activity for all industries within the region as well. The High Plains states cannot support profitable agriculture without irrigation because dry farming is economically unfeasible given current policy on subsidies, global demand and inputs involved contemporary agricultural operations on the Plains. It has been predicted that by the year 2020, there will be five million acres of irrigated cropland reverted to dry land agriculture due to groundwater exhaustion if current trends of water withdrawal continues (Buchanan, Buddemeier, & Wilson , 2009). Under this prediction agricultural, economic and population growth will be substantially decreased. As the water table continues to decline the High Plains will have to take drastic actions for rural farming

communities to be sustained. For this reason, redistribution of the irrigated agricultural land use will be important for the livelihood of the High Plains aquifer region.

Literature Review

Human use of land has drastically changed both functional and structural organization in the natural and human systems. We use land and its resources to meet a variety of needs and serve our purposes and in doing so we change the natural balance in systems. To understand the impacts of our changes spatially and temporally the concept of land use modeling was developed. In the 1950's, the concept of computerized land use modeling was thought to be the "new tool" for planning decision-making process (Wegner, 2013). Since this time landscape architects and planners have developed and used land use modeling to address the question of feasibility through opportunities and constraints analysis aimed at the question, "where can we grow?" (Kelly & Becker, 2000).

Urban land use models were developed to simulate temporal decisions of land development in a finite spatial scale and were established on the notion of how cities grow and change dynamically through development (Batty, 2005). In urban system modeling, there are many models are built on complex decision-making process which are based on customized applications to explored the effectiveness of a scenario (Batty, Xie, & Sun, 1999). Typically, these models involve aggregated spatial process to simulate future changes of land use conditions. This development process is generated by repetitive application of the rules beyond the initial condition (Liu & Phinn, 2003). Urban models are often analyzing links between land use and transportation, as well as economy and demography of the urban area. However, these models required both spatial and social interactions that are difficult to run, as a result, a class of model start to developed rapidly, consistent with GIS and cellular automaton principles (Batty, Xie, & Sun, 1999).

The widespread use of urban models began and grew with the evolution of computer technology in the 1960's along with the development of CA concept. Simulation models were developed with the intention of being large scale and cross-sectional in structure for comparative analysis of long term changes under the assumption that policy has already changed. As guidelines of land use policies set forth by most local municipalities changed, the models'

abilities to generate meaningful predictions of urban growth were challenged as not practical for their lack of dynamics that characterize urban characteristics (De Almida, et al., 2003).

As a result, modelers began to tackle problems of making urban land use models more real by creating a dynamic simulation that would expand to integrate demographic and economic aspects not included previously. Consequently, the a new generation of urban land use models based on simulating temporal decisions concerning land development were developed at a finite spatial scale. These models are established on the notion of how cities grow and change dynamically through development and land use policy influenced by economics and demographics.

During the 1990's, a new type of planning approach emerged as a reaction towards more procedural and instrumental traditional planning and focused on developing analytical computer applications to address "what if" scenarios of land use and spatial modeling (Pettit, 2003). Additionally, increasing interest in environmental aspects of urban development began to integrate into models of urban land use due to the growing awareness of the negative environmental impacts of urban development. However, this posed a new challenge to the land use models in integrating detailed information on household demographics, employment characteristics and local policies, while trying to simulate not only economic but also environmental impacts of land use (Wegner, 2013). This type of model integrates both dynamic and spatial characteristics which are self-organized. New approaches were developed based on a cellular structure for the data and local neighborhoods were developed. This element of complexity theory is the key to the new focus of urban land use models.

Development of Land Use Model

Urban land use models today are comprised of two key elements: 1) the nature of land use, which relates to localized activities; and 2) the level of spatial accumulation, which indicates intensity and concentration of activities. Land use considers the level of spatial accumulation of activities and their related level of movements. There are several descriptive and analytical models of urban land use that have been developed over time, each with increased levels of complexity. The following provides an overview of the categorization of key concepts in urban land use theories (Rodrigue, 2013).

Central Places and Concentric Land Use Model

This model, referred to as Von Thunen's Regional Land Use Model, is based on a central node such as a market place and its impact to surrounding land uses. The model was developed in 1826, to analyze agricultural and use patterns in Germany. The concept was based on rent economics to explain spatial organization where different agricultural activities are competing for the usage of land. Key principles of this model have been use in many other models where economic considerations are incorporated. The main assumption is that the agricultural land use is patterned in the form of concentric circles around a market that consumes the products and transportation.

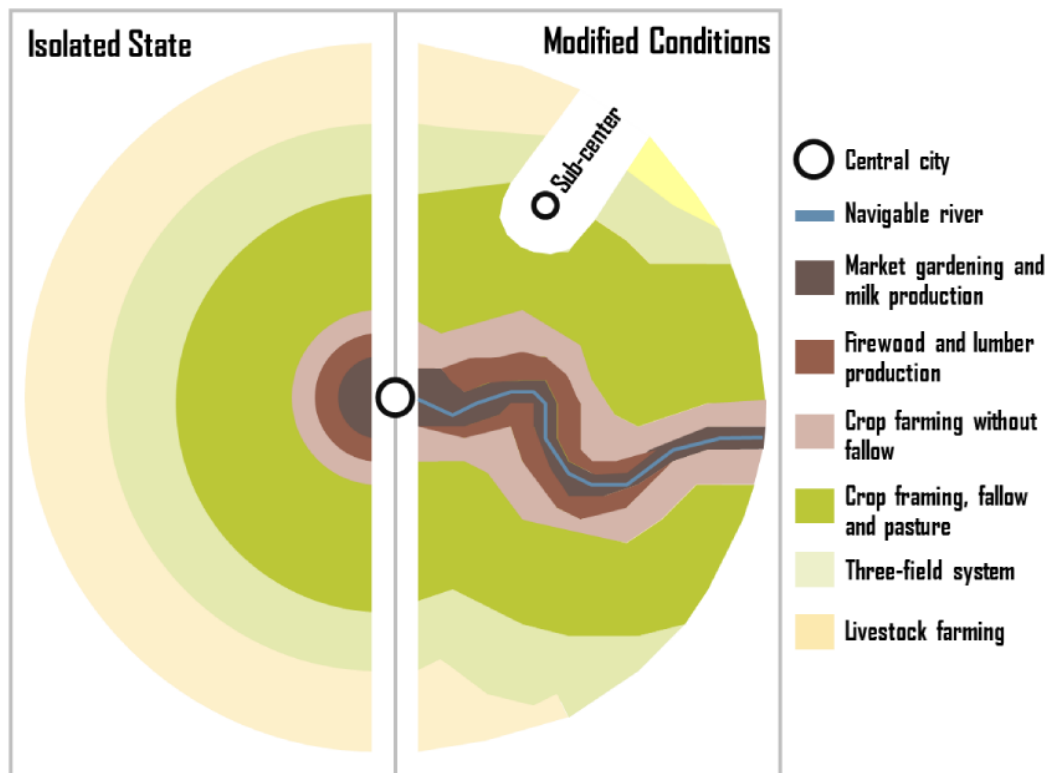


Figure 2.17 Von Thunen's Regional Land Use Model

Image: Rodrigue, 2013

Concentric Urban Land Use

The concentric model also known as the Burgess Urban Land Use Model was theorized and developed in 1925. It initially attempted to investigate spatial patterns at city scale. The purpose was to analyze urban social structure and indicated that mobility was an important factor for urban spatial organization. At the center of the concentric ring is a prominent node, the central business district (CBD) from which the city expands with different socioeconomic urban landscapes. Conceptually, this model is an adaptation of the Von Thunen's model.

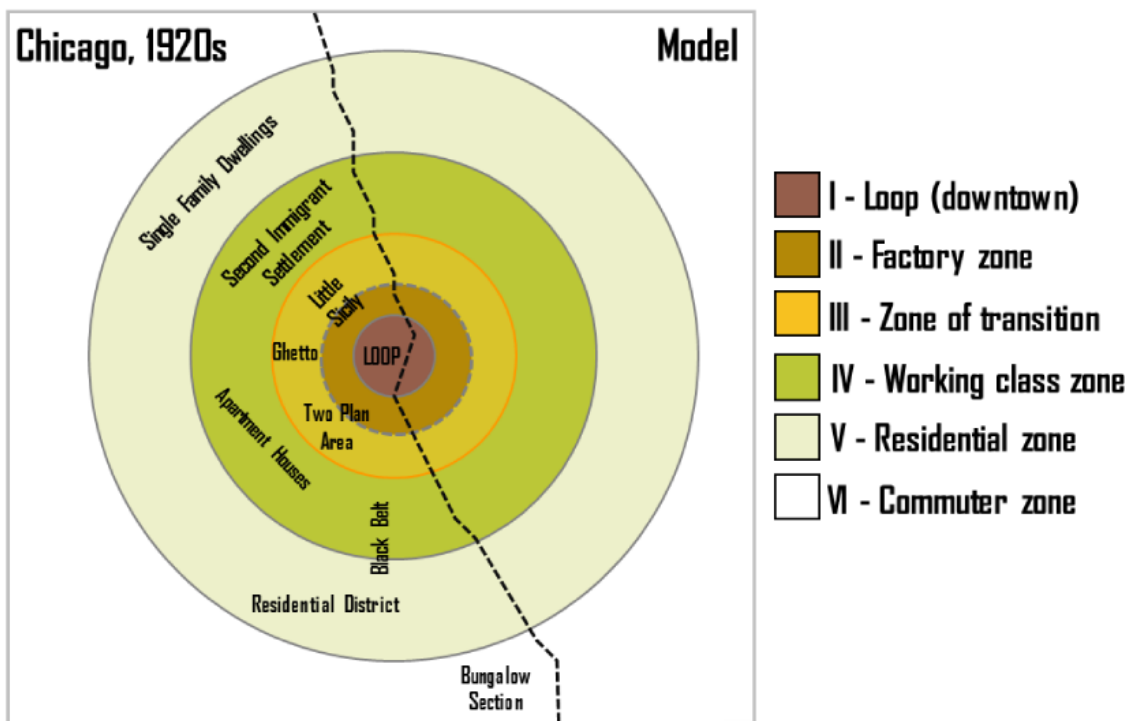


Figure 2.18 Burgess Urban Land Use Model

Image: Rodrigue, 2013

Sector Urban Land Use

This model was developed to include considerations that were not considered in the concentric model. One approach to the sector model, developed by Homer Hoyt in 1939, is simply a concentric zone model modified to account for the impact of transportation systems on accessibility based on his observations of consistent land use patterns in the United States. His analysis of patterns found not random distribution, or sharply defined in rectangular areas or concentric circles, but rather sectors. He speculated that cities tend to grow in wedge-shaped patterns, deriving from a CBD and centered on major transportation routes.

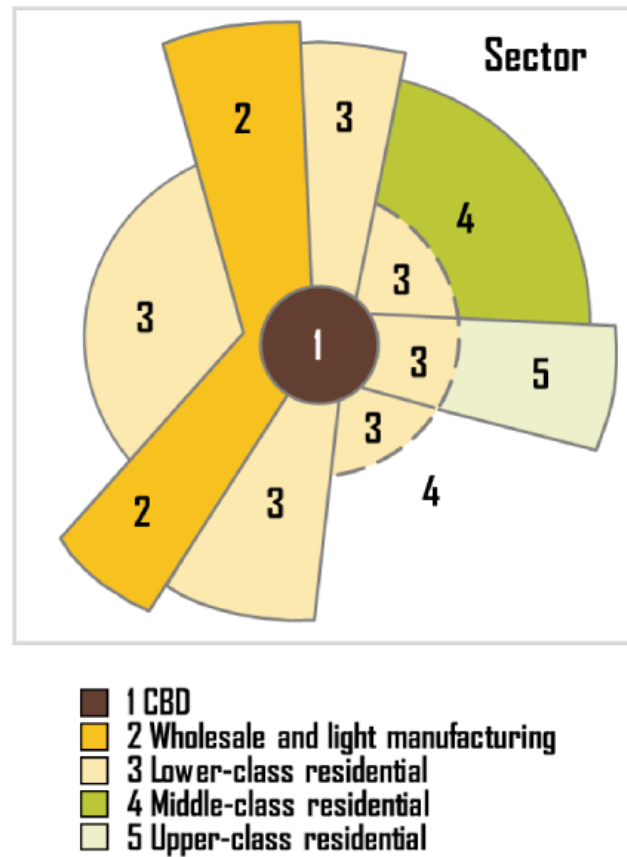


Figure 2.19 Sector Urban Land Use

Image: Rodrigue, 2013

Multiple Nuclei Urban Land Use

Following Hoyt's development of a sectorial land use theory, Chauncy Harris and Edward Ullman (1945) introduced a different generalization of urban land uses. It was realized that large cities may not grow around one CBD, but are also formed by smaller business districts. These smaller nodes become specialized and differentiated in the growth process and were viewed as not being located in relation to any distance attribute, but rather were bound by a number of factors such as accessibility, land use compatibility and suitability. Cities of greater size were developing substantial suburban areas and some of the suburbs of significant size were functioning like smaller business districts. These smaller business districts acted as satellite nodes, or nuclei, of activity around which land use patterns formed.

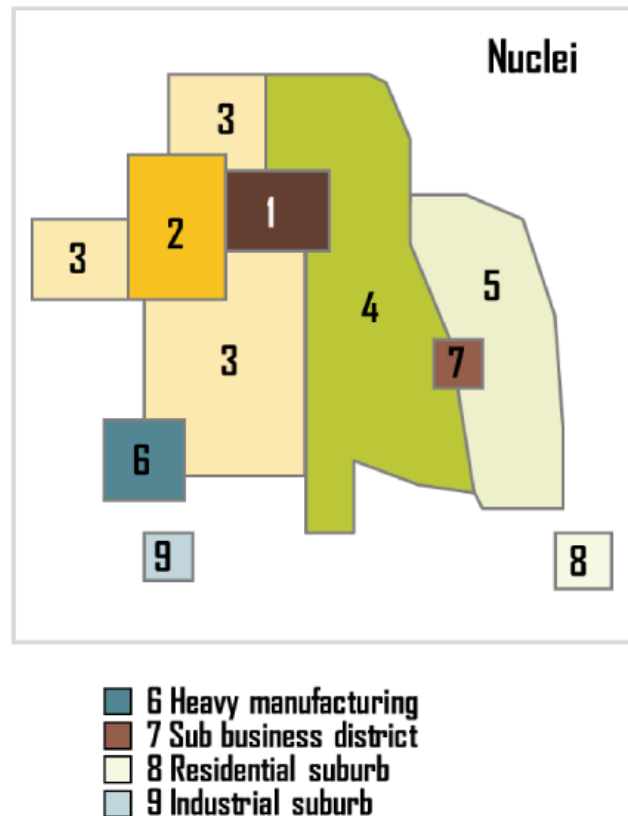


Figure 2.20 Nuclei Urban Land Use

Image: Rodrigue, 2013

Hybrid Land Use

The hybrid model integrates characteristics from concentric, sector and nuclei land use models and was developed by Walter Isard in 1955. The model illustrates that most urban development occurs along major transport axes (or sectors). At the same time, other development such as industrial and commercial are located around a common CBD. This urban land use model attempts to overlay multiple transport routes.

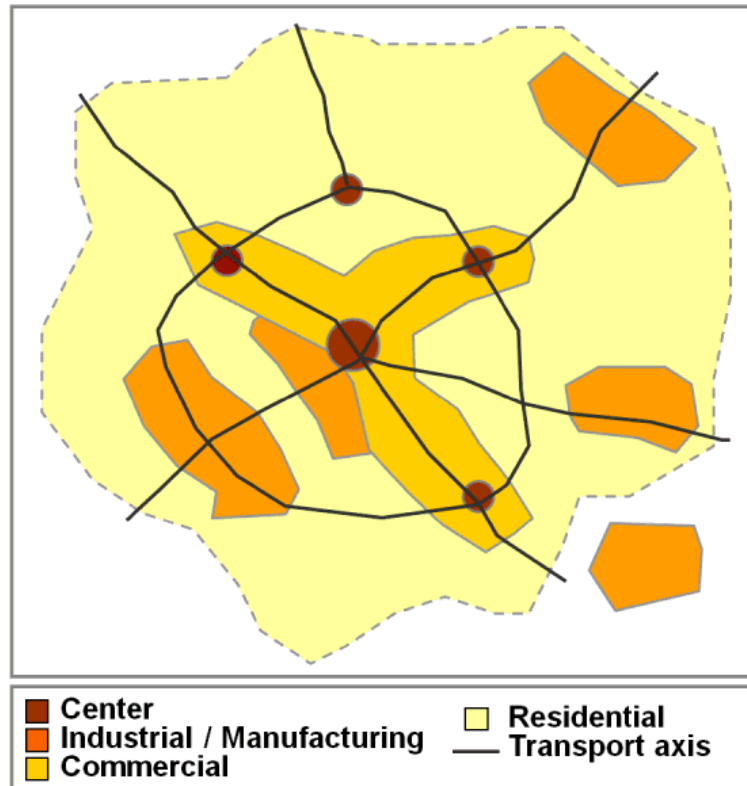


Figure 2.21 Hybrid Land Use

Image: Rodrigue, 2013

Land Use Market

Land rent theory was developed to later explain land use as a market. In this model, different urban activities are competing for land usage at a location. It is heavily based on the market principle that stakeholders are competing to secure and maintain their presence at a specific location. The more desirable a location is, the higher its rent value.

Transportation or accessibility is a strong factor on the land rent and its impacts on land use.

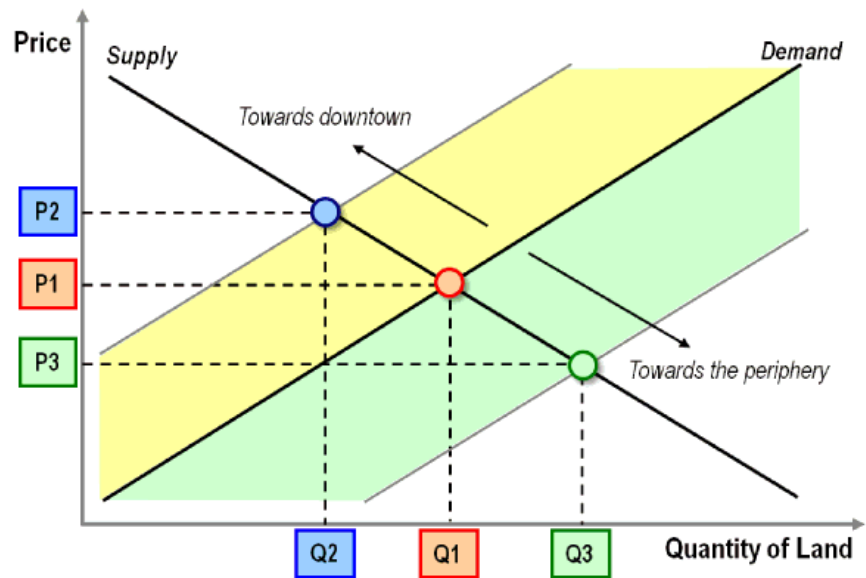


Figure 2.22 Land Use Market

Image: Rodrigue, 2013

Cellular Automata

Cellular automata or automaton (CA) is a dynamic land use model developed on the principle that space can be represented as a grid and each cell is a discrete land use unit. Cell states symbolize land use and transition rules to determine the likelihood of a change from one land use state to the next. In the model each cell is symbolically connected and interrelated to adjacent cells. The CA model is used to iterate dynamics, evolution, and self-organization of land use systems. They are readily implementable within Geographic Information Systems and are designed to work effectively with grid-based spatial representations.

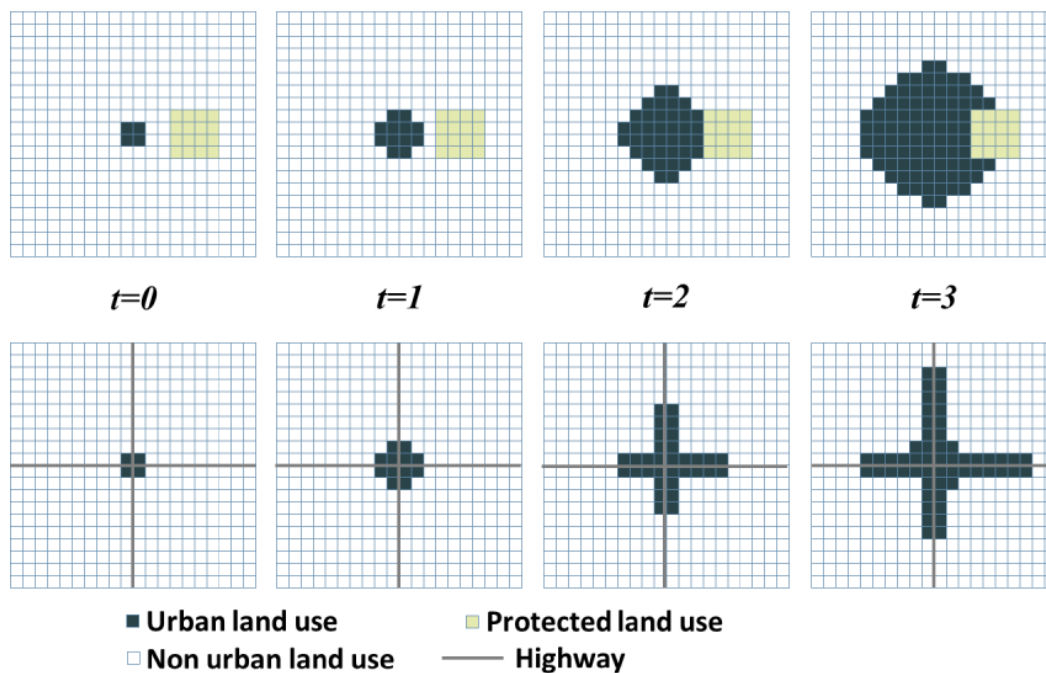


Figure 2.23 Cellular Automata Land Use Model

Image: Rodrigue, 2013

Cellular Automaton Model

CA models have been used as a simulation technique in variety of disciplines and for urban phenomena including regional growth, urban sprawl, economic activities and land use development. It is a spatial model reliant upon a collection of spatial data to produce information that often is in a form of map (Hegde, Nagaratna P; MuraliKrishna, IV; ChalapatiRao, KV, 2007). The CA model is a dynamic system with discrete space and time with a finite set of values.

The word “cellular” in CA means “consisting of cells,” therefore, a cellular automaton model is made up of cells. Each cell contains an “automaton,” which is a coded condition with limited possibilities (Niesche, 2006). Stephen Wolfram, a British scientist and mathematician defined cellular automata as a “simple mathematical idealizations of natural systems.” It consists of a lattice of discrete cells, each cell taking on a finite set of values. The values of the cell evolve in discrete time steps according to determined rules which specify conditions of neighboring cells (Kier, 2012).

Von Neumann Neighborhood

The concept of CA modeling began in 1947. The theory was introduced by John Von Neumann, a Hungarian born American mathematician who was trying to develop an abstract model of self-reproduction in biology. Von Neumann was interested in the possibility of finding a logical abstraction of self-production (Chopard & Droz, 2005), a topic which emerged from investigation in cybernetics at the time in the world of science (Wolfram, 2002) to create a machine to mimic the behavior of human brain to solve complex problems. He began by thinking about a model described by partial differential equations. Later, he explored the concept of self-replicating. In 1951, Stanislaw Ulam, a Polish-American mathematician, suggested Von Neumann simplify his model.

As a result, a 2-Dimensioned model was developed around the concept of cells where each cell is characterized by internal states consisting of a limited number of information bits. As a system evolves in discrete time steps, the model would calculate, based on the same input rules for all cells, a new internal state for each cell. The model function is similar to a typical biological system, where the activity of cells takes place simultaneously. The evolution of the model is based on the neighboring cell state. The method of calculating a new state as a function

of the four nearest neighboring cells is called the “Von Neumann Neighborhood” (Niesche, 2006).

The Von Neumann neighborhood is comprised by four cells orthogonally surrounding the center cell in a nine cell square grid that may affect the evolution of a two-dimensional cellular automaton. Cells are aligned symmetrically and are described by directions on the compass (North, West, Center, East, South), as shown in Figure 2.24. Figure 2.25 shows the Von Neumann neighborhood range in finite grids (or generation) $r = 0, 1, 2, 3$. The first original centered cell is $r = 0$, with each iteration, the centered cell changes with the input algorithm. Von Neumann’s neighborhood is one of most frequent used neighborhoods in the CA model approach (Wolfram, 2002).

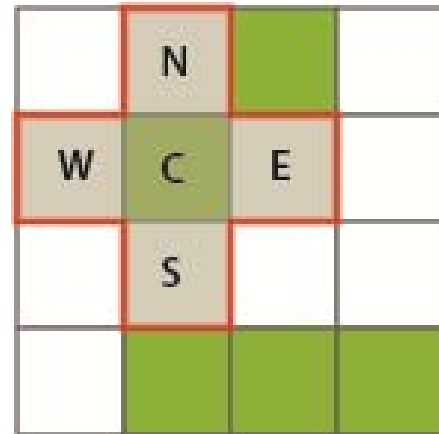


Figure 2.24 Von Neumann Neighborhood

Image Adapted from Wolfram Mathworld, 2013

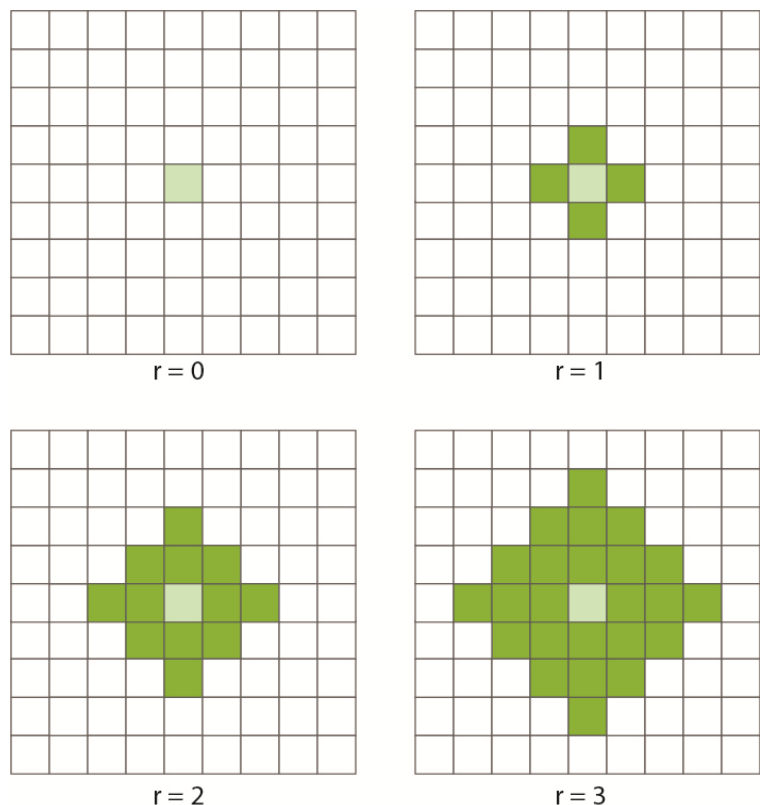


Figure 2.25 Iteration of Von Neumann Neighborhood from Original Cell

Image Adapted from Wolfram Mathworld, 2013

The Moore neighborhood is very similar to Von Neumann's with cells arranged in simple square-shape surrounding a center cell. Unlike Von Neumann, Moore also includes intermediate direction such as northwest, northeast, southwest and southeast (Figure 2.24 and Figure 2.25).

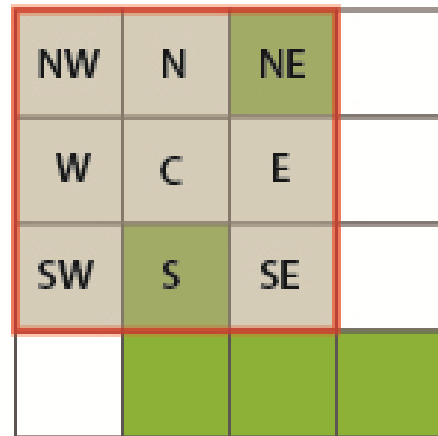


Figure 2.26 Moore Neighborhood

Image Adapted from Wolfram Mathworld, 2013

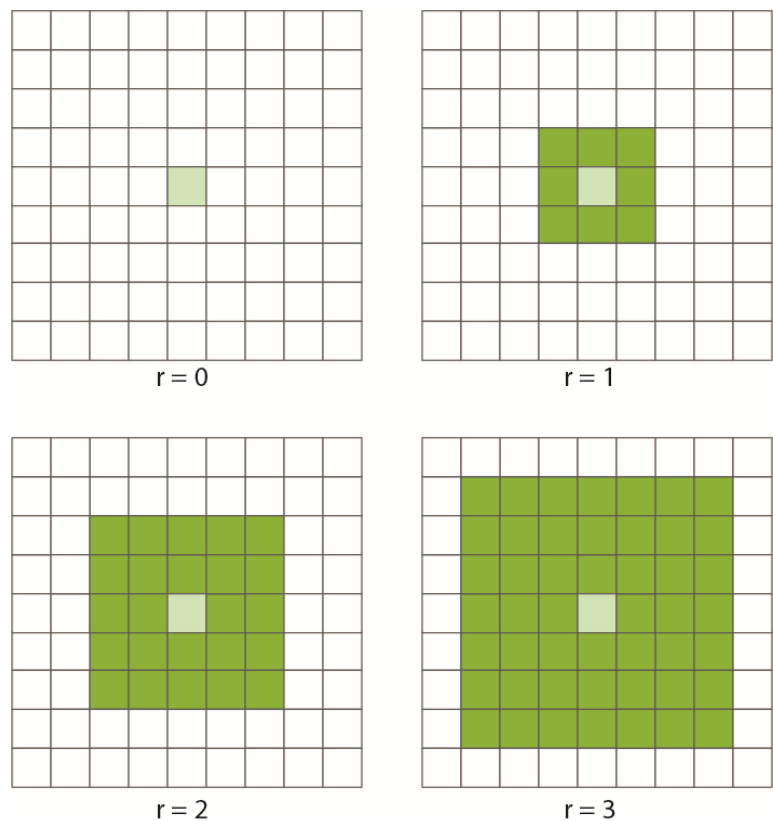


Figure 2.27 Iteration of Moore Neighborhood from Original Cell

Image Adapted from Wolfram Mathworld, 2013

Conway's Game of Life

In 1968, John Conway, a British mathematician was experimenting with variety of 2-Dimensioned cellular automaton rules. By early 1970's, Conway had developed a simple set of rules he called "The Game of Life," which exhibited a range of complex behaviors. Through the popular mathematics and science writer Martin Gardner's Science America, "Life" became widely known. The concept of "Life" is run by placing a number of filled cells on a two-dimensional grid. Each generation switches cells on or off (birth or death) depending on the state of the cells that surround it. The rules are defined as follows (Wolfram, 2002):

- Death:
 - 1) Any live cell with fewer than two neighbors dies, as if by loneliness.
 - 2) Any live cell with more than three neighbors dies, as if by overcrowding.
- Survival:
 - 1) Any live cell with two or three neighbors lives, unchanged, to the next generation.
- Birth:
 - 1) Any dead cell with exactly three neighbors comes to life.

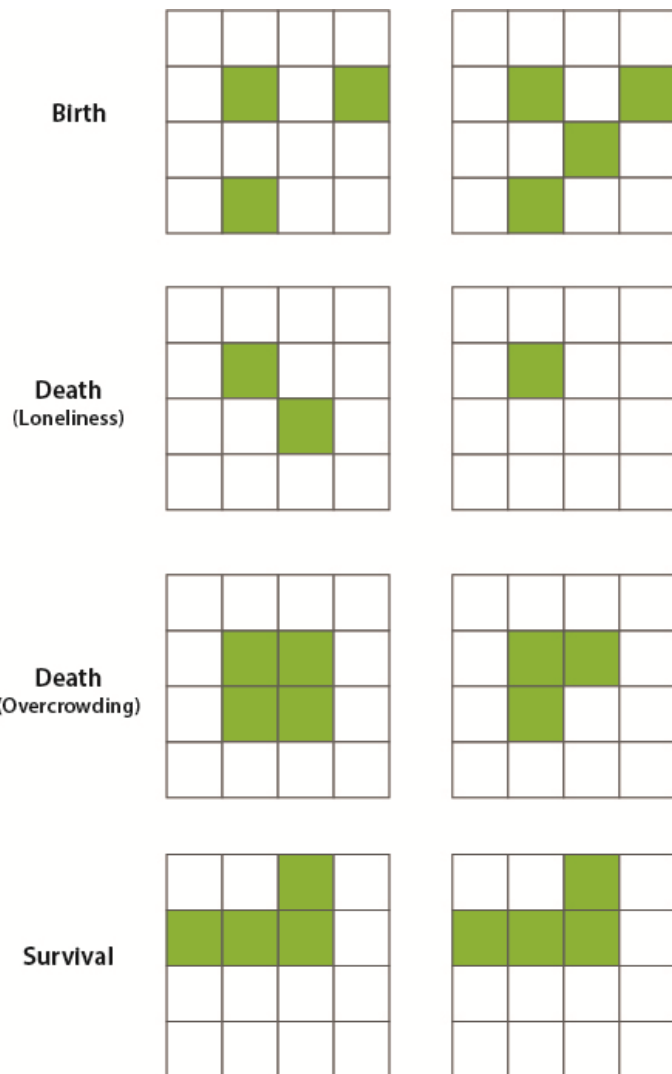


Figure 2.28 Illustration of Conway's Game of Life

Image Adapted from Wolfram Mathworld, 2013

The “Life” cellular automaton is run by placing a number of fill (or alive) cells on two-dimensional grids. The first generation is the initial pattern. Each generation then switches cells on or off (dead or alive) depending on the condition of surrounding cells defined by input rules. The same procedure is repeated to produce subsequent generations. The “Game of Life” demonstrates the repeated application of simple rules to random initial state could generate recurring patterns as the state of system evolves (Jacob et al, 2008). Figure 2.28 illustrates the concept of Game of Life.

The main concept of CA is a collection of cells comprising a grid that evolves through discrete time. Cells are extended via neighborhood interactions based on defined transition rules and determined neighborhood states. The rules are applied iteratively for as many time steps as desired (Wolfram, 2002).

Cellular automata are rigid in their cellular or grid structure. For that reason, researchers have adapted the formalism of the traditional cellular automata to suit their simulation needs (Figure 2.29).

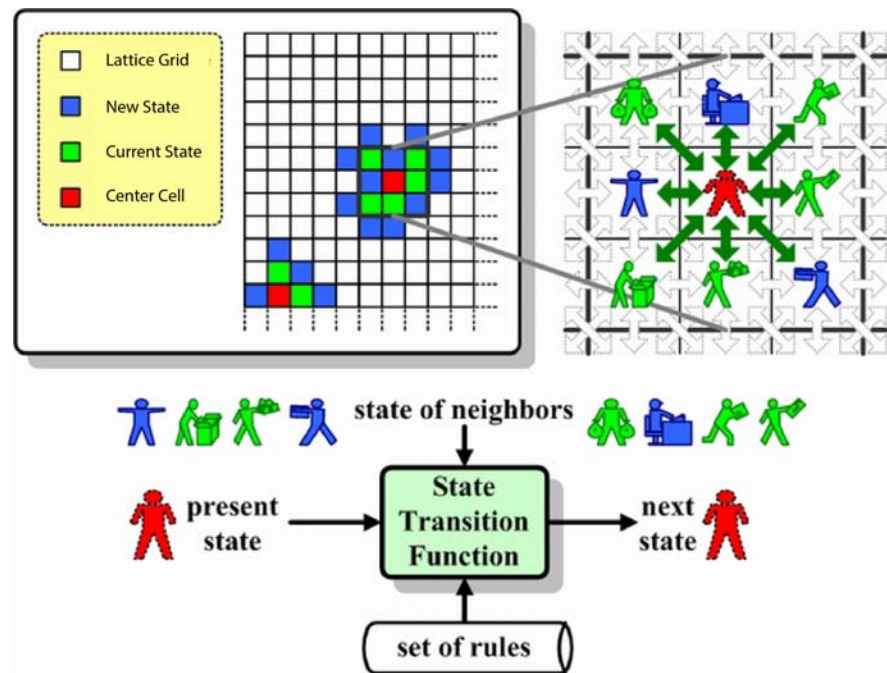


Figure 2.29 Diagram shows concept of transition rule in CA model Moore neighborhood

Image: Huang, Sun, Hsieh & Lin, 2004

In urban land use simulation, the cell space CA operates in is considered equivalent in an urban sense to an environment, a landscape, or a territory. The cell space in a cellular automaton is assumed to be both a regular and structured grid like a chess table. The individual cells in a cellular automaton are occupied at given time. In an urban context the cell state can be made to represent any attribute of the urban environment or land use that is represented by residential or commercial zoning; high or low density, and land cover, such as forested or farmland (Torrens, n.d).

Many researchers apply a linear or non-linear distance function to extend neighborhoods to better capture their spatial dependence on selected variables (Liu & Phinn, 2001). Typically, spatial factors are considered in the transition rules (Benenson, 2007) such as distance to biofuel plants and concentrated animal feeding operations (CAFOs) in this project.

An example of simulation of land use using a CA model is shown in Figure 2.30. In the image, raster cells are represented by lattice grids that have two states, current and next. Based on the input set of rules, each cell will determine what is the next state based on the neighboring current state of the center cell. An example of transition rule is:

IF irrigated farmland has saturated thickness > 30 feet,
THEN stay irrigated, **ELSE** change to dry land.

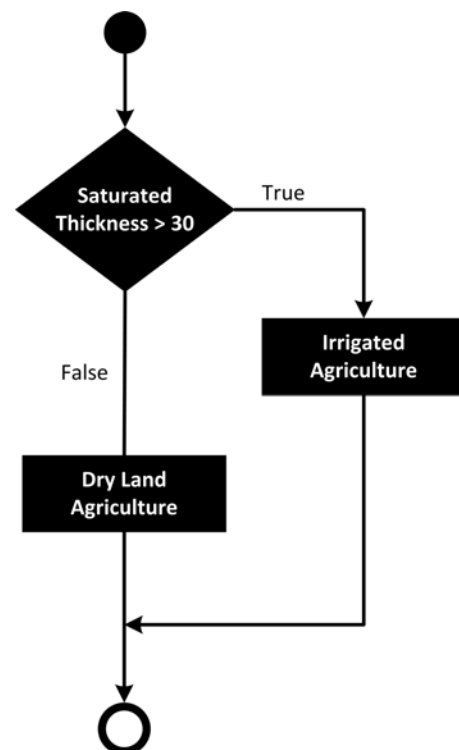


Figure 2.30 Diagram shows transition rules in the CA model

Illustrated by Author

Land Use Model Simulation Applications

Urban land use models often incorporate a variety of land use categories as inputs to account for different classifications of urban conditions. The common goals of these model simulations are to provide an output to forecast future urban land use changes. Some models offer an environmental approach and others concentrate more on economic aspect of the urban development. It is essential for a well-designed model to address not only the main policy systems but also subsystems such as economics and transportation. However, this is a difficult task for modelers to achieve and requires in-depth knowledge from various professional fields coalesced to integrate each disciplinary aspect into the modeling system. However, as in most modeling systems the importance of distribution of patterns is recognized in all urban land use models (Wegner, 2013). Common distribution patterns accounted for in urban simulations are:

- Distribution of land use—such as residential, industrial and commercial over the urban area determines the location of human activities;
- Distribution of human activities—required spatial interaction in the urban environment;
- Distribution of infrastructure—which creates opportunities for spatial interaction and can be measured as accessibility; and
- Distribution of accessibility in space—co-determines location decisions and results in change of land use system.

In recent technological advances, computers allowed modelers to developed better tools to simulate land use changes. These land use models are typical simple deterministic systems that are orderly and predictable. These applications mainly are using linear progression of events that are evolved through time, which includes economic, social and natural environment. The concept is simple and effective. However, it does not include randomness that is found in real world (Agostinho, 2007). In urban systems, dynamic of self-organizing, spontaneity, cooperative behaviors of evolution are mostly ignored in urban land use models (Batty M. , *Cities and Complexity: Understand Cities with Cellular Automata, Agent-Based Model, and Fractals*, 2007). The land use decision is the results of human decision – mostly likely are influence by other individuals. The problem is that human influences are difficult to calibrate in a model is highly complicated. Most land use models are developed to gain insight to what is possible in an urban system under a static condition, in a series incremental of how these changes

affecting it (Vliet, Hurkens, White, & Delden, 2012). Over recent decades, there are several approaches for modeling land use is offered. To understand the existing models and what applications are offered, Table 2.31 and text provide an overview of common urban land use models used today.

Model	Description
Land Use Change Analysis System (LUCAS)	Multidisciplinary land use management that examines the impact of human activities on land use and the subsequent impacts on environment
The SLEUTH Model (Clark Cellular Automata Urban Growth Model)	Developed by Keith C. Clark. The model integrates 2 sub-models: 1) the Urban Growth Model (UGM); and 2) the Deltatron Land Use/Land Cover Model (DLM). The model is to assess historical trends and predict future land use change.
UrbanSim	Simulation system for planning and urban development with interaction between land use, transportation, economy and the environment.
What if?	GIS-based planning support system simulate future land use based on population, housing and employment.
TRANUS	Integrated land use and transportation model includes land use and real estate market analysis.
Smart Places	A resource modeling system allows users to interactively design and evaluate land use alternatives and indicators of environmental performance.
Land Transformation Model (LTM)	Land use forecasting model examines driving force of land use change. It uses spatial interaction rules through neural net technology.
IRPUD Model	Projects the long range economic and technological change on housing transportation, public policies, land uses and infrastructure.

Table 2.31 Table of Existing Urban Land Use Simulation Applications

Compiled by Author

- The Land Use Change Analysis System, or LUCAS model was developed in 1994 to study the impact of human activities and land use on natural resource sustainability. LUCAS analyzes data derived from remote sensing images, census data, ownership parcels, topographic maps, and outputs using the open source GIS software Geographic Resources Analysis Support System (GRASS) (LUCAS, 2013).
- SLEUTH, or the Slope, Land Use, Exclusion, Urban Transportation, Hillshading Model, also commonly known as the Clarke Cellular Automata Urban Growth Model, is intended to simulate urban growth to help understand expansion in urban areas effects surrounding environment and local policy. The model simulates the transition from non-urban to urban land use using grid of cells (cellular automaton) based on local factors such as roads, existing urban areas, topography, and other random factors (SLEUTH, 2013).
- Urban Sim is a system designed for planning and analysis of urban development with considerations of land use, transportation and public policy. It also addresses environmental impacts of development by simulating land cover, water demand and nutrient emissions (UrbanSim, 2013).
- What if? was developed to forecast land use planning alternatives. The model provides modules that allow users to perform suitability analysis (suitability module), project future land use demand (growth module), and allocate projected demand to more suitable location (allocation module) (What if?, 2013).
- TRANUS is designed as an integrated land use and transport planning system intended to model transportation, economic, and other environmental policies at an urban, regional and national scale. The model assesses implications of transportation policies on location and interaction of activities and effects on the land market. It also forecasts the future growth and activities within the study area (TRANUS: Integrated Land Use and Transport Model, 2013).
- Smart Places is a geographic decision support system created to design and evaluate land use development alternatives with user specified criteria. The model provides interactive tools that allow users to explore and design alternative development plans and evaluate impacts on environment and local economics (Smart Places, 2013).

- The Land Transformation Model (LTM) uses landscape ecology principles and patterns of interaction to simulate land use change processes and forecast land use changes. The model contains smaller sub-modules, which are policy framework, driving variables, land transformation, intensity of use, processes and distribution. Other variables include: population growth, agricultural sustainability, transportation, and farmland preservation policies (Land Transformation Model, 2013).
- The IRPUD Model projects the location decisions of industry, residential household travel patterns that result from location decisions, construction activities and land use development. It also includes factors such as public policies, facilities and transportation within an urban area. IRPUD also consists of smaller sub-models to address transportation, changes to population, employment, long term socioeconomic trends, private constructions, regional labor market and housing market (IRPUD, 2013).

These models listed above are used in context of urbanization and social economy. Although in some model structure such as TRANUS or IRPUD, they are including other sub-models when performing simulation, as a unified modeling structure, but in reality they are structurally autonomous sub-systems. Each still has its own independent structure (Wegener, 2004). The biggest drawback for most models is that space is only as distance from urban center or central business districts, as well as in some models excluded environmental features such as surface elevation, natural resources or transport hubs. The only exception of SLEUTH model developed by Clarke is the only cellular automaton. However the model is designed to simulate urban growth condition, specifically with urban extensions. It generates results that reflect the pattern or trends of urban development (SLEUTH, 2013). The model primarily is focus on urban environment or areas that are transitioning to urban system.

While SLEUTH uses CA approach and is dynamic in simulation in urban systems, but it is not designed specifically to simulate with the complex agricultural systems, specifically the High Plains region which is based on a finite groundwater resources. Traditionally, simulation models solely focus their disciplinary aspect and not accounted for other factors, very much many of above mentioned urban land use model simulations. In this research, the important variables that are used particularly to simulate high plains aquifer system are coupling with other disciplinary models. For example, groundwater model is to simulate characteristics of the

aquifer, such as estimated saturated thickness and depth to groundwater. Then, economic and crop model uses output that is generated from groundwater model to assess crop choices that will maximized benefits to individual farmers and location of irrigated agricultural operations. The land use model will use the resulting output from both models to determine the allocation of irrigated crop distribution. This tightly –coupled approach enables the predictions in this research to be more holistic rather than focus on only one aspect of modeling system.

Coupled Model Approach

The Consortium for Global Research on Water Based Economies (GROWE) at Kansas State University formed around the issues of the High Plains/Ogallala Aquifer with the goal to help decision makers across scales make more informed decisions about water use and its short and long-term implications. Through time GROWE has developed a coupled multi-disciplinary modeling approach (Steward, 2006; Steward, 2007; Steward, 2009) implementing geodatabase data models (Yang, 2010; Bernard, 2005) and Open Modelling Interface (OpenMI) (Bulatewicz, 2011; Bulatewicz, 2012; Bulatewicz, 2013).

As illustrated in Figure 2.32 a common geodatabase provides data upon request by a model to the ODM Database (Observations Data Model) (CUAHSI, 2013) in a standard time series format consumable by the model which requested it.

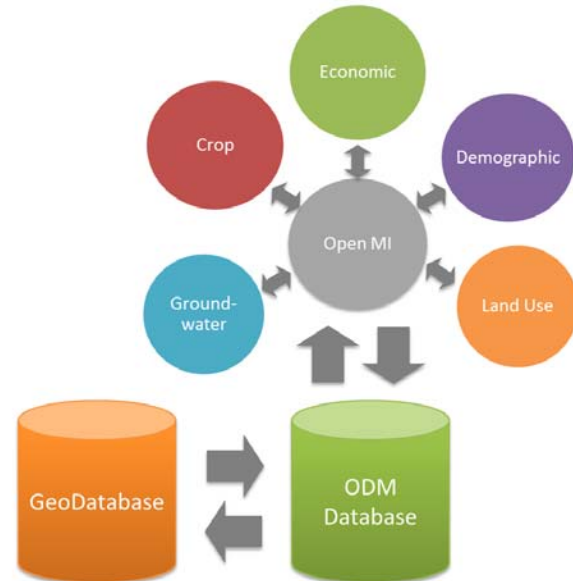


Figure 2.32 Coupled Models Integration Using OpenMI, GIS and ODM

Image Source: Bernard, 2013

The model then runs until it requires another input, often the result of another model, or provides results to the ODM in an output time series format. OpenMI facilitates coupling the multi-disciplinary models to exchange data and request and return data to the databases while allowing the models to run in their normal environment (Gregersen, J. B.; Gisbers, J. A.; Westen, S. J. P., 2007).

OpenMI also serves as a bridge to various scripting language such as MATLAB, language for mathematics, SAS for statistics and Python for Geographic Information Systems (Bulatewicz, T; Allen, A; Peterson, J.M; Staggenborg, S; Welch, S.M; Steward, D.R, 2012). In OpenMI, various models would share data when needed. For instance, land parcels provide location and areas which are related to assets like wells which are related to groundwater resources that are used to irrigate a particular crop which under certain growing conditions produces a certain yield. Figure 2.33 illustrates interactions between data models in OpenMI environment.

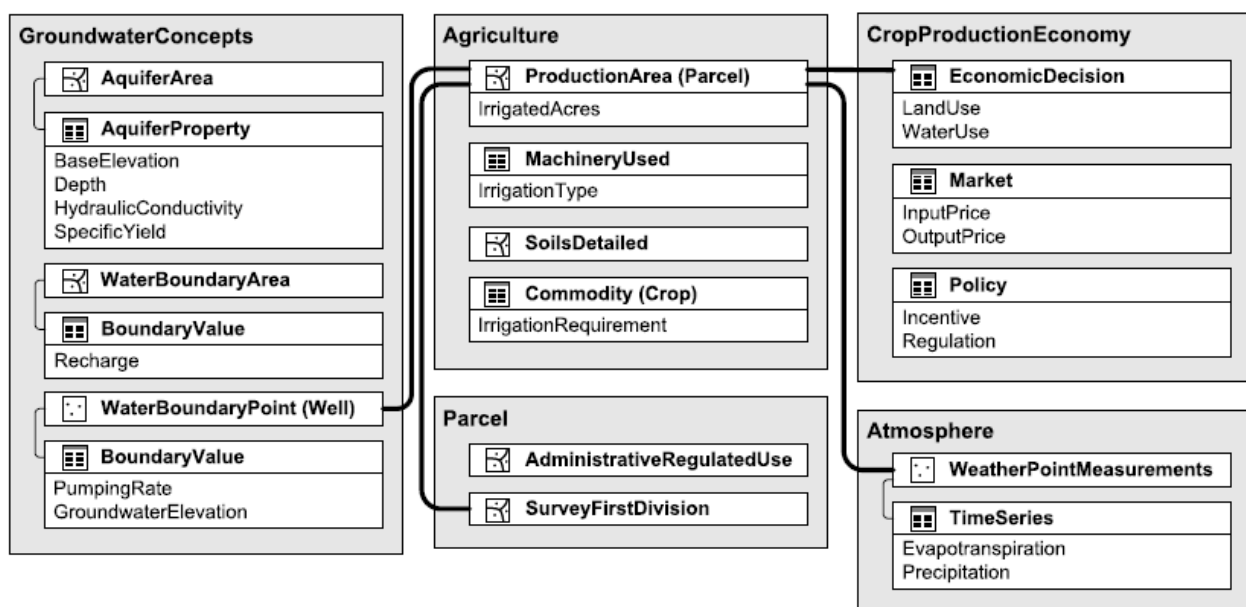


Figure 2.33 Interactions and data exchange between multidisciplinary models

Image Source: Bernard, 2013

At present the groundwater model simulates characteristics of the aquifer, such as estimated saturated thickness and depth to groundwater which are important variables used in the economic model to determine crop choice based on water available to irrigate and cost to pump the water to the surface. The economic model is also reliant upon the EPIC crop model for estimates of crop yield based upon localized growing conditions such as soils and climate, while the Hydrologic model makes use of the EPIC results for excess water beyond the root zone as an estimate of recharge. Stated simply, the coupled modeling system tightly couples groundwater, economic and crop (EPIC) models where the:

- Hydrologic Model provides estimates in groundwater elevation and saturated thickness of the aquifer;
- Economic Model provides estimates of crop choice based on maximizing profit;
- EPIC Crop Model provides estimates of crop production and recharge.

What is not known from the results of running the models is where spatially the crop choices will be distributed locally in the landscape or where land use will change from irrigated to dry land practices. This is largely attributable to spatially aggregated economic data about crops and yields which have historically been reported at a county scale by percentage of crop type grown. The results returned from the economic model to the ODM and geodatabases provide an estimate for the four major irrigated crops—corn, sorghum, soybeans and wheat—by percentage grown in the modeled area. The question then is where exactly are the crops grown? This question is critical when running temporal simulations as the next model run is reliant upon understanding the water available, depth to water, etc. for each irrigated area. It is also important to understand where areas change from irrigated to non- irrigated based on available water in the aquifer. These key questions indicate the need for a irrigated agriculture land use and land cover model which makes use of the same data sets used by the models as well as the results of the coupled models.

Chapter 3 - Research Method

The scope of this study is the development of a method to simulate land use changes to or from irrigated agriculture and to spatially allocate coupled model results for the four predominate irrigated crops grown in the High Plains/Ogallala Aquifer area in Kansas. The approach taken herein incorporates cellular automata techniques to simulate agricultural land use in the Kansas High Plains/Ogallala aquifer region. As well as the ability to simulate irrigation demand based on type of agricultural land use.

Input parameters such as saturated thickness, prime farmland soil type were used to define transition rules in the CA model. Other peripheral factors such as irrigated crop types from 2006 to 2011, distance of ethanol plants, grain elevator, Concentrated Animal Feeding Operations (CAFOs) are used to determine best service area distance for farmland in the High Plains aquifer region using conditional statement functions in ArcGIS. The resulting output is use to define transition rules in the CA model, which provides information to both spatial and temporal aspects of agricultural land use in the studied area. The GIS-based CA model is implemented through ArcGIS Spatial Analyst tools and Python scripts with represented conditions derived from the collected data at a finer scale classification in comparison to a typical urban model.

Interdisciplinary modeling attribute values are to be used to determine the future development of the High Plains aquifer region's agricultural land use based on refinement and calibration of the simulation in the CA model. However, at the time of completion for this report, results from interdisciplinary models are not yet available. Consequently, most of the variables used in the CA model presented are based on historical data or assumptions such as corn requires more water than wheat and the aquifer decline is approximately 1.5 feet per year on average. Since this project aims to indicate transitions in irrigated agricultural land to other land uses, and distribution of irrigated crop types to areas where irrigation can occur based on water availability the actual input parameters are not essential in the development of the theoretical framework and proof of concept presented here.

The Cellular Automaton (CA) approach was selected in this study for its ability to interact with other models in the larger research project and simulate a complex land use change in a dynamic interaction among cells. Another key consideration for choosing cellular automaton

is the simplicity of the model. A CA model can be composed of a limited set of If/Then/Else statements (or transition rules) capable of exhibiting complex behaviors. As long as the process and method is well documented, the logic of a CA model can be easily understood by non-CA model users.

CA model inputs and outputs are raster or cell based formats, which are easier to handle in a large geographic region with less required storage space and run time in comparison to vector data. Raster data also is quicker for the user to determine the definition of neighboring cells (Liu & Phinn, 2001). Most importantly, the CA model transition rules are able to be consumed by ArcGIS using python. All these characteristics of a CA model make it a logical option for simulating irrigated agricultural land use change and irrigated crop land cover.

The initial step in implementing a CA model is to find the parameters which define transition rules and the numerical values of these parameters. Ideally these parameters are generated from longitudinal land use change historical data. The rules generated here are based on the author's understanding of the process at play in the system. Once transition parameters are determined there are two types of transition rules that can be used in CA model implementations: conditional or mathematical (Wu, 2002). In ArcGIS, transition rules can be expressed as either or both. For this

research given the coupled mathematical and statistical model results the author has chosen to use conditional statements to define transition rules.

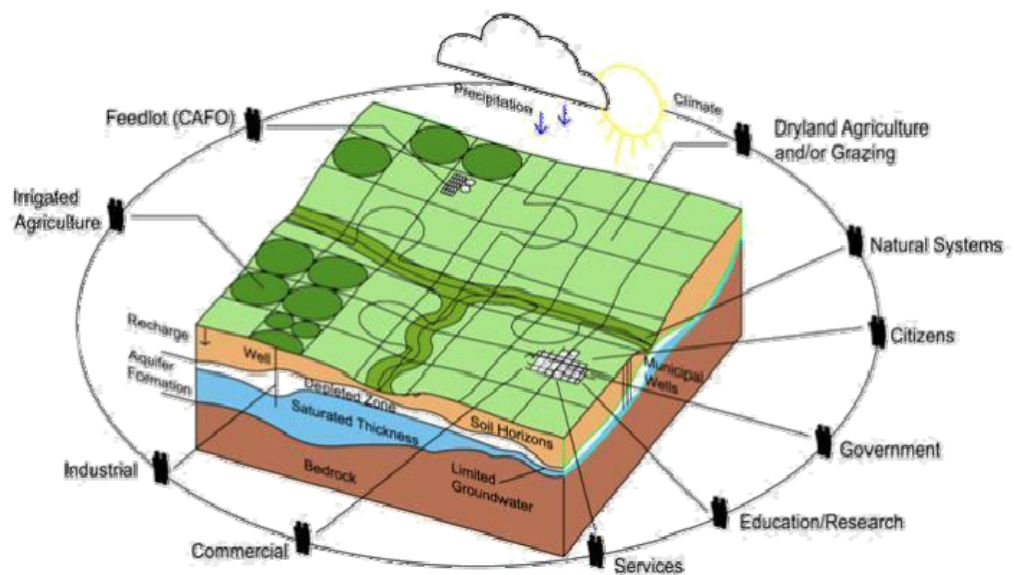


Figure 3.1 Driving Factor for the CA model

Image Source: Bernard, 2013

During the process of developing transition rules, an automated method was used to produce a set of descriptive rules or decision trees that are defined by the author through literature review. They are values such as minimum saturated thickness for farmland to stay irrigated and distance to facilities such as biofuel plants, CAFOs and grain elevators (Figure 3.1). When the transition rules are established, the input condition statements iterate cells in the original input raster.

Study Area and Dataset

The CA model used in this project has been developed specifically for the Kansas High Plains aquifer region. The historical agricultural crop type data for the area was obtained from USDA NRCS Geospatial Data Gateway (Geospatial Data Gateway, 2013). The data available for use is from 1997 to 2011. However, only data from 2006 to 2011 are usable for this study because prior to 2006 there was no coverage for the state of Kansas. Biofuel and grain elevator data was provided by Department of Geography at Kansas State University. The dataset was geocoded and up-to-date until 2011. GIS data on Concentrated Animal Feeding Operations (CAFO) was obtained from Kansas Department of Health and Environment. Center pivot data for 2006 and 2008 were digitized by students working with Professor Eric Bernard in Landscape Architecture at Kansas State. Table 3.2 provides a summary of data sets used in this project and by the coupled modeling system.

Data	Geometry	Source
High Plains Aquifer Saturated Thickness (2007-2009)	Raster	U.S. Geological Survey
Cropland Data Layer (2006-2011)	Raster	Geospatial Data Gateway
Biofuel Plants	Point	Dept. of Geography (KSU)
Grain Elevators	Point	Dept. of Geography (KSU)
Concentrated Animal Feeding Operations (CAFO)	Point	Kansas Dept. of Health and Environment
Center Pivot Irrigation Fields (2006 & 2008)	Polygon	Eric Bernard
Prime Farmland Soil	Table	Geospatial Data Gateway
SSURGO	Polygon	Geospatial Data Gateway

Table 3.2 GIS Data Sources

Compiled by Author

The Cropland Data Layer (CDL) is a 56 meter cell size raster land cover dataset for Kansas from 2006-2009. In the attribute table, there are 38 land use classes for cell values illustrated in Table 3.3. These classes were reduced to five primary crop types using the Reclassify tool in ArcGIS to reduce computation time during the simulation. The study crops are: corn, sorghum, soybeans and wheat (spring and winter). An example of before and after reclassify cropland data can be seen in Figure 3.4 and 3.5. This process was performed for all cropland data 2006-2009.

Value	Class_Names
1	Corn
2	Cotton
4	Sorghum
5	Soybeans
6	Sunflower
21	Barley
23	Spring Wheat
24	Winter Wheat
25	Other Small Grains
26	Dbl Crop WinWht/Soybeans
27	Rye
28	Oats
29	Millet
31	Canola
36	Alfalfa
42	Dry Beans
43	Potatoes
44	Other Crops
53	Peas
58	Clover/Wildflowers
61	Fallow/Idle Cropland
62	Pasture/Grass
71	Other Tree Crops
87	Wetlands
111	Open Water
121	Developed/Open Space
122	Developed/Low Intensity
123	Developed/Med Intensity
124	Developed/High Intensity
131	Barren
141	Deciduous Forest
142	Evergreen Forest
143	Mixed Forest
152	Shrubland
171	Grassland Herbaceous
181	Pasture/Hay
190	Woody Wetlands
195	Herbaceous Wetlands

Table 3.3 Cropland Data Layer Classes

Data Source: USDA NRCS

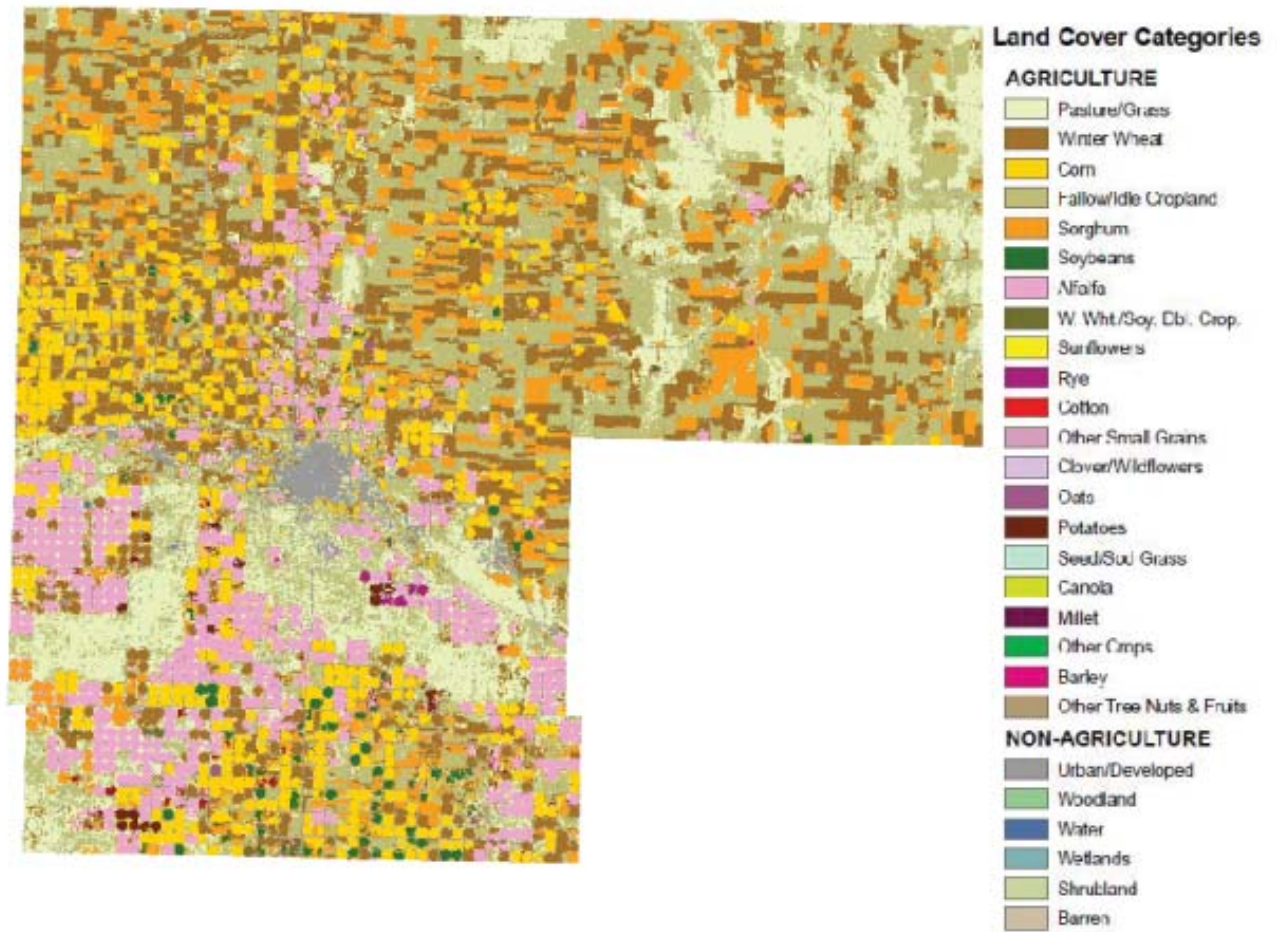


Figure 3.4 Finney County Cropland Data Layer 2006, before reclassify

Data source: USDA NRCS



Figure 3.5 Finney County Cropland Data Layer 2006, after reclassify

Data source: USDA NRCS

Proximity and transportation distance factors considered in developing the transition rules were standardized from varying data types stored in the geodatabase in a consistent raster or cell format with same resolution 56 meters resolution as the Cropland Data Layer. The proximity rule factors used in this research are:

- Distance to biofuel plants;
- Distance to concentrated animal feeding operations (CAFOs); and
- Distance to grain elevators.

These proximity factors implicate profit for farmers given transportation costs and for biofuel and grain facilities for the same reasons. In the case of biofuel plants, research has shown these plants not only impacted the production, feed use and exports of corn, but also general price level of corn. Research has also shown that cost benefit for crop field is expected to be concentrated in the 50 mile radius surrounding a new ethanol facility is most likely to be profitable (Taylor, Mattson, Andino, & Koo, 2006).

CAFOs are also influential to individual crop choices. Most feed lots now are switching to “grain feed” or “corn fed” for animal health reasons. This means that irrigated farmlands closer to a feed lot are more likely to have higher demand of corn or grain crops. Although there is not a definitive in the literature indicating the most profitable distance to a CAFO, one could reasonable assume the 50 mile radius for biofuel plant crop sourcing would also work for feeding operations. Additionally, one could consider the typical geographic definition of local distance defined as a 30 mile radius (Martinez, et al., 2010). Thus, the distances to facilities were calculated using multi-ring buffers in ArcGIS with distances of 30 and 50 miles. Figures 3.6, 3.7 and 3.8 illustrate the output results of the buffer distance for each type of facility.

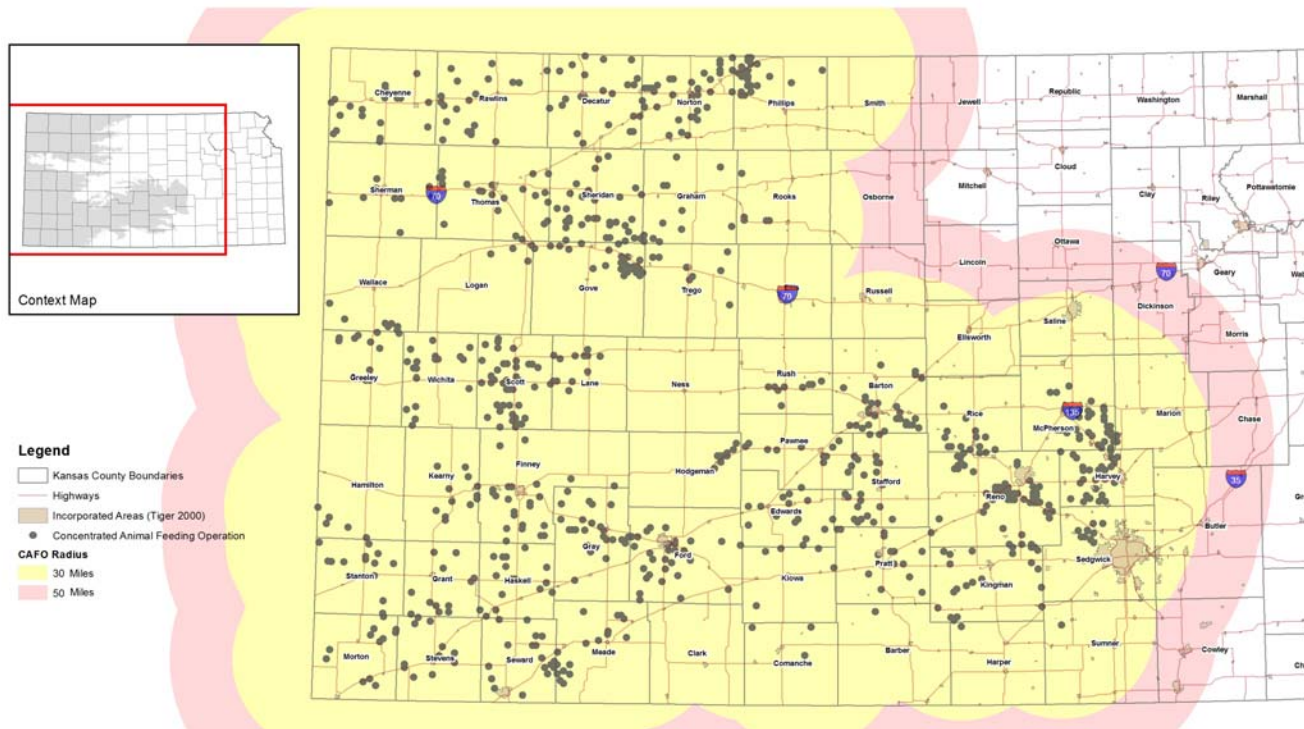


Figure 3.6 CAFOs 30 and 50 Mile Radius Map

Data source: USGS, KS DASC & KS Dept. of Health and Environment

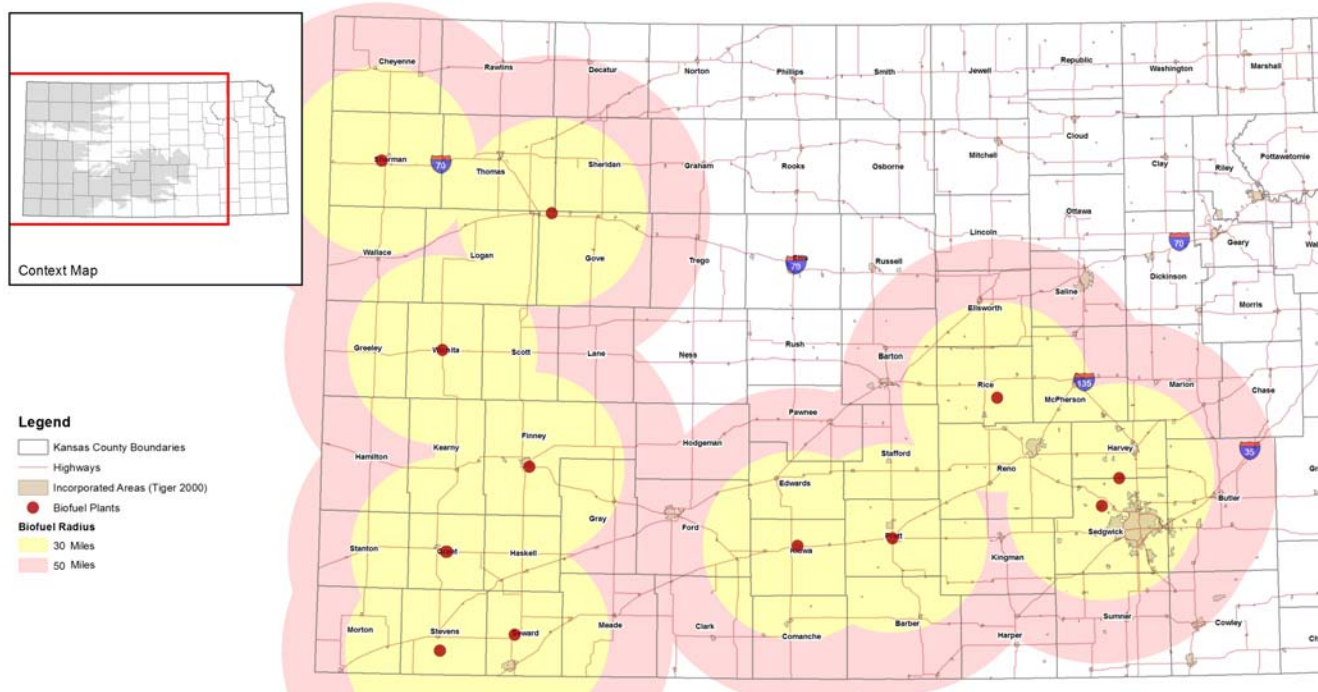


Figure 3.7 Biofuel Plants 30 and 50 Mile Radius Map

Data source: USGS, KS DASC & KS Dept. of Health and Environment

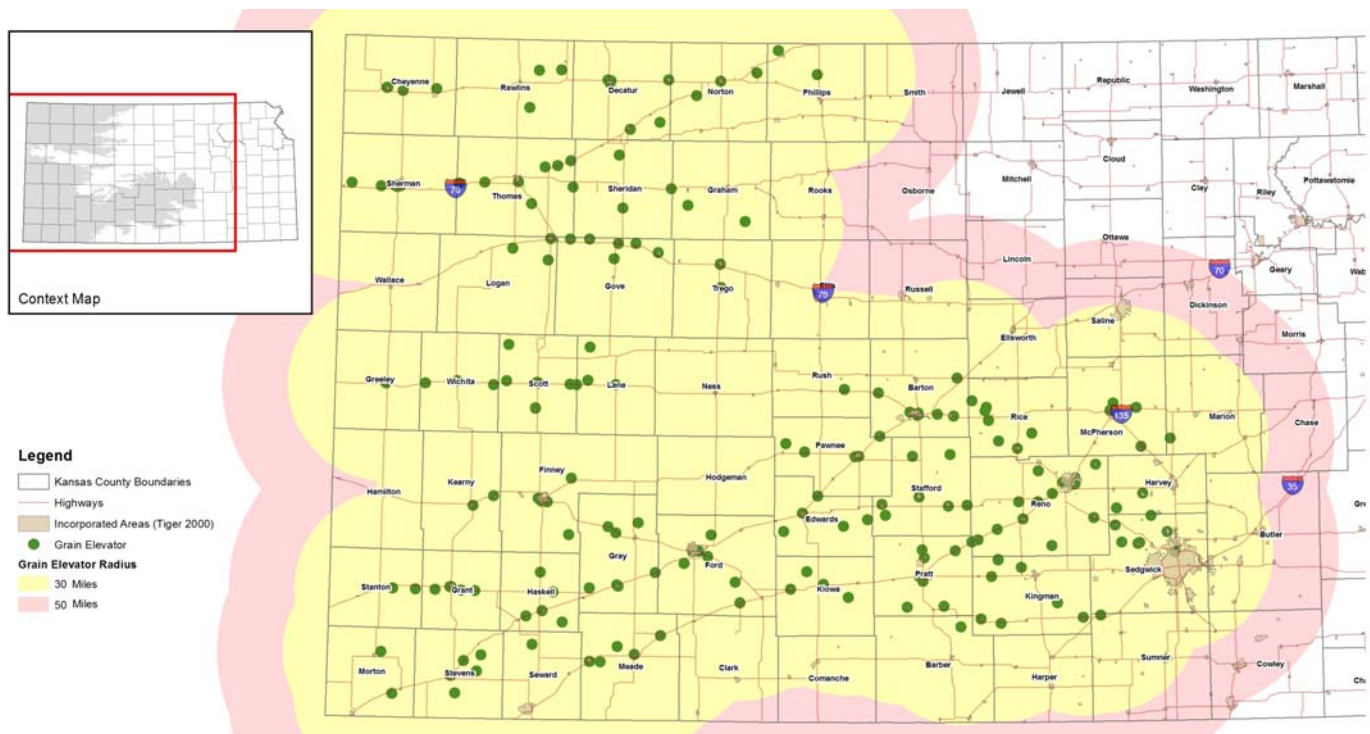


Figure 3.8 Grain Elevators 30 and 50 Mile Radius Map

Data source: USGS, KS DASC & KS Dept. of Health and Environment

The Prime Farmland soil classification is based on the definition by U.S. Department of Agriculture to determine soils with significant importance to agriculture. A soil with the “prime farmland” designation is considered to be land with best combination of physical and chemical features for the production of agricultural crops. This indication is important in the economic model and land use and land cover models as these areas are higher yield producing soils. While this factor is important it must also be considered with the areas climate conditions. Given the low total precipitation in the area, high water demand crops like corn must be irrigated to produce average to high crop yields in most years. “Farmland of statewide importance” is land other than prime farmland, which still has good combination of physical and chemical properties for the production of high water demand crops and again requires irrigation under average precipitation years.

Prime farmland soil does not have much influence in allocating irrigated farmland in this analysis because nearly the entire area has a Prime Farmland designation. Because irrigated farmland is established on the basis of water availability or proximity of well location for

irrigation, these factors must be considered. However, soil factors may be important for determining crop type in more refined results of crop production from the EPIC Crop Model. Figure 3.9 is an example of two types of classes included in the analysis.

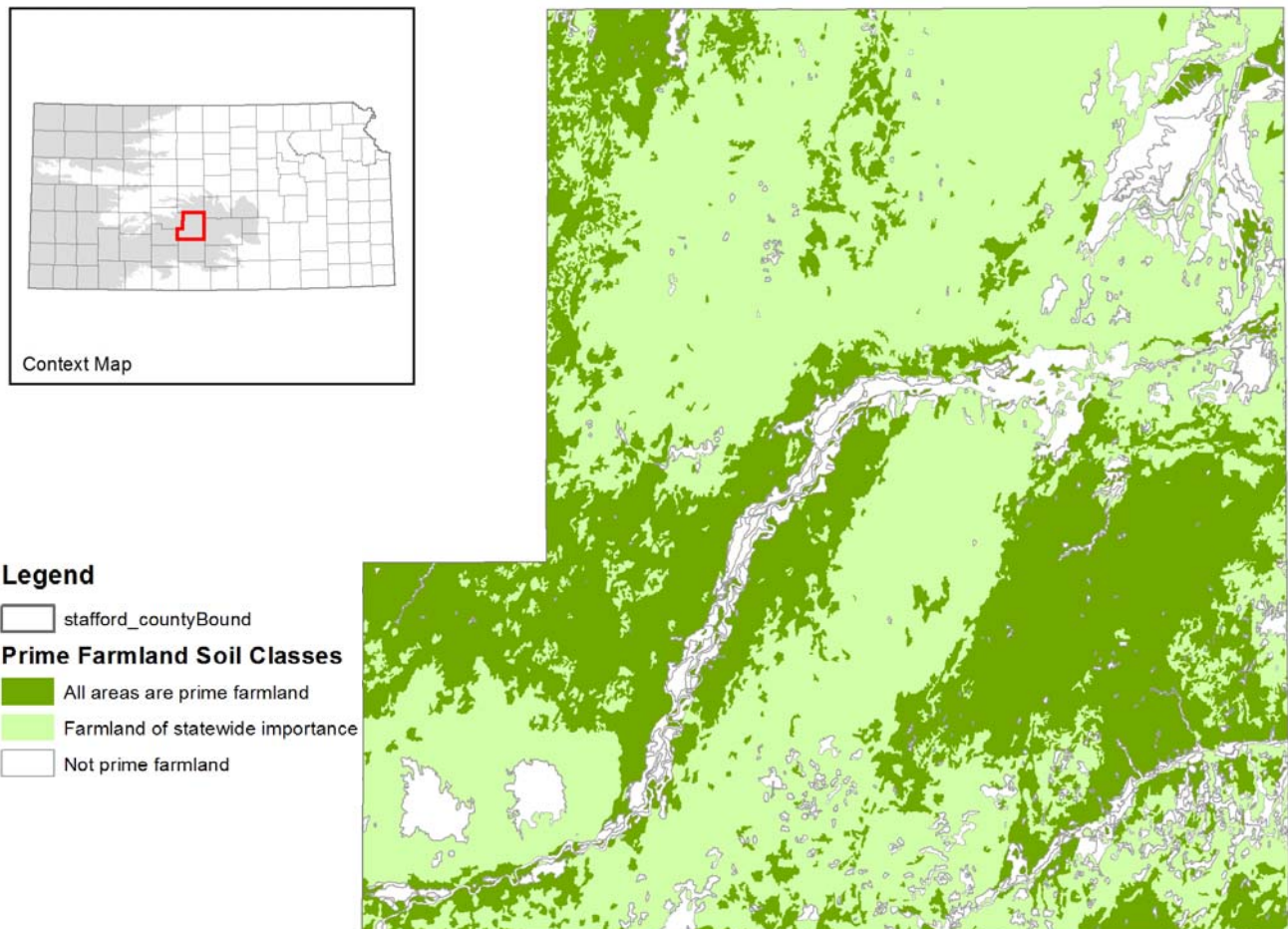


Figure 3.9 Stafford County Kansas Prime Farmland Soil Coverage

Data source: Soil Data Mart & KS DASC

Figure 3.10 is a map of prime farmland soil with irrigated farmland overlayed. For Stafford county, both Prime Farmland and Farmland of Statewide importance soils maintain all irrigated land use and cover the majority of the land area of the county. This fact limits the potential value of Prime Farmland soil as a transition rule in the CA model.

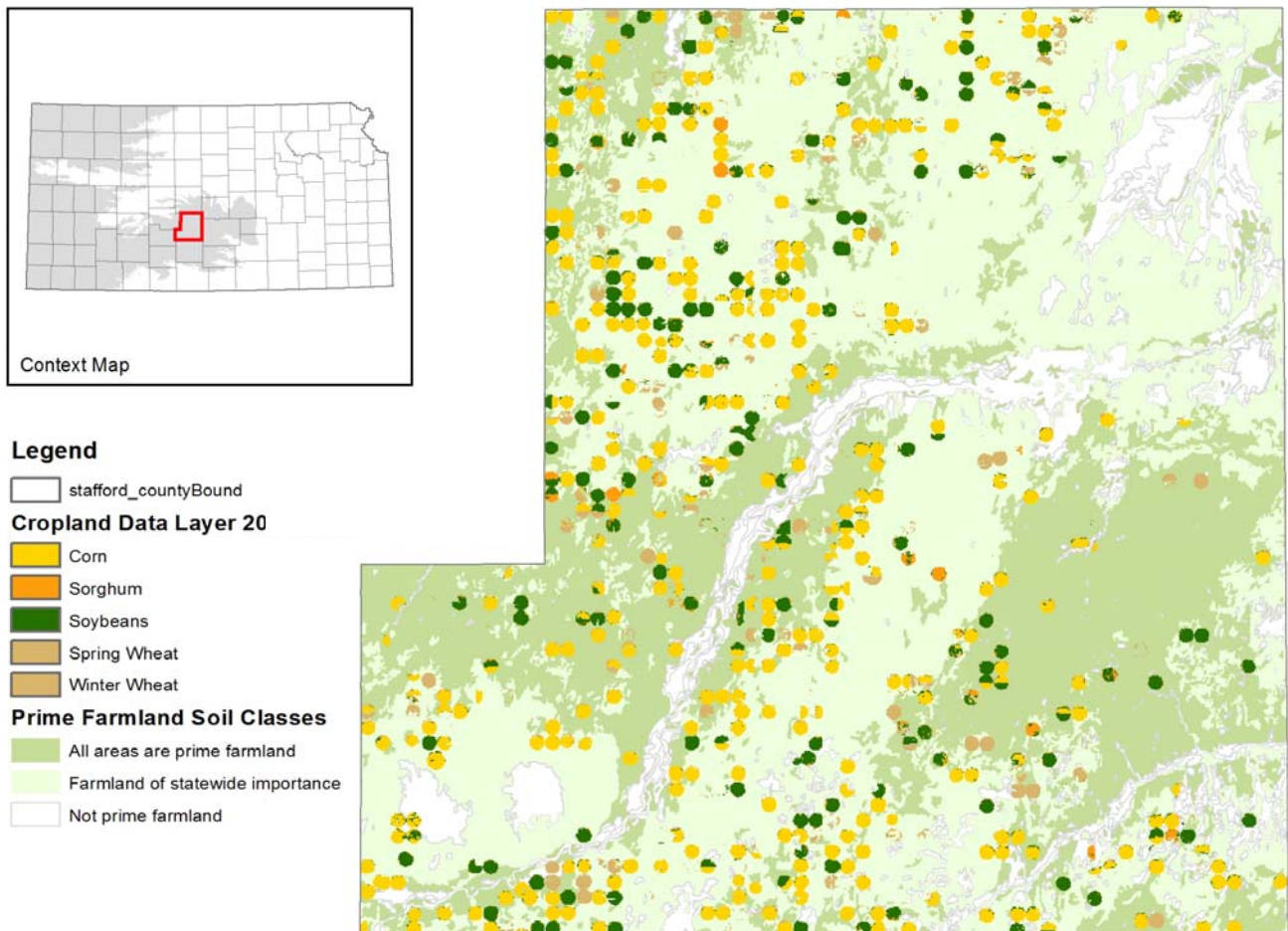


Figure 3.10 Stafford County Prime Farmland Soil Coverage Overlay with Irrigated Cropland Data

Data Source: Soil Data Mart & KS DASC

Before developing transition rules and calibration of the model the definition of neighborhood and an extraction of irrigated agricultural land use are required. Defining the neighborhood in ArcGIS allows three options to analyze cell neighborhoods: 1) Local (cell-by-cell), 2) Focal (cells overlap), and 3) Block (block of cells do not overlap). Earlier in the research, Moore's neighborhood was selected as the best approach to analyze cell neighborhoods for this model. Therefore, the cell-by-cell option was not considered. Given the software options, the focal neighborhood was determined the most appropriate neighborhood analysis because of its ability to analyze overlapping cells. An illustration of focal and block statistics function is shown in Figure 3.11.

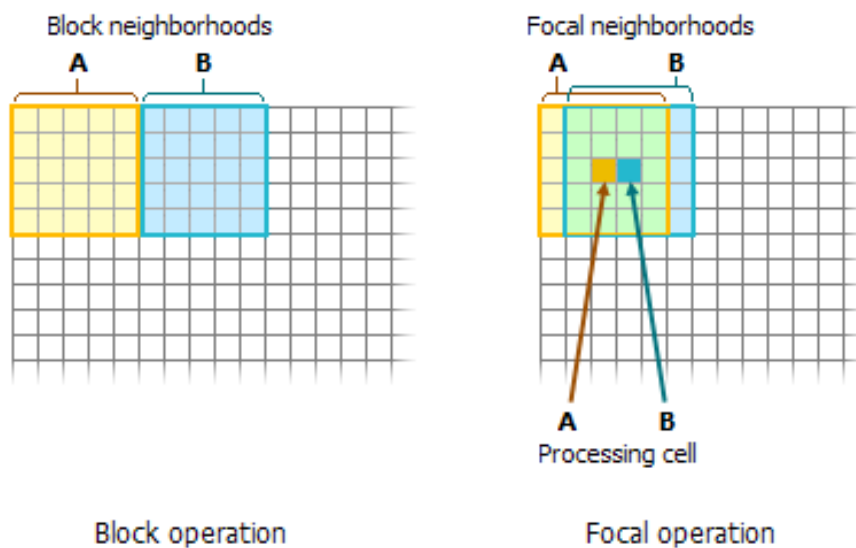


Figure 3.11 Block statistics vs. Focal statistics in calculating cell neighborhood

Image Source: ESRI

With focal neighborhood selected, the next choice involves selecting of of the ten options for statistical analysis to perform on the neighborhood (ESRI, 2013). The choices are:

- 1) Mean: calculates the average value of the cells in the neighborhood;
- 2) Majority: calculates cell value that are occurring most often in the neighborhood;
- 3) Maximum: calculates the largest value of the cells in the neighborhood;
- 4) Minimum: calculates the smallest value of the cells in the neighborhood;
- 5) Range: calculates differences between largest and smallest value of the cell in the neighborhood;
- 6) Minority: calculates the cell value occurring least often in the neighborhood;

- 7) STD: calculates the standard deviation of the cells in the neighborhood;
- 8) SUM: calculates the total of all value of cells in the neighborhood; and
- 9) Variety: calculates the cell with unique value in the neighborhood.

The Majority statistics option was selected to assess which crop type occurs most often in the neighborhood and use it as the primary crop to eliminate noise and speckles in the raster.

The neighborhood shape was also specified inside the function and chosen as a rectangle neighborhood using the default 3x3 neighborhood cell dimensions. This means cells in the 3x3 neighborhood will be included in each calculation process. The value of the processed cell and the cell value in the identified neighborhood are included in the calculation. Additionally, neighborhoods are allowed to overlap so cells in one neighborhood may also be included in the neighborhood of another processing cell.

The extraction of irrigated agricultural land use involves two separate datasets. One, the center pivot irrigation data set containing center pivot polygons digitized in 2006 and 2008 from NAIP imagery in those respective years. The polygons indicate the total irrigated area under the pivot as well as divisions of acreage under the pivot growing different crops.

As shown in the attribute table for the Cropland Data Layer, irrigated crops are not differentiated from non-irrigated crops. Therefore the polygons from the center pivot dataset were used to extract the irrigated farmland area. The irrigated crop areas were extracted in ArcGIS using a mask function. The extracted results of irrigated cropland dataset were compared with National Agricultural Statistics Services (NASS) to validate its accuracy. This process was very simple because the center pivot polygon was digitized prior to the implementation of this model (Figure 3.12). Otherwise this would be very difficult at best.

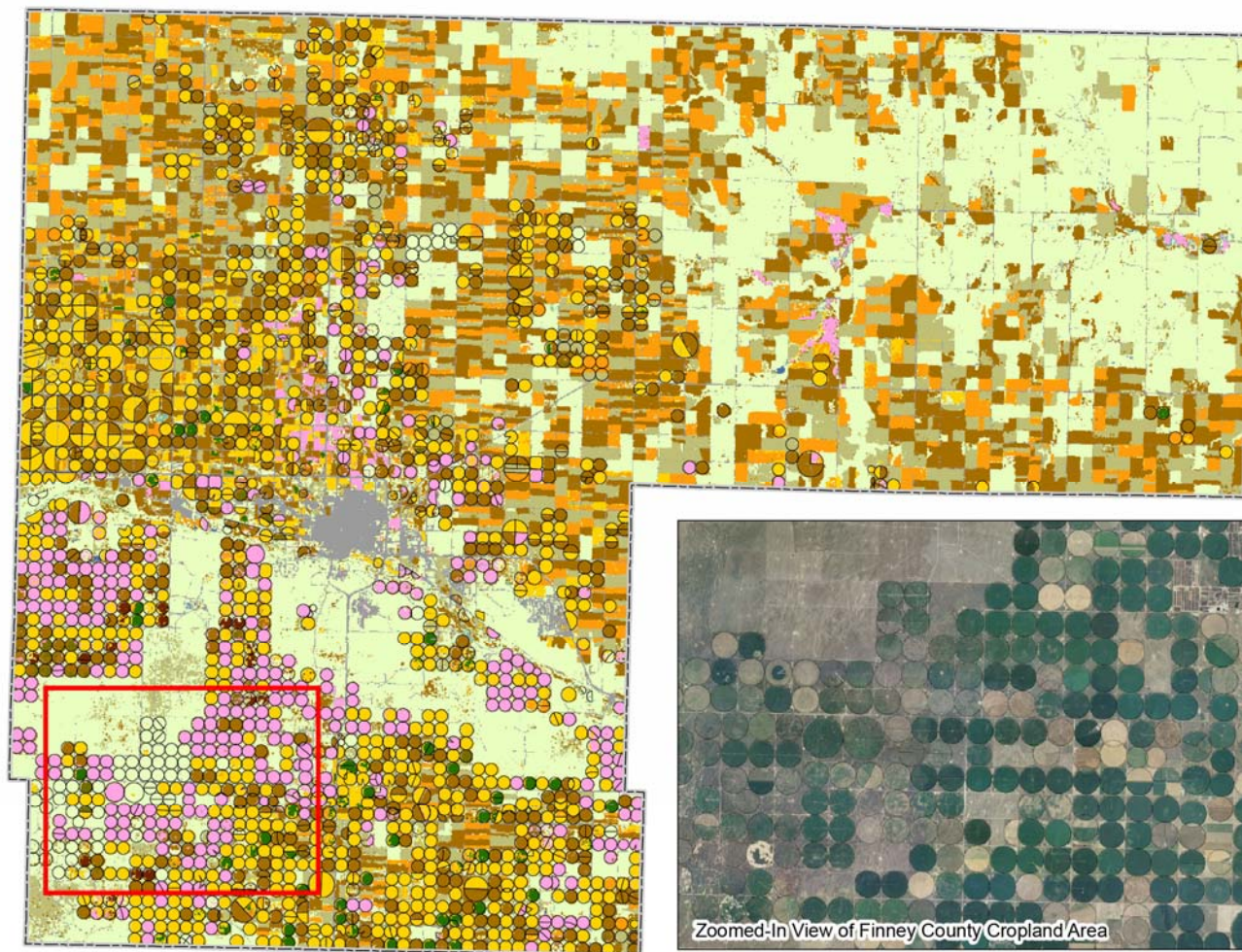


Figure 3.12 Example of Extracted Irrigated Cropland Using Center Pivot Polygon Data

Data source: Bernard, USGS & KS DASC

Defining Transition Rules

The first stage in creating transition rules is to develop condition statements to identify the constraints of land use change. The following rules were identified to drive the conditions of irrigated agricultural land use change:

IF irrigated farmland has saturated thickness > 30 feet, **THEN** stay irrigated, **ELSE** change to dry land;

IF irrigated farmland has saturated thickness > 34 feet, **THEN** corn/sorghum/soybeans/wheat as crop choice **ELSE** change to dry land;

IF irrigated farmland has saturated thickness > 33 feet, **THEN** sorghum/soybeans/wheat as crop choice **ELSE** change to dry land;

IF irrigated farmland has saturated thickness > 32 feet, **THEN** soybeans/wheat as crop choice **ELSE** change to dry land; and

IF irrigated farmland has saturated thickness > 31 feet, **THEN** wheat as crop choice **ELSE** change to dry land.

The first rule is defining the condition of irrigated cropland based on the saturated thickness of the aquifer. If the saturated thickness is greater than 30 feet, which is the established as a minimum threshold for this models development, then it should stay as irrigated cropland or **ELSE** change to dry land. The results of from the coupled hydrologic model will provide simulated results for the ability of an cell in the aquifer to produce enough water to irrigate at varying levels required by the different crops. V As this simulation is not yet complete for the entire aquifer area, the previously State of Kansas Division of Water Resources previously used a 30 feet minimum saturated thickness to allow pumping which was used here for model development.

The remaining condition statements indicate the required saturated thickness of greater than 30 feet PLUS an additional saturated thickness required for increasing water dependency crop types. Again the assumptions presented here will eventually come from EPIC crop model simulations but are used in place of those forthcoming results for the entire aquifer area. The annual irrigated amount each crop type would need if irrigated is a simple assumption based on crop water need. In this proof of concept model, to be able to plant irrigated corn there would have to have at least of 34 feet of saturated thickness available for irrigation, 33 feet for sorghum, 32 feet for soybeans and 31 feet for corn. Figure 3.13 illustrates the concept of the condition statements.

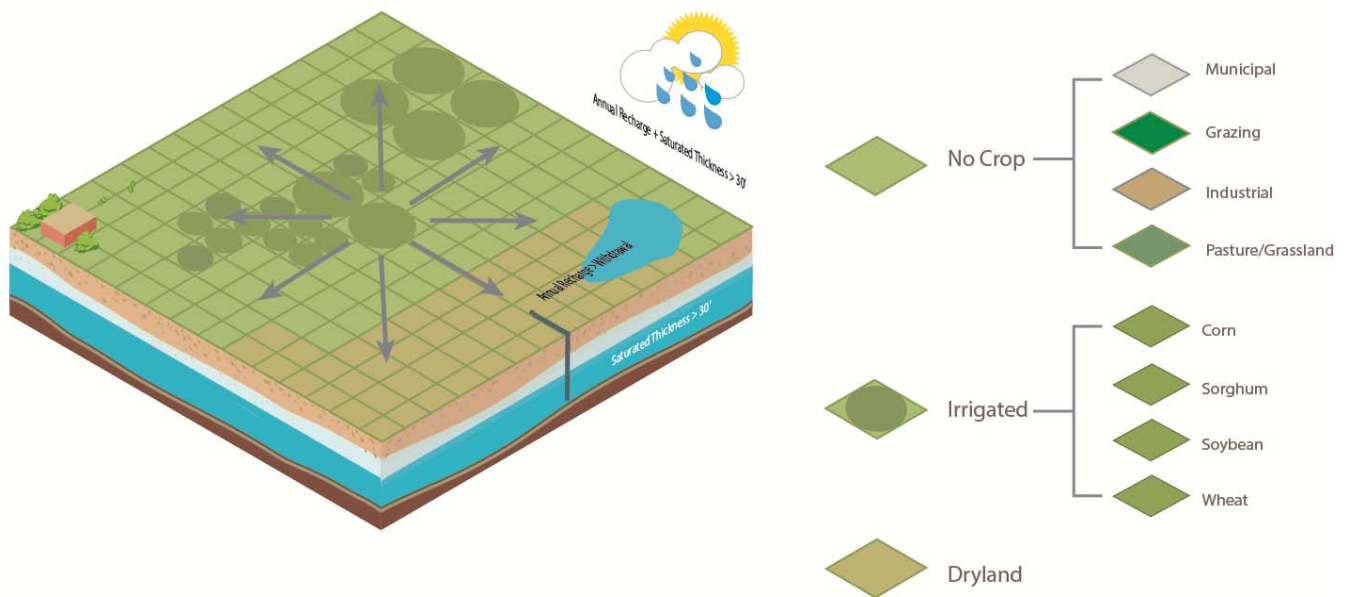


Figure 3.13 Diagram of CA Model Land Use Transition Rules

Illustrated by Author

CA Model Simulation Results

The initial results of the model aim to answer where irrigated crops would be grown in the High Plains Aquifer area? Figure 3.14 illustrates the areas in blue which exceed 30 feet of saturated thickness in the aquifer for irrigated crops. Red indicates areas that have less than 30 feet of saturated thickness as of 2006-2009 average saturated thickness. For each year of the simulation the aquifer saturated thickness was reduced by 1.5 feet, or the average decline in the aquifer on an annual basis. Again these results will eventually represent the results of the hydrologic model. The 1.5 foot annual reduction was calculated for each time step using a simple arithmetic equation in ArcGIS Spatial Analyst and Python where 1.5 feet was subtracted from the total saturated thickness surface obtained from the Kansas Geological Survey for Kansas saturated thickness estimates between 2006 and 2009. The results indicate an annual decrease in irrigated land use area, or said differently, the results indicate an annual transition in land use from irrigated land to another use as water levels decline.

The next step in the transition rules begin to determine the distribution of land use based on the required water availability for each crop type. The conditional statements provide a simple means of answering where the four crops would be grown in the irrigated land use areas of the aquifer region? The conditional statements indicate the amount of water in saturated thickness assumed for this proof of concept to be required to grow the crop as follows:

- 1) Corn > 34 feet of saturated thickness
- 2) Sorghum > 33 feet of saturated thickness
- 3) Soybean > 32 feet of saturated thickness
- 4) Wheat > 31 saturated thickness

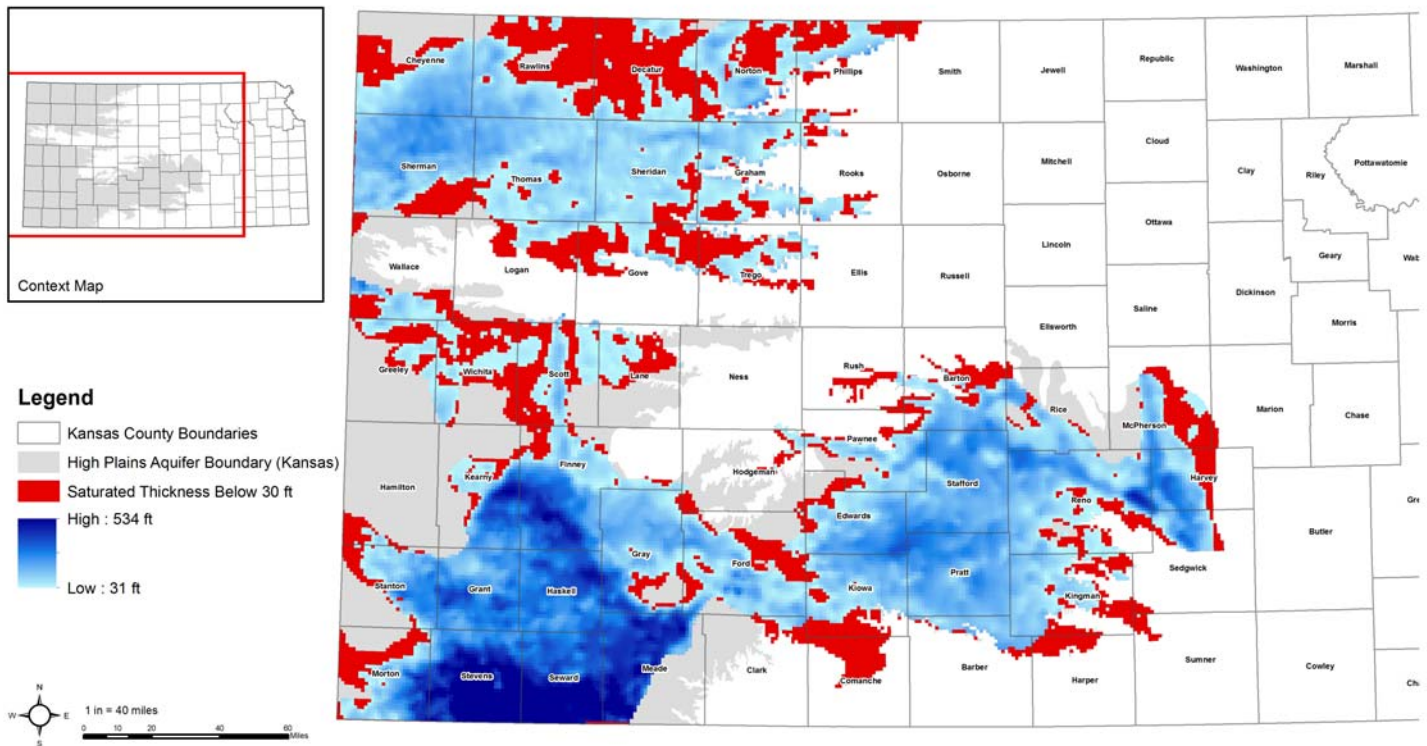


Figure 3.14 Map of Saturated Thickness that Met Minimum Required Threshold of 30 Feet

Data source: USGS & KS DASC

Please again note that each time step is an annual step, and all variables used as inputs were generated at the 56 meter cell size matching the resolution of the cropland data layer. Also note that the updated iterations of cells are based on the state of the neighborhood defined using focal statistics. The output raster from one iteration or transition rule calculation is used as input for the next calculation.

Figure 3.15 shows the existing irrigated land use on an area of thinner saturated thickness in South Central Kansas as indicated from the digitized center pivot mask of the CDL for 2006.

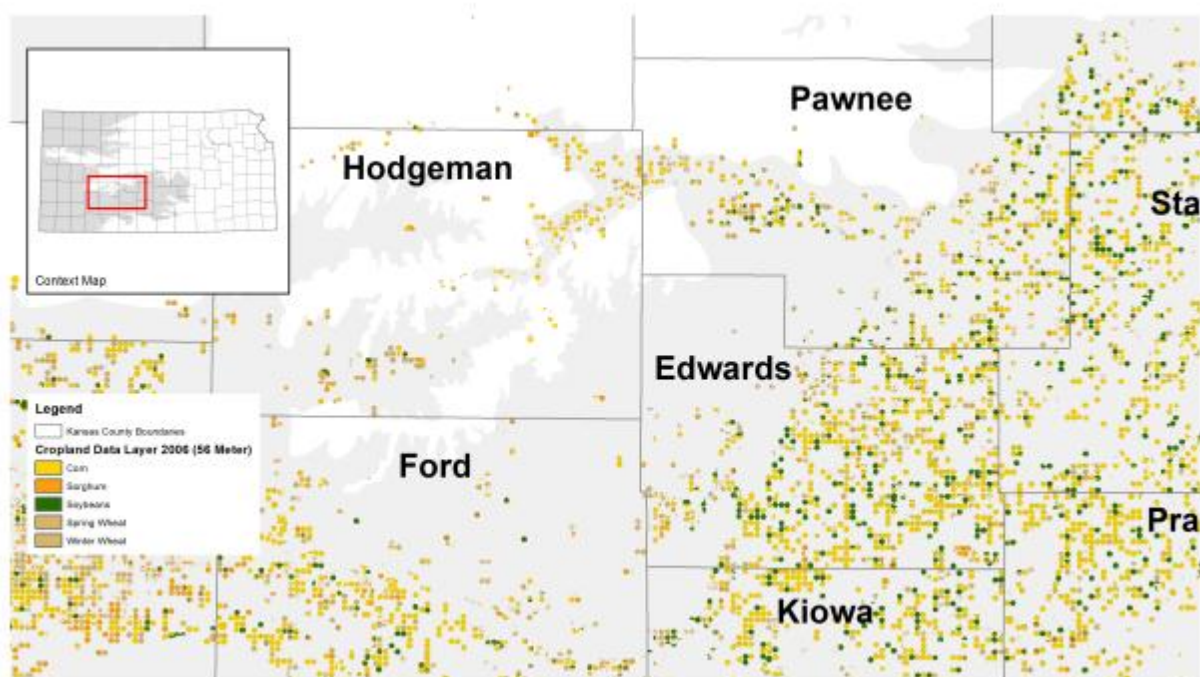


Figure 3.15 Existing Irrigated Land Use by CDL Crop Type in 2006 in South Central Kansas
Data source: USDA NRCS & KS DASC

Figure 3.16 illustrates results of the first calculation of the CA algorithm based on the minimum required threshold of saturated thickness mentioned previously to stay irrigated after a 1.5 foot reduction in each saturated thickness cell value. The result indicates that irrigated land located on the edge or fringe of the aquifer, which is the thinnest part of the formation, is the first irrigated land transitioned, or removed. This result indicates the model is working to transition land use based on water availability as illustrated by the change from yellow and green irrigated areas to grey indicating non-irrigated land.

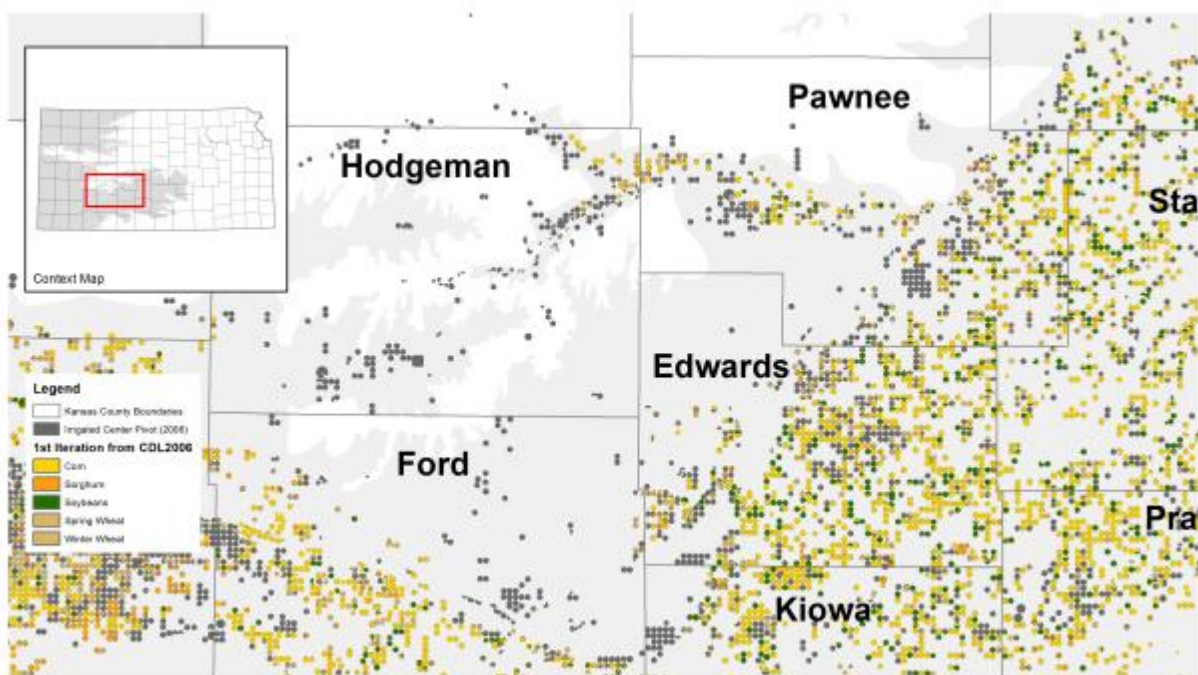


Figure 3.16 First CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes

Data source: USDA NRCS & KS DASC

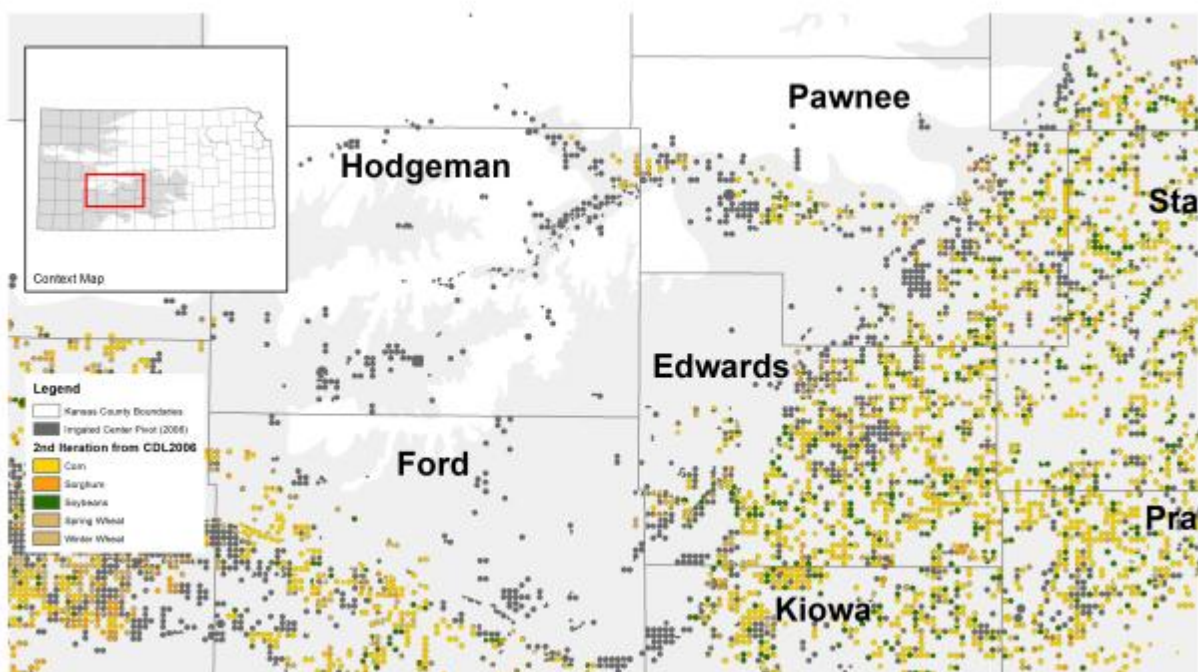


Figure 3.17 Second CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes

Data source: USDA NRCS & KS DASC

Note the changes after another uniform 1.5 foot decrease in each saturated thickness input cell value used for proof of concept. Gray dots represent changes from irrigated land use which removes them from a crop cover allocation. Colored dots are irrigated farms which received one of the four crop types based on the condition statements for each crop type. Also note that changes for irrigated farmland are somewhat less noticeable because most of the irrigated land met the minimum required saturated thickness in the previous iteration. However land use and land cover changes were still present in this iteration (Figure 3.17).

Figure 3.18 is the fifth iteration of the CA model with the saturated thickness uniformly decreased by another 1.5 feet, for a total of 7.5 feet (1.5 feet annually x 5 years) since the model began running. The changes in irrigated land use are more significant after five iterations as shown. Note the increase in grey area in, or decrease in irrigated land from the edge of the aquifer in Edwards County and the decrease in corn coverage after 5 iterations across the area shown.

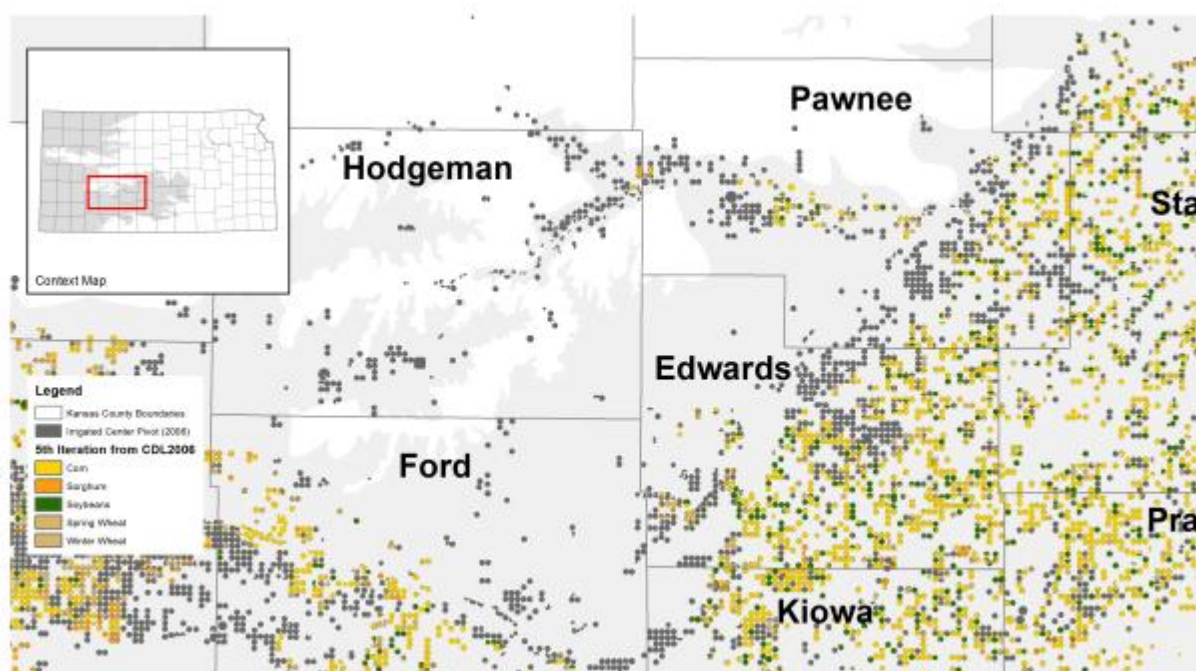


Figure 3.18 Fifth CA Model Iteration Illustrating Irrigated Land Use and Crop Cover Changes

Data source: USDA NRCS & KS DASC

As presented, for each specified iteration the model analyzes each cell using the neighborhood parameters to determine land use then land cover. The count of each cells for each CA model iteration are displayed in the attribute table based on crop types. The bar chart, Figure 3.19 shows the declining of acreage in each iteration. These results indicate a somewhat linear decrease in acreage from the original 2006 irrigated cropland data set after each model iteration. Overall the results of five iterations of this proof of concept CA model indicates about 25 percent loss of irrigated crop areas of the four major crop types spatially occurring most often in areas at the edge of the mapped aquifer formation.

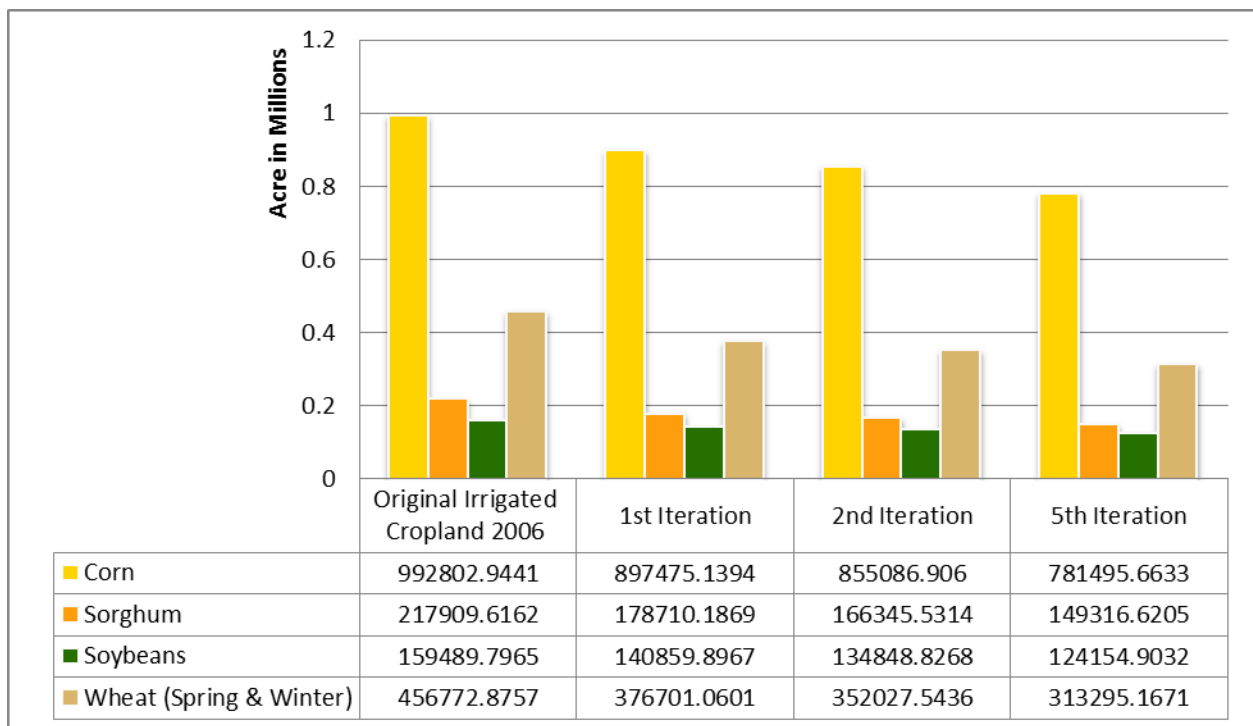


Figure 3.19 Comparison of CA Model Cell Acreage from First, Second and Fifth Iterations

Chapter 4 - Conclusions

The Cellular Automata approach developed herein has the capacity to simulate irrigated land use changes and crop cover type based on water availability and crop water requirements. Although the input parameter for the saturated thickness variable was a general average, and the saturated thickness required for a certain crop type assumed, the proof of concept indicates the potential in this coupled model GIS and geodatabase CA methodology. While validation and calibration of the CA model is limited due to the lack of longitudinal data sets in the Crop Land Data and center pivot data sets, the patterns are not atypical of other models of total irrigated land use and crop type changes.

When the input variables from the coupled multi-disciplinary models become available they can easily be added into the geodatabase implementing the ODM standard and OpenMI and consumed as raster inputs in this CA model. These results, especially for the mathematically modeled annual variation in the aquifer saturated thickness and crop type water requirements modeled in EPIC should greatly improve the accuracy of the results when compared to on-ground conditions going forward.

Most importantly the graphical display of the spatial temporal results in map form afforded by using ArcGIS aids users understanding of the complex inter-related issues of the aquifer dependent landscape. The spatial mapping helps communicate areas that should be considered or prioritized in land use land cover management and policy strategies. The patterns also provide a clear picture of where significant changes in local economy are likely to occur in the future based on transitions from irrigated to non-irrigated land uses.

The proposed method for validating the CA model simulation results once all variables are received from the interdisciplinary model is using a spatial random sample method comparing model generated results and the National Land Cover Dataset from USGS and Kansas Land Cover Dataset or other field tests or producer provided records.

The objective of this research was to simulate changes in the irrigated land use in the Kansas High Plains aquifer area using CA model. Tightly coupling the CA land use land cover model in the OpenMI multi-disciplinary model framework is a future goal likely using Python scripting. The influence of additional driving factors should also be assessed after receiving variables and outputs from other multi-disciplinary models during the integration process.

Please note this project is the first attempt for the Author to use a scripting language, as well as model simulation using ArcGIS. While there were, and are still, many obstacles much has been learned and a reasonable approach demonstrated. Although this CA model seems overly simple the concept and framework seem very applicable. The author intends to continue developing the model and once all variable are input into the model and the process streamlined, the plan is to create a custom tool box usable by producers and decision makers to simulate different scenarios.

In closing, the importance of this research became apparent during the record drought of 2012 now documented as one of the hottest and driest summers on record for the High Plains region. In response to the drought conditions maximum pumping of groundwater occurred causing a rapid depletion of the aquifer in some areas. The linked consequences of such issues can be modeled as demonstrated here to help make decisions under such difficult circumstances. This is critical given the finite nature of the aquifer and vital for local farmers and communities to understand the short and long term issues and short and long term sustainability options. For example the USDA estimated in June 2012 the price of corn rose 34 percent as a result of U.S. crop losses due to the drought (United States Department of Agriculture, 2012). This impact would indicate a high futures price for corn going forward which could earn a handsome profit, however corn is the most water intensive crop grown in the region. If all producers decided to grown corn based on the price incentive, imagine the consequence on water. Herein lies the value in models and simulation to be able to allow local farmers and decision makers to visually see the spatial temporal linkages between the aquifer resource and agriculture production options.

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