Distribution, Proliferation and Significance of Small Impoundments in Kansas

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ABSTRACT

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The proliferation of small impoundments across the global and US landscape represents a widespread and little understood man-made environmental change. Small impoundments in the conterminous US number at least 2.6 million and cover a combined area comparable to the large, more studied and understood reservoirs, making their aggregate biogeochemical impact likely significant. Until recently, most water body inventories greatly underestimated the occurrence and extent of ponds and small reservoirs in the US leading researchers to either ignore or underestimate their landscape significance. Little research has attempted to understand either the spatial occurrence or impact of constructed ponds to any given region. Because Kansas has a high density of constructed ponds and a complicated human history of small dam building in an originally lakeless region, the state is a good candidate for understanding the regional history, occurrences, and impacts of small impoundments. This thesis inventories the small impoundments of Kansas while describing their occurrence, spatial distribution, and possible significance in terms of stream hydrology and ecology. Further, this research attempts to understand the cause for continued impoundment proliferation by quantifying the change in impoundment occurrence and use over a 60-year period in Douglas County, Kansas.

According to this research, Kansas contains 241,295 small impoundments that cover a surface area of 74,880 ha (288 mi^2) and store roughly 1,299,483 acre/feet of water. While the small impoundments in Kansas dominate both in occurrence and surface area, the medium to

large reservoirs in the state still contain 83.8% of the surface water storage. In terms of hydrologic and stream ecological impacts, small impoundments have impounded Kansas streams 80,862 times, converting 7,498 kilometers of stream habitat to lacustrine. While stock water ponds were overwhelmingly dominant in 1950's, by 2013 only 41% were used for the purposes of maintaining stock water. Impoundment uses appear to have shifted away from stock water ponds to more recreational and aesthetic ponds that are now the dominant purpose of at least 26.9% of impoundments. Recreation and aesthetic purposes may be driving much of the current proliferation of small impoundments.

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Introduction

Introduction

Small impoundments are diminutive in size but represent a widespread anthropogenic change to the landscape. For this research, a small impoundment is defined in accordance with the American Fisheries Society's definition of "a small impoundment" or "artificial pond" as any man-made water body under 40 hectares in surface area (Willis & Neal, 2012). Artificial water bodies larger than 40 hectares in surface area are referred to as large impoundments or reservoirs. Small impoundments appear in large concentrations on every continent, especially North America. The global number of small (100-1000m^2) ponds and lakes could be as high as 3.2 billion and the accumulative spatial extent (surface area) of ponds and small lakes is thought to rival that of the world's large and well documented lakes and reservoirs (Downing, 2006). This high global occurrence and spatial extent includes both naturally occurring lakes and man-made impoundments but underscores the global significance of small water bodies. Such a numerous occurrence of small water bodies in the global landscape means any associated impacts (positive or negative) of these features happen on a widespread and global-scale.

In the last 150 years, we have built a great number of small impoundments across the US landscape and these impoundments have proliferated because of their value to the public and private sectors. Swingle (1970) roughly estimated the number of small impoundments increased from just 20,000 in 1934 to over 2 million in 1965. Several decades later, Smith, Renwick, Bartley, and Buddemeier (2002) estimated the occurrence of 2.6 million small artificial impoundments spanning the contiguous US, and Renwick, Smith, Bartley, and Buddemeier (2005) suggested the number could be closer to 9 million.

The purposes for impoundment construction vary depending on local needs. Large impoundments are typically built for flood control, public drinking water, recreation, power generation and irrigation. Small impoundments are usually associated with rural areas and used for agriculture, recreation, aesthetic value, and watershed protection (Boothby, 1999). As with large reservoirs, small impoundments have become a critical component in the US surface water infrastructure in terms of numbers and utility. Their functional role and ubiquity means that they have become inextricably linked in the US agricultural and economic landscape and will continue to persist and proliferate.

Until recently, research in the water sciences has mostly ignored all small water bodies, including small impoundments, as significant landscape features. Early 20th century attempts to catalogue the world's freshwater supply excluded small water bodies and led to the pervasive idea that the world's large lakes and reservoirs covered more surface area and were more research-worthy than small lakes and reservoirs (J. A. Downing et al., 2006). This assumption led to decades of subsequent research partial to large water bodies, generally ignoring small water bodies in the landscape (J. A. Downing, 2010). The prevailing scientific attitude that underreports small water bodies means we have yet to fully understand their significance. This research shifts focus away from the large, better understood water bodies to the spatial characteristics and impact of these small landscape features.

The Biogeochemical and Ecological Impact of Small Impoundments

Impoundments interrupt the natural flow of water and suspended material across the terrain, impacting the biogeochemical regimes of their local surroundings. Biogeochemical cycling includes hydrologic, climatic, chemical, and ecological cycling regimes of any given area. The slowing of water and transported material by the dam changes rates of evaporation, ground water retention, and alters the speed and location of aquatic chemical reactions (Brainard & Fairchild, 2012; Chin, Laurencio, & Martinez, 2008; G. Winfield Fairchild & Velinsky, 2006; Graf, 1999). Ecologically, the damming of streams and rivers both fragments riverine aquatic habitat and increases lacustrine aquatic habitat (Knutson et al., 2004; Markwell & Fellows, 2008). Because small impoundments influence the hydrology, chemistry, and biology of an area, these numerous and man-made features represent a major player in our interaction with the environment. This anthropogenic impact may be especially true in Kansas, with its relatively high density of small impoundments.

Impoundments affect the climate by storing or releasing carbon. Carbon, an important greenhouse gas, enters the lake system through water-transported sediment (sedimentation). Impoundments process the carbon through atmospheric interaction, store it on the lake bottom, or transport it downstream. Most impoundments are sources of both atmospheric carbon dioxide (CO_2) and methane (CH_4), both well documented greenhouse gases (J. J. Cole, Caraco, Kling, & Kratz, 1994). Of the carbon that flows into a lake, at least 42% is released through the atmosphere, ten percent is deposited and stored on the lake bottom, and the rest makes it way to storage or release in the ocean (J. Cole et al., 2007). Because the extent and occurrence of small impoundments are poorly understood, their impact on the carbon budget may be understated. Also, impoundments as influencers of the regional carbon budget may be particularly important to a region such as Kansas where high erosion rates have caused widespread sediment deposition in the region’s reservoirs (deNoyelles & Jakubauskas, 2008).

Impoundments trap and store sediment, thus affecting regional sedimentation. Sedimentation refers to the deposition of eroded sediments in river beds, lakes, reservoirs, or the ocean floor. Dams reduce incoming water velocity, creating a means for sediment to settle on the reservoir bottom. Many artificial reservoirs in an area alter the natural flow of sediment through the entire riverine system. For example, the Gulf of California has seen an order of magnitude drop in sediment due to impoundments in the Colorado River Basin (Meade, Yuzyk, & Day, 1990). The trap efficiency, or sediment retention, of reservoirs depends on several factors including regional soil erosion, hydrology, and size of watershed. Individually, ponds can accrue 81 to 98% of all incoming sediments (Dendy, 1974). Regional estimates of sediment retention by small reservoirs are difficult to calculate because individual retention rate information is sparsely available in sufficiently high detail (Verstraeten & Poesen, 2000), but crude regional estimates show small impoundments retain about half of the sediments of all reservoirs in the US (Smith et al., 2002). Kansas has high erosion rates compared to other areas, meaning our numerous small impoundments may retain relatively more sediment. Sediment deposition in small impoundments may actually be beneficial by keeping sediment out of larger, more expensive reservoirs that supply water for public use.

Small impoundments can negatively affect down-stream biodiversity by changing hydro-chemical regimes, severing hydro-connectivity, and facilitating the spread of invasive species. The negative impact is especially true for 'in-line' impoundments which directly dam a stream, as opposed to 'off-line' impoundments that do not directly impede stream flow. Altered flow regimes by dams negatively affect biodiversity by changing the physical habitat downstream, impacting species natural cycles that rely on seasonal flow (Bunn & Arthington, 2002), often favoring an estimated 1,000 aquatic invasive species that can thrive in the unbalanced conditions (Rahel, 2002). For the native species that migrate along stream corridors, dams can fragment the stream, creating an impediment to their movement (Johnson, Olden, & Vander Zanden, 2008).

However, this same mechanism of fragmentation by dams can halt the spread of invasive species, protecting upstream biodiversity (Jackson & Pringle, 2010). In some areas, the retention of water and sediment by impoundments decrease and replace downstream wetlands, raising some concern about habitat loss for wetland endemic species (Tiner, 1989). Aside from retaining sediment normally deposited in wetlands, the numerous off-line impoundments supply water-associated habitat and may actually have a net positive impact on biodiversity.

Small impoundments may increase regional biodiversity, especially for species reliant on lentic-type habitat. The increase in biodiversity appears in and immediately surrounding the pool. In some areas, the low fish biomass and high richness and abundance of aquatic plants in small water bodies increases biodiversity of aquatic birds, amphibians and invertebrates (Scheffer et al., 2006). Compared to large lakes, small water bodies contain more species of most taxa per unit area (Dodson, Arnott, & Cottingham, 2000), suggesting that an area dominated by many small ponds will have a higher biodiversity than an area dominated by large reservoirs (in terms of spatial extent). The proliferation of water bodies in an area deficient in surface water increases lentic aquatic habitat connectivity (Gee, Smith, Lee, & Griffiths, 1997). This seems especially true for amphibians, which migrate over the terrestrial environment to seek new aquatic habitat (Griffiths, 1998). Because intensive agriculture in the Midwest has reduced much biodiversity and habitat connectivity, the creation of ponds in an area lacking adequate habitat may actually alter an ecosystem in favor of more biodiversity by providing lentic habitat and migration pathways

Small impoundments appear to improve overall stream chemistry, especially in agriculturally intensive areas. Because impoundments are often dispersed in headwater areas and built for agricultural purposes, they have direct hydrological interaction with poor water quality associated with the runoff from agricultural landscapes. The slowing of water by ponds creates radiant heating and promotes primary production, allowing for these chemical alterations to occur (Baxter, 1977). Impoundments help reduce inflow concentrations of nitrate and phosphate and increase pH and levels of dissolved oxygen (G. Winfield Fairchild & Velinsky, 2006). On a microbial level, ponds have been found to reduce concentrations of enterococci and Escherichia coli bacteria, consequences of cattle production (Fisher et al., 2000). The water chemistry changes affect downstream biodiversity directly through removing toxicity or indirectly by altering food webs. The net positive impact of ponds manifests itself not only as a net increase in regional biodiversity, but as an ecosystem service to improve water conditions for human use.

Regional Impoundment Inventories

Small impoundments have regional and global significance when their accumulative impact is considered. The global or regional importance of an ecosystem is a function of both the intensity of biogeochemical processes within the system and the accumulated spatial extent of that system (J.A. Downing, 2009). Knowing the extent and function of an ecosystem is the first part in understanding its impact on a larger region. For example, we can only extrapolate individual sedimentation, carbon storage, or ecological impacts by knowing the true number and extent of impoundments within a region. We know to a certain degree that individual ponds influence the biogeochemistry of the immediate surroundings and it is likely that their impact is regionally or even globally significant. Unfortunately, we currently know very little about the spatial distribution and characteristics of small water bodies, making it difficult to quantify their regional or global biogeochemical impacts to the landscape.

The US lacks a spatial dataset that accurately represents small water bodies. An appropriate spatial inventory of small water bodies would include their location and geometry at a resolution appropriate for their diminutive size. Historically, large-scale lake and reservoir mapping efforts lacked the technology, funding, time, and motivation to accurately inventory the location of small water bodies. One of the first and most cited national spatial inventories of water bodies, the National Inventory of Dams (NID) published in 1999, quantified the geographic extent and intensity of dams for the first time, motivating many researchers to study the cumulative and large-scale impact of reservoirs in the US (Graf, 1999). Because the NID only includes larger federally registered dams (~74,000), it leaves out most small impoundments. Later published databases, such as the US Geological Survey's National Land Cover Dataset (NLCD), the US Census Bureau's inventory of inland water bodies, and the original USGS National Hydrography Dataset (NHD) also underrepresent small water bodies (Smith et al., 2002). In Kansas, Buddemeier (2004) found the two main water body databases, the Kansas Surface Water Database (KSWD) and the Surface Water Information Management System (SWIMS) only represented 1 and 3% of small water bodies, respectively. Our understanding of the accumulative significance of small water bodies in this region (the US) has been deficient because we neither fully understand nor are able represent their spatial characteristics. Fortunately, technology and motivation have substantially improved in recent years, creating the means for a more representative small water body spatial dataset across the United States.

The 2007 upgrade to the National Hydrography Dataset improved the inventory of small impoundments and lakes in the US. The "high resolution" upgrade, also known as the High Resolution National Hydrography Dataset Plus (HR NHD) was the result of cooperation between the USGS, the Environmental Protection Agency, the National Forest Service, and state and local agencies (Simley, 2003). The new standard improved the data resolution from the original 1:100,000 scale to 1:24,000 (1:12,000 in some areas), increasing the number of small water bodies represented (US Geological Survey, 2008). The water body source data of the HR NHD comes from digitized 1:12,000 USGS Digital Line Graphs (DLGs) and supplemental Digital Orthophoto Quarter Quads (DOQQs). Also, the HR NHD allows continuous database updates by users who can add newly created impoundments or correct existing features. For the first time we have an inventory with the capability and resolution standard necessary to analyze small water bodies across the US landscape. With some improvement the HR NHD allows for meaningful regional spatial analysis on small water bodies. To date, only a few studies have utilized this database for landscape or regional studies of small impoundments (McDonald, Rover, Stets, & Striegel, 2012; Willis & Neal, 2012). In this thesis, the HR NHD is the primary inventory used to create a composite dataset representing the small impoundments of Kansas.

Early History of Small Impoundments in Kansas

"Earth, air and water are fundamental human needs. Kansas has always had her share of good earth as well as plenteous and never-failing supply of air. Not satisfied with these two requisites, popular and insistent demand by the people of the state has resulted in the building of over a hundred lakes in an originally lakeless state."-1946 editor of the Transactions of the Kansas Academy of Science

The Kansas landscape was nearly absent of water bodies of any type before European settlers. Water bodies that existed before the beginning of European immigration in the 1830s were the result of natural formation, which Kansas landscape conditions generally do not favor. Kansas's semi-arid climate and with deep, infiltratable and erodible soils prevent natural water bodies from forming and persisting, with the exclusion of the occasional oxbow, slough, and playa lake. Also, the continuous and gently rolling downhill topography from west to east forces water flow relatively uninhibited, not allowing the formation of lakes either from natural geological dams (e.g. Rocky Mountain lakes) or flat topography (e.g. the Everglades) (Stene, 1946). The current ponds and reservoirs in Kansas are almost entirely the product of human intervention in the landscape. The location of ponds and small reservoirs in Kansas cannot simply be attributed to the natural and often predictable processes that form natural lakes, but more from complex and not well understood human motivations that vary across space and time.

The lack of expansive natural water bodies created the need for artificial water supplies when 19th century settlers populated and developed Kansas. The new incoming population required water for domestic, agricultural and industrial use. The settlers in more arid regions of Kansas especially needed water storage because the streams and rivers, an often used source of water, only had intermittent and unreliable flow. For simplicity, surface water storage, such as impoundments, was the preferred water supply for agricultural and industrial purposes, and sometimes for domestic drinking water. Surface water storage for the cattle industry was ideal because ponds allowed the cattle to disperse over a wider area instead of needing to keep close proximity to a pumped water source (USDA:NRCS, 1997). Railroad companies also built some of the earliest lakes as water supplies for passing trains and often developed these lakes further for local recreation. Crystal Lake (1888) and Santa Fe Lake (pre-1925) are examples of reservoirs built by the railroad industry (Kansas Water Office). Early impoundments built by cattle ranchers and the railroad industry were just the beginning of the human factor that influenced surface water growth in Kansas. As Kansans became thirstier for surface water, government and technology encouraged rapid impoundment development.

By the early 20th century, the state began to support reservoir building for economic improvement, especially from hunting and fishing tourism. Surface water from small and larger impoundments created habitat for waterfowl, big game, and fish, providing the opportunity for revenue from hunting and fishing. In the 1920s, state officials sought to keep Kansas wildlife potential on par with surrounding states, as a means to keep competitive in immigration and outside investment (Kansas State Fish and Game Department, 1924). At the time, Kansas had 384 square miles of surface water (including rivers), while Nebraska and Oklahoma had 712 and 643 square miles of surface water, respectively (Stene, 1946). The state game warden used this relative deficiency to create a sense of economic urgency communicated to the Kansas legislature and county commissioners, who in turn funded public dam building projects (Kansas State Fish and Game Department, 1924). Reservoirs as a means for economic and recreational improvement were such a popular idea that "lakes in every county" was said to be a campaign slogan and soon public funds were allotted for reservoir development throughout the state. In the 1920's, the State opened Kansas's first fish hatchery to provide stock for both public and private ponds (Stene, 1946). The desire to build ponds as a recreational outlet is one of several motivations that spurred the growth of impoundments in Kansas. Also, the influence and incentives provided by the government showcase the influence governing agencies had on impoundment development.

By the 1930's, municipal, county, state, and federal governments were building reservoirs all across the state. Some examples of city and county built lakes are Augusta City (1931), Herington (1922), Lonestar (1939), Gardner City (1937), and Wyandotte County Lakes (1936). In the late 1930s, the Great Depression dried up most local and state financial support for small reservoir development. However, Federal economic booster programs, especially the Civilian Conservation Corps, provided cheap labor and funding for over 130 small to large impoundment projects (e.g. Woodson County Lake) and 38,000 erosion control check dams from

1933-1942 (Merrill, 1981). After the Civilian Conservation Corps, other big federal projects, more focused on flood control and navigation, began to build reservoirs in the state. The US Army Corp of Engineers (USACE), and to a lesser extent the Bureau of Reclamation and Department of Interior, built the large multi-purpose reservoirs that appeared from the 1950s to the 1980s, including Perry, Clinton, Marion and Pomona Reservoirs (Kansas Water Office, 2000). Although most of these federal flood control projects were medium to large reservoirs, they represented dam building as a major public-sanctioned effort and priority during this era. Many of these reservoirs are still functional and continue to influence the landscape.

While governing agencies built impoundments, from small to large, for public use, private land-owners were constructing their own small impoundments at a high rate. Impoundments on private land differ from public reservoirs because landowners are primarily responsible for their development. In terms of occurrence, small privately owned impoundments exhibited the largest increase in water bodies in the mid-20th century. For example, impoundments in the Allen Quadrangle in Kansas increased from 25 in 1941 to 420 in 1976, a 1580 percent rise. The Midland Quadrangle, just north of Lawrence, KS, doubled its number of ponds between 1945 and 1980, from 245 to 499. Douglas County grew from a few dozen impoundments in the 1930s to around 3,300 in 1960 (Hastings & Cross, 1962). These high impoundment growth rates were not unique to Kansas but were also recorded in Ohio and Pennsylvania (Buddemeier, 2004; G.W. Fairchild, Robinson, Brainard, & Coutu, 2012). The thousands of impoumdments built by private landowners were far more numerous and widespread than the ~100 impoundments built for public use. Because of the inconspicous nature of small impoundments on private land, their proliferation across the landscape went relatively unnnoticed compared to the larger, but fewer, publicly developed reservoirs.

In mid-20th century, government incentives, mostly from the Flood Control Act of 1936, encouraged land-owners to construct small to medium sized impoundments in an effort to control flooding and erosion. A "watershed dam" is often the name applied to smaller upland impoundments tasked with flood and erosion control. Federal policy makers during the 1930s and 1940s were motivated by the then-recent Dust Bowl and the Great Mississippi Flood (1927) to implement protection measures against erosion and flooding (Holmes, 1972). Watershed dams built during this era were strategically placed relative to the movement of water and eroded material to prevent damage downstream (Douglas Helms, 1988). Federally-sanctioned impoundments, or watershed dams, were often seen as a less destructive alternative, especially by environmental groups, to the large reservoirs built by the USACE (Holmes, 1979; Kollmorgen, 1953, 1954). The Soil Conservation Service (SCS), later the Natural Resource Conservation Service (NRCS), tasked with implementing federal legislation, provided technical assistance and monies to watershed dams projects. Technical assistance included instruction on dam construction, placement, and maintenance. The SCS also convinced farmers of Dust Bowl-stricken land to convert their cropland to grassland, indirectly causing an increase in livestock-associated ponds (D. Helms, 1990). In the State of Kansas, the 1930s Kansas Emergency Relief Water Conservation Program put hundreds of people to work building 27 medium sized county and state lakes throughout the state, and constructing around 2,900 "farm ponds." With government aid, land-owners could build impoundments to serve personal needs such as water supply or recreation while contributing to downstream erosion and flood control. The dual private and public benefits made the federal and state incentives popular among landowners who used government assistance to build thousands of impoundments across the US.

The post WWII technology and manufacturing boom increased tractor and heavy machinery necessary for land-owners to build impoundments. The earth moving necessary to build small to medium dams required monetary and physical expense, conditions not always available to early Kansas farmers. The wartime increase in technology and production of heavy machinery subsequently caused efficiency increases in farm machinery production (Rasmussen, 1962). For example, the average tractor became more efficient, affordable, and widely available. This allowed farmers to build the dams required for small impoundments with fossil fuel-driven earth movers instead of mules and man power (D. Helms, Economics, & Division, 1992; Stabilization & Service, 1981). This increase in available technology reduced the cost and amount of labor needed to build the dams required for an impoundment. Farmers who previously lacked the means could now build impoundments with less investment, likely leading to an increase in small dam construction.

While the large dam building culture associated with the mid-20th century is mostly over, small impoundments continue to be a dynamic and increasing feature in the landscape. Here, dynamic refers to ponds being both created and destroyed over time and space from natural and man-made causes. Impoundments are created through dam building and lost through sedimentation, eutrophication, and human development. Of areas studied in eastern Kansas, 57% of ponds built in the 1950s disappeared by the year 2000, usually having a lifespan of 10-50 years (Renwick et al., 2005). Small impoundment numbers increased by 1-3% per year between the 1930s and 2000s. In the agriculturally dominated Allen township of Kansas, pond numbers increased roughly 10% per year from 1945 to 1955, while Midland Kansas, a township moving from agriculture to more exurban type development, experienced a steady 11% per year increase from the 1930s to 2000. This fluctuation in small impoundment numbers as the landscape changes means development differs in both time and space. With a long sustained positive small impoundment construction rate, the trend suggests impoundment numbers will continue to increase and overcome pond loss. Therefore, the aggregated biogeochemical impacts of small impoundments will continue to increase in the foreseeable future.

Problem Summary

Because small impoundments in Kansas are the result of human activity and alter the biogeochemical nature of an area, their proliferation makes them a substantial anthropogenic change to the landscape. Therefore, we have a vested interest in inventorying the occurrence of these small landscape features in any given region. Smith et al (2002) was the first major US effort to estimate the occurrence of small impoundments, and later Renwick et al. (2005) used this inventory to approximate their importance to the US sediment budget. However, it is often the case that major efforts in water resources are accomplished at the state or at regional watershed level, creating the need for more detailed analysis on a smaller scale. To date, researchers have mapped and quantified the significance of small impoundments in only two major US regions: Arkansas and the Apalachicola-Chattahoochee-Flint river basin in parts of Florida, Georgia, and Alabama (Chaney, Boyd, & Polioudakis, 2012; Ignatius & Stallins, 2011).

A key to fully grasping any anthropogenic alteration is to not only understand its occurrence and extent, but the factors that create and sustain its proliferation. In the case of small impoundments, the purpose for their construction and the reasons why they are still proliferating has received little attention. Renwick et al. (2005) and G.W. Fairchild et al. (2012) both implicitly suggest that rate of impoundment construction in recent decades appears to be, at least in part, caused by higher population densities in rural areas, a relationship that was not seen before the 1960s. However, it is not clear why more densely populated rural areas have higher impoundment densities and how impoundment use has changed to create this phenomenon. In fact, no analysis has classified impoundments based on their purpose, i.e. beyond the general distinction “pond” or “small impoundment.” Detailing the purpose or use of an impoundment such as stock water pond, watershed impoundment, or recreational use across time would improve our understanding of continued impoundment proliferation.

Understanding the distribution, proliferation and significance of small impoundments is particularly important in the impoundment-dense state of Kansas which suffers from many water quality and quantity issues. With Kansas, we have taken a landscape once remarkably deficient in surface water and created one of the more water-body dense regions in the US (Graf, 1999; McDonald et al., 2012; Smith et al., 2002). Existing water bodies in Kansas, which number over 215,000 are almost entirely the result of human development (Callihan, 2011; Stene, 1946), and their rate of construction is not declining (Renwick, et al. 2005). These issues restrict our ability to use water as a resource for industrial, agricultural and domestic purposes. For example, sediment is quickly filling many medium to large Kansas reservoirs, causing concerns for water storage loss (deNoyelles & Jakubauskas 2008). In terms of quality, monitoring by the Kansas Department of Health and Environment (KDHE 2001) showed that 71% of streams and 91% of reservoirs had some type of water quality impairments, caused by a range of pollutants including pathogens, metals, pesticides, nutrients, and sediment. Small impoundments in Kansas directly and indirectly affect water quality and quantity impairments through biogeochemical interactions and sediment retention (e.g. Dendy, 1974; J. A. Downing, 2010; Foster, 2011; Renwick et al., 2005). Because small impoundments influence the processes that impair water in Kansas, quantifying their development, distribution, and impact can lead to more informed decision making regarding the future of water in the State.

This thesis inventories the small impoundments of Kansas while describing their occurrence, spatial distribution, and possible significance in terms of stream connectivity and habitat alteration. Further, this research attempts to understand the cause for continued impoundment proliferation by quantifying the change in impoundment occurrence and use over a 60-year period in Douglas County, Kansas.

Objectives

In order to understand the distribution, proliferation and significance of small impoundments in Kansas, this research had three main objectives: 1) Inventory the current and historic distribution of small impoundments in Kansas and describe their spatial distribution across the state, 2) Estimate the possible significance of current small impoundments to hydrology, stream connectivity, and habitat alteration, 3) Quantify how impoundment use has changed over time and make inferences regarding the current drivers of impoundment proliferation.

The first and second objectives are addressed in Chapter Two. To create the inventory of current Kansas small impoundments, I compiled and modified three water body datasets: the High Resolution National Hydrography Dataset (HR NHD), water features of the 2005 Kansas Land Cover Patterns, and the National Wetland Inventory. The resulting composite dataset, referred to as the Kansas Small Impoundment Inventory (KSII), was used to map small impoundment spatial distribution across the state, compare this distribution to a 1936 record of small impoundments, and estimate total water storage and surface area of small impoundments in the state. Further, the KSII was used in conjunction with a modified NHD Flowline dataset to measure the number and type of streams that are impounded and calculate the original length of stream habitat converted to lacustrine habitat.

Chapter Three addresses the third objective and in doing so answers the questions: 1) what is the current number and surface area of impoundments in Douglas County, Kansas and how has this changed from the 1950s and 2) has the use of small impoundments changed since the 1950s and how has this possible change influenced their recent proliferation? To assess the change in use of small impoundments over time, I compared the current inventory of Douglas County small impoundments and their use, derived from a combination of road-side surveying and aerial imagery interpretation, to a similar study that inventoried the occurrence and purpose of small impoundments in the county in 1954-1955 (Hastings & Cross, 1962).

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Chapter II

The Current and Historic Distribution and Significance of Small Impoundments in Kansas

Introduction

A considerable amount of attention has been paid to the hydrologic and biogeochemical influence of large reservoirs. The visibility and obvious hydrologic influence of large reservoirs and lakes led to decades of research that mostly ignored smaller water bodies (J. Downing et al., 2006; J. A. Downing, 2010). With the focus on larger reservoirs, we have some understanding of their impact on regional and global water storage/loss, sedimentation rates, chemical cycling, and riverine connectivity (Chao, 1995; Graf, 1999; Heppner, 2007).We lack this same knowledge in regard to small impoundments (<40 ha of surface area), which appear with much greater frequency across the landscape.(J. Downing et al., 2006). Only recently have researchers started to recognize the possible significance of small impoundments, especially to regional and global biogeochemical cycles and habitat connectivity (J. A. Downing, 2010; Renwick, Smith, Bartley, & Buddemeier, 2005; Smith, Renwick, Bartley, & Buddemeier, 2002). The research here continues the shift in focus away from the large, better understood water bodies to ponds and small impoundments that occur with high frequency in the landscape.

In the past 100 years we have built a great number of small impoundments across the US landscape that proliferated because of their value to the public and private sectors. Swingle (1970) estimated the number of small impoundments increased from just 20,000 in 1934 to over 2 million in 1965. More recently, Smith et al. (2002) suggested that the US contains at least 2.6 million artificial ponds. The purposes for impoundment construction vary depending on local needs, but all rely on their ability to store water. We typically build large impoundments for flood control, public drinking water, recreation, power generation and irrigation. Ponds or small impoundments (< 40 ha) are usually associated with rural areas and used for agriculture, recreation, aesthetic value, and watershed protection (Boothby, 1999). As with large reservoirs, small impoundments have become a critical component in the US surface water infrastructure in terms of numbers and utility. Their functional role and ubiquity means that they have become inextricably linked in the US agricultural and economic landscape. It appears this importance is likely to increase as studies in Kansas, Ohio, and Pennsylvania indicate that impoundments are continuously proliferating (G.W. Fairchild, Robinson, Brainard, & Coutu, 2012; Renwick et al., 2005).

Small impoundments are diminutive in size, yet still impact the landscape by changing the biogeochemical regimes of their local surroundings. Small impoundments interrupt the natural flow of water and associated suspended material across terrain. The slowing of water and transported material changes rates of evaporation, ground water retention, and alters speed and location of aquatic chemical reactions (Chin, Laurencio, & Martinez, 2008; G. Winfield Fairchild & Velinsky, 2006; Graf, 1999; Verstraeten & Poesen, 2000). Individual impoundments, via reduced flow velocity, can accrue 81 to 98% of all incoming sediments (Dendy, 1974). Climatically, most lakes and reservoirs are sources of gaseous carbon dioxide (CO_2) and methane (CH_4), both well-known greenhouse gases (Cole, Caraco, Kling, & Kratz, 1994). Ecologically, the damming of streams and rivers both fragments riverine aquatic habitat and increases lacustrine aquatic habitat (Knutson et al., 2004; Markwell & Fellows, 2008). Because global or regional importance of an ecosystem is a function of both the intensity of biogeochemical processes within the system and the accumulated spatial extent of that system

(J.A. Downing, 2009), we must not just consider ponds as individual systems but as parts of a greater network. Knowing the extent and function of the ecosystem is the first component in understanding its impact on a larger region. Unfortunately, we have historically known very little about the true spatial extent and characteristics of small impoundments, making it difficult to quantify their regional and global importance.

Because small impoundments are the result of human activity and alter biogeochemical cycles on the local and regional level, their widespread 20th century proliferation makes them a substantial anthropogenic change to the landscape. Therefore, we have a vested interest in inventorying the occurrence of these small landscape features in any given region. This is especially the case with small, privately owned impoundments that are often constructed with the highest frequency but are typically not regulated, inventoried or monitored. Smith et al. (2002) was the first major US effort to estimate the occurrence of small impoundments, followed by Renwick et al. (2005), who used this inventory to approximate their importance to the US sediment budget. However, it is often the case that major efforts in water resource management happen at the state or at regional watershed level, not national, creating the need for detailed analysis on a smaller scale. To date, researchers have mapped and quantified the significance of small impoundments in only two major US regions: Arkansas and the Apalachicola-Chattahoochee-Flint river basin in parts of Florida, Georgia, and Alabama (Chaney, Boyd, & Polioudakis, 2012; Ignatius & Stallins, 2011).

Kansas currently faces water quantity and quality problems from drought, sedimentation, and pollution. Diminished water quality and quantity is problematic for regional habitat, industrial water use, and public drinking water. Recent and prolonged drought is creating pressure on the state’s surface water supply in both streams and reservoirs, causing water shortages in the hardest hit areas (Kansas Water Authority, 2012) . Climate models project added pressure on Kansas's water supply in the next several decades due to higher evaporation rates without a corresponding precipitation increase (Brunsell, Jones, Jackson, & Feddema, 2010). Sedimentation, from erosion, is filling Kansas's water supply reservoirs, also causing concerns for water storage loss. For example, two large water supply reservoirs, Tuttle Creek and John Redmond, have lost more than 40 percent of their storage capacity due to sedimentation (deNoyelles & Jakubauskas 2008). Point and non-point sources of pollution have impaired, to some degree, the water quality of 71% of streams and 91% of large reservoirs (Kansas Department of Health Environment, 2010). Small impoundments in Kansas directly and indirectly affect water quality and quantity through biogeochemical interactions and sediment retention. Because small impoundments influence the processes that impair water in Kansas, quantifying their development, distribution, and overall impact can lead to more informed decision making regarding the future of water in the State. No research specific to the state has adequately mapped the current distribution of small impoundments or estimated their biogeochemical significance.

This research considers a large region with a high concentration of small impoundments (Kansas) and quantifies the occurrence, spatial distribution, proliferation over time, and estimates their significance in terms of hydrology and stream fragmentation. Through the creation of a spatial inventory of small impoundments, this research answers the following questions: What is the current inventory and spatial distribution of small impoundments in Kansas? How has the occurrence and spatial distribution changed over time (1936-2012)? What is the significance of Kansas small impoundments in terms of stream connectivity and habitat alteration?

Methodology

Creation of the Kansas Small Impoundment Inventory (KSII)

In the literature, artificial pond, small impoundment, and small reservoir are often used interchangeably with no clear distinction on how class sizes are defined. For this research, a small impoundment is defined in accordance to American Fisheries Society as any man-made water body under 40 hectares in surface area (Willis & Neal, 2012). Any artificial water body larger than 40 hectares in surface area is referred to as a large impoundment or reservoir. Also, while most of the impoundments, or artificial ponds, in Kansas are embankment style ponds that use a dam to collect overland water flow, this research also includes levee and excavated ponds.

To inventory small impoundments, this research assembled, modified, and combined disparate datasets to create a composite dataset of impoundments less than 40 ha. The decision to use a composite dataset, as compared to deriving one automatically from remotely-sensed imagery, was a combination of time/labor and spatial accuracy considerations. After comparing the results of several studies that used either methodology (Buddemeier, 2004; Chaney et al., 2012; Ignatius & Stallins, 2011), it was decided a composite dataset, using up-to-date inventories, had better potential to account for the very small impoundments (< 1 ha) than current remote sensing methods (Buddemeier, 2004). The methods employed to create this composite dataset for Kansas is similar to the work of Ignatius and Stallins (2011), who used a similar approach for a large watershed in the southeastern U.S. The process used here is composed of 5 major steps: 1) Prepare, process and merge datasets 2) remove natural water bodies 3) manually review 4) add attributes 5) perform accuracy assessment (Figure 1).

The composite inventory, referred to as the Kansas Small Impoundment Inventory (KSII), is comprised of three datasets: the USGS High Resolution National Hydrography Dataset+ (HR

NHD), US Fish and Wildlife Service's National Wetlands Inventory (NWI), and the 2005 Kansas Land Cover Patterns (KLCP) level IV map and database, produced by the Kansas Applied Remote Sensing Program (KARS). The characteristics sought for the KSII were fine spatial resolution (sufficient to include small impoundments), up-to-date, and spatially consistent. Individually, no single utilized inventory meets these qualifications, but when merged, the HR NHD+, NWI, and the KLCP combine to produce an inventory that exhibits these characteristics better than any individual dataset with Kansas coverage.

The backbone of the KSII is the HR NHD+, which provides the most accurate spatial and attributed features. To create the HR NHD+, the USGS used 1:24,000 (some areas 1:12,000) Digital Line Graphs (DLG) classified from Digital Orthophoto Quadrangles (DOQs) (Allder & Elassal, 1984). Since the source DLGs were created over several decades, one problem is that impoundments represented were mapped as far back as the 1980s and may no longer exist. To mitigate for potential outdated data, the HR NHD+ allows for the removal and addition of water bodies through crowd-sourced user input. Because the user-sourced updates rely on volunteers, the changes are spatially and temporally inconsistent. Before merging with the other datasets, the HR NHD+ water bodies were extracted and any features > 40 ha in surface area were removed.

The NWI was created through manual interpretation of high-resolution ortho-imagery from the late 1980s (US Fish & Wildlife Service, 1985). The purpose was to map wetlands, but ponds were included and attributed in the assessment. In total, the NWI had ~480,000 polygons in Kansas, mostly classified as wetlands. Many water body features in the NWI are also outdated (before 1990) and the NWI is not frequently updated like the HR NHD+, so deference was given to the HR NHD+. Where intersection occurred between the two datasets, NWI features were removed. Although the NWI is focused on wetlands and is several decades old, the dataset complements the HR NHD+ by providing another source of high resolution water body features.

The NWI required pre-processing before it was merged into the KSII. Features were extracted that were attributed as ‘freshwater ponds’ caused by an impoundment (denoted by an ‘h’ in the attribute field), leaving ~263,000 polygons. Preliminary assessment showed that NWI ponds showed high commission error (~90%) in areas that were cropland in the 2005 KLCP, so any ponds inside 2005 cropland were removed (~6,707 polygons). Any of the remaining features that intersected the HR NHD+ were removed, which left 22,264 pond features from the NWI to be merged into the KSII.

The purpose of using the 2005 KLCP was to include newer ponds that were not included in the HR NHD+ and the NWI. Water bodies in the 2005 KLCP were mapped using Landsat Thematic Mapper (LTM+) with a user’s and producer’s accuracy of 94 and 96%, respectively (Peterson, Whistler, Egbert, & Martinko, 2010). This accuracy assessment also included larger impoundments, so the true accuracy may be less for small (<40 ha in area) impoundments. The KLCP’s purpose is land-use/land-cover and does not distinguish between types of surface water. For the 30m^2 spatial resolution of the LTM imagery, the MMU was ~900m^2, so water bodies below this threshold are not mapped. Due to the propensity of water to dominate Landsat’s sensor pixels, edge pixels or “mixels” along shorelines tend to be classified as water, which overestimates the surface area of water features with a high shoreline to surface area ratio (i.e. small impoundments). To combat this, the ‘simplify’ feature in ArcGIS was used in the raster to vector conversion to convert small vectors into triangles, therefore downsizing their surface area.

Before merging the KLCP water bodies with the HR NHD+, the water bodies were recoded and converted to vector polygons, totaling 153,704 polygons. To remove streams and rivers from the KLCP, the NHD RiverStream polygon was used with a 90m buffer to remove streams and stream-associated lakes and wetlands. This process did not remove all stream-associated features, mostly due to inaccurate stream positioning in the NHD. Much time was spent manually removing water bodies from streams. Also, a preliminary accuracy assessment showed the majority of classified small water bodies inside (<.08 ha) wooded areas were a misclassification due to tree shadow. To remedy this, water bodies < .08 ha in surface area and residing completely inside woodland areas (according to the KLCP), were removed (~6,900 polygons). Finally, any polygons that intersected with water bodies in the HR NHD+ were removed (~90,000 polygons). After the removal of streams, rivers, and intersection with the HR NHD+, ~8422 polygons were left and merged into the KSII.

In the interest of understanding the man-made water bodies of Kansas, known natural lakes were removed by intersecting the data with inventories of playas, oxbows, and wetlands from the Playa Lakes Joint Venture (PLJV) and National Inventory of Wetlands. This removal of natural water bodies is critical for isolating only man-made water bodies. In the NHD in particular, many natural lakes, especially playas and oxbows, were wrongly categorized as reservoirs or not correctly marked as natural lakes. Wetlands were removed through intersection with known wetlands in the NWI, removing ~5,500 water bodies from the KSII. Roughly 6,100 playa lakes were removed using known playas from the PLJV. Although the intersection with the NWI and PLJV removed many natural water bodies, upon initial review it was clear the process missed many features, especially natural water bodies adjacent to higher order streams. As a result, much time was spent manually removing wetlands, oxbows and misidentified streams from near 3^{rd}, 4^{th}, 5^{th}, and 6^{th} order streams.

In the third major step, the KSII underwent a review process where features were manually added or removed using high-resolution imagery for reference. A scale of 1:30,000 was used to review ortho-imagery for the entire state. Missing impoundments discovered in this review were digitized but at a scale more reasonable for delineating the pond perimeter (usually < 1:10,000). NAIP imagery from 2008 and 2011 was used, depending on the surface water conditions of the particular region under review (i.e. if ponds were adequately full from precipitation). No attempt was made to fix the polygons of correctly identified features that were either correct in shape and size but spatially offset (common with the NWI features), or features that had polygon size and shape different from the pond perimeter shown in the imagery. In total, the manual review processes, resulted in the addition of 7,220 impoundments not originally included in KSII and the removal of 13,402 misidentified impoundments. Although this process removed and added several thousand impoundments, because of the small scale used (1:30,000), many impoundments, especially under .5 ha were missed.

1936 Impoundment Inventory

To understand the historical distribution of artificial ponds in Kansas, a 1936 Kansas State Board of Agriculture Division of Water Resources map of ponds (Jones, 1936) was used. This inventory is the only known historically complete (or near complete) inventory of ponds and lakes in Kansas prior to the 1990s. The map was sanctioned by the state's Division of Water Resources in the post-Dust Bowl era, when understanding the state's water resources was a priority. The 1936 inventory of ponds was geo-referenced and the locations of all ponds were digitized.

Accuracy Assessment

The accuracy of the KSII was determined through comparison with a stratified random sampling of manually digitized ponds using 1 m^2 resolution National Agricultural Imagery Program (NAIP) imagery. ArcGIS was used to randomly pick 36, 1:24,000 USGS quadrangles. Sample quadrangles were stratified based on 1:100,000 USGS quadrangles, so 3 sample 24k quads were picked per 100k quad (Figure 2). Two years of NAIP imagery, 2008 and 2012, were used to digitize the 'current' or observed number of ponds in each 24k quad. The near-infrared band in the 2008 NAIP imagery was used to better distinguish water bodies from the surrounding landscape. The combination of NAIP imagery from multiple years was needed, especially in more arid regions of the state. Regional drought can eliminate water storage, making impoundments difficult to detect in these areas during dry periods. Only ponds with standing water, not dry pond basins, were digitized. Both errors of commission (ponds 'predicted' but not observed) and omission (ponds observed but not 'predicted') were recorded for the accuracy assessment. A scale of 1:5000 was used for finding errors of commission and omission.

Impoundment Storage

Estimating total water storage in Kansas ponds is difficult due to lack of bathymetric data for smaller impoundments. The method employed was similar to Ignatius and Stallins (2011), who used 'Normal Storage' taken from the National Inventory of Dams (NID) to compute a regression and extrapolate to other impoundments. In this case, a linear relationship exists between reservoir volume measures (max depth, volume, and mean depth) and surface area (Sawunyama, Senzanje, & Mhizha, 2006). Here, the "Normal Storage" measure from the NID was related to surface area calculated in the KSII. Because reservoir volume not only depends on dam height, but varies depending on regional topography, individual regressions were computed for each of Kansas' physiographic regions (Figure 3)(Table 3) (Wong, Breen, & Somes, 1999).

Point locations in the NID, especially for smaller impoundments, suffer from major positional inaccuracies, therefore NID point locations were manually moved inside corresponding polygons in KSII. A 'spatial join' was used to join the "Normal Storage" field from the NID to the surface area of the KSII, while making sure each physiographic region had a representative number of joined samples. In total, 755 impoundments were joined with the NID (i.e. n = 755). In many joined samples, the impoundment perimeter was re-digitized to better reflect the true surface area. The samples were grouped by physiographic region and imported into the R statistical package for linear regression calculation. For simplicity, two smaller physiographical regions, the Cherokee Lowlands and the Ozark Plateau, were merged into the Osage Cuestas.

The results from this method must be interpreted with caution. First, this method assumes the accuracy of the NID's volume measurements, which are not derived from consistent sources (U.S. Army Corp of Engineers, 2010). Second, because the NID only contains dams that are big enough for state or federal regulation, the samples favored larger impoundments (> .5 ha surface area), differing from the actual distribution of impoundments in Kansas (most < .5 ha). This means the sample distribution of values used to compute the regression is different from the population distribution and is in violation of regression assumptions. However, because bathymetric data is lacking for small impoundments (< 1 ha), this assumption is difficult to meet.

Spatial Distribution

Small impoundment distribution was summarized for the entire state and by region and county. For spatial distribution, impoundments were summarized by county and physiographic region. Both Kansas counties and physiographic regions were joined with impoundment count, surface area, and volume. To understand how annual rainfall impacts the distribution of impoundments in Kansas, a simple correlation was made by relating impoundment count per 24k quad and annual rainfall. SPSS was used to calculate the correlation.

Stream Fragmentation

Impounding a stream has both biogeochemical and ecological impacts through stalling or halting the overland flow of material and water, and fragmenting the stream network (Bunn & Arthington, 2002; G. Winfield Fairchild & Velinsky, 2006). Therefore, quantifying the degree of stream impoundment can give insight into the degree ponds are affecting both stream biogeochemistry and ecological pathways. In this research, the impact of stream impoundment was measured by quantifying the length of stream habitat converted to lacustrine, calculating the distribution of impounded streams by stream order, and inventorying the number of on vs. off-line ponds.

The length of streams impounded is a measure of habitat conversion (and fragmentation) from stream habitat to the lacustrine (i.e., flowing vs. standing water). This was accomplished by intersecting the KSII with the NHD Flowline. This intersection creates a single line, usually from mid-dam to the inlet area of the impoundment. For impoundments placed at the confluence of two streams, the flowlines of both tributaries and the resultant reach are used. The flowlines remaining after the intersection were measured for length and summarized.

To calculate the distribution of impoundments by stream order, the KSII was joined with an augmented version of the NHD flowline that included the Strahler stream order extracted from the Surface Water Information Management System (SWIMS) (Kansas Biological Survey, 2013). Before the spatial join, the augmented NHD Flowline was buffered by 10 meters to accommodate the inherent positional inaccuracy of the stream centerline locations (Bayley, 1995). While buffering helps include stream impoundments where flowline position is inaccurate, it may have included some impoundments within 10 meters of the stream that do not intersect stream flow. In the case where the polygon of an impoundment intersected multiple flowlines, only the highest Strahler order value was joined. Finally, if a feature from the KSII intersected the modified NHD Flowline, the feature was labeled "on-line" and all other features "off-line".

While the NHD is frequently updated and created at a high resolution, the location of streams depicted is often displaced or missing. With the high omission error in the NHD Flowline, especially in 1st order streams, results should be interpreted with caution. Also, NHD streams, or flowlines, are created by calculating the convergent flow inside USGS's Watershed Boundary Dataset (WBD). These WBD's are sourced from various data at disparate resolutions, creating spatial inconsistency. Because of the ambiguous definition of a stream and the fractal nature of stream networks, it is difficult to define stream locations in some areas, especially in headwater areas where flows are intermittent or ephemeral. For the purposes of this research, any NHD Flowline will be considered a stream.

Results & Discussion

Accuracy Assessment

In the 36 quads sampled, the KSII predicted 7808 small impoundments. Of this number, 446 ponds, or 5.7%, were not actually observed in the NAIP imagery (errors of commission). Another 593 ponds, or 7.6%, were observed in the imagery but not exhibited in the KSII (errors of omission). This gives a user's and producer's accuracy of 94.2 and 92.5%, respectively. The total observed impoundments for all sample areas was 7995 ((Predicted - Commission) +

Omission)), giving a predicted over observed accuracy of 98.1%. This high overall accuracy is partly misleading because the number of impoundments omitted from the KSII was similar to the number ponds the KSII incorrectly predicted.

Figure 3 and Table 1 show the accuracy (predicted/observed) for each sample quad. In general, as sample sites move west, the accuracy moves further away from 100%. Many sample quads in western areas exhibited high levels of percentage commission and/or omission error. The reason for low percent accuracy in these areas is twofold: 1) the arid nature of the region makes mapping lakes very difficult, as water frequently is absent in the impoundment basin. The NHD, NWI, and KLCP datasets in the KSII likely all suffered due to difficulty in identifying waterless water bodies through aerial imagery. 2) These areas usually had a low actual impoundment count, so any commission or omission error had an exaggerated impact on the accuracy percentage. For example, one sample quad in the Scott City area had only one observed impoundment and no predicted impoundment. However, because fewer small impoundments existed in the areas with the higher observed/predicted error, there was minimal impact on the overall accuracy.

With an overall accuracy of 98.1%, the KSII is a good tool for understanding relative densities of ponds and calculating total metrics such as volume and surface area for a large region or the state. However, the KSII is less useful for any work that depends on the accuracy of individual features. Because the KSII mostly relies on legacy data, especially with the inclusion of impoundments from the NWI, most of the producer error (8.5%) stemmed from ponds that were once features in the landscape but have since silted in or have been removed. Also, the KLCP created some producer error because, in some areas, concrete, especially along highways, was misclassified as water. The source of the 5.8% user error was nearly all from ponds that were built in the last 20 years or so. While the NHD is often updated by users, ponds are not updated to match the frequency with which they appear on the landscape. Also, because the NHD relies on users, the updates are not spatially or temporally continuous across the state. The inclusion of the 2005 KLCP ameliorated this error to some degree, but failed to identify impoundments that were highly turbid, had little water in 2005, or were too close in size to the minimum mapping unit (MMU) of 900 m^2.

This analysis differs from Ignatius and Stallins (2011) and Chaney et al. (2012) because Kansas ponds, especially in the arid regions of Kansas, are not full perennially and frequently reach capacity only during especially rainy years. This creates complications in pond identification and digitization, as surface area measurements may have been derived from imagery from dry years where pond volume, and therefore, surface area is reduced. This can be somewhat accounted for by using multi-year imagery; however, this project relied primarily on other databases (NHD, NWI, KLCP), which mostly used single year imagery. Because of this, the KSII likely underestimates an impoundment's actual surface area at capacity and may miss some water bodies entirely.

Number, Surface Area and Storage of Small Impoundments

According to the KSII, Kansas contains 241,295 small impoundments, covering a surface area of 74,880 ha (288 mi^2). The size distribution of impoundment surface area is highly positively skewed (Figure 4), with 95.1% (229,621) of ponds having a surface area below 1 ha. Only 393, or 0.1%, are larger than 10 ha (Table 2). While impoundments between 1 and 40 ha only make up ~4.9% of the count, they make up a disproportionate 42% of the total impoundment surface area. Total small impoundment surface area is larger than all of Kansas's

24 large federal reservoirs combined (74,880 vs. ~60,019 ha). In fact, small impoundments have a greater surface area than all 129 reservoirs in Kansas greater than 40 ha (68,288 ha).

In general, size to density distribution of lakes and impoundments is thought to follow the Pareto distribution (J. A. Downing et al., 2006), but this often depends on location and data used for analysis (Frazier & Page, 2000). Here, the distribution closely resembles the Pareto distribution but deviates when impoundment size approaches .05 hectares or less (Figure 4). The reason for this deviation is likely twofold: 1) there is a lower limit to the size of artificial impoundments, i.e. reservoirs begin to lose functionality or usefulness below a certain size and are therefore not constructed 2) the methods employed here might not accurately represent extremely small impoundments, especially if they are too small to be discerned from 1 meter aerial imagery. Beyond the deviation under .05 hectares, the size distribution seen here closely follows documented US and global distributions (Chaney et al., 2012; J. Downing et al., 2006; Ignatius & Stallins, 2011; McDonald, Rover, Stets, & Striegel, 2012; Smith et al., 2002).

Even though small impoundments make up over 99% of total Kansas impoundments in terms of occurrence, they only account for 28.1% of the total reservoir volume in Kansas. Impoundments under 40 ha have a total volume of 1,299,483 acre/feet, while, according to the NID and KWO, reservoirs over 40 ha have a total volume (at normal pool) of 3,312,383 acre/ft. Of the small impoundments, a disproportionate volume, roughly 40%, is contained in the 11,572 impoundments over 1 ha. Therefore, impoundments less than 1 ha, which number 229,621 (or 95.2% of all impoundments), only contain 16.2% of the total reservoir storage in Kansas. Kansas's federal reservoirs only number 24, but contain 2.1 times the volume of water than all 241,295 Kansas small impoundments (Table 2).

While there have been no previous explicit attempts to map all the small impoundments of Kansas, the 241,295 occurrence mapped here is higher than any previous estimates or inventories of total Kansas impoundments. The 1996 Surface Waters Information Management System (SWIMS) database was the most comprehensive digital inventory to date, but only included 12,735 impoundments under 40 ha (Heimann & Krempa, 2011). Similarly low, the last publicly released NID in 2010 contained only 6,087 reservoir locations (U.S. Army Corp of Engineers, 2010). In 2008, deNoyelles & Jakubauskas roughly estimated a total of 120,000 small and large impoundments in Kansas using the water class from the 2005 KLCP. The highest published reservoir count was Willis and Neal (2012), who used the 1:24,000 version of the NHD to document 139,733 ponds for Kansas. Because the number of impoundments mapped here is nearly twice the previous highest estimate, their significance to water managers should be reconsidered. Likewise, the significant underestimation of impoundment numbers has probably caused their impacts on hydrology or total water storage to be understated.

Spatial Distribution

The location of small impoundments exhibits strong spatial dependency throughout the state. Most notable is the continuously increasing gradient of impoundment density as one moves west to east, a spatial distribution strikingly similar to rainfall patterns in the state. The relationship between annual rainfall and pond density has a strong positive correlation of 0.845 ($p < .01$) of the number of ponds per area with annual rainfall (Table 5). This strong correlation is to be expected, considering the vast majority of ponds function by collecting surface water. This relationship was documented by Smith et al. (2002) in their assessment of pond density across the US. However because Kansas has such a strong gradient of rainfall within the state, the relationship is likely much stronger than in other states. Similarly scaled studies in other regions, such as Alabama and Georgia, did not report such a strong dependence on rainfall, likely due to the lack of a strong rainfall gradient within those areas (Chaney et al., 2012; Ignatius & Stallins, 2011).

While rainfall accounts for much of the variation of pond density through Kansas, it is clear through examining impoundment density in high detail (Figure 5) that some physiographic and social factors likely contribute to especially high and low densities around Kansas. A few areas have exceptionally high densities, at upwards of 80 impoundments per km^2. These high concentrations, mostly contained in Crawford and Cherokee Counties in southeast Kansas, are the result of early 20th century strip pit mining efforts that created long surface escarpments that changed the landscape in a rather dramatic way. Many of these strip pit mines were left to fill with water, giving this isolated region the highest concentration of small impoundments in Kansas.

Though not as extreme as in Crawford and Cherokee Counties, other high concentrations (>4 per km^2) of small impoundments exist throughout eastern and south-central parts of Kansas, mostly in areas where there is urban encroachment in the rural landscape. These areas are usually characterized by dispersed housing developments, located near recently idle grass and cropland outside of urban/suburban centers. This phenomenon is clearly seen within 40 km from the outside perimeter of the suburban regions of Wichita and Kansas City. For this reason, Leavenworth and Miami Counties, just outside the greater Kansas City region, have the highest impoundment densities outside of southeast Kansas, some places having greater than 10 impoundments per square km. From the details afforded in aerial imagery, it appears the ponds in these areas function mostly as aesthetic or recreational features in the landscape. Smith et al. (2002) first noted this phenomenon and suggested that this type of urban/rural development is driving much of the pond proliferation in the Midwest and possibly in other regions. The urban influence on the rural landscape as a driver for artificial pond proliferation has not been described in detail or quantified in the literature.

Areas with relatively low densities of ponds, compared to immediate surroundings of urban areas, include urban centers, stream/river valleys, large swaths of cropland, and areas where large reservoirs already exist. The absence of impoundments in these regions comes as no surprise. Impoundments in urban centers require costly space and are usually only reserved for city parks or small aesthetic ponds used in landscaping. Also, increased sedimentation and nutrient input cause urban ponds to degrade quickly, making them liabilities and therefore less desirable (G.W. Fairchild et al., 2012; Foster, 2011). Several reasons exist for the lack of ponds in stream corridors. First, the low slope in floodplains make building small impoundments that capture overland run-off difficult (Flickinger, Bulow, & Willis, 1993). Second, stream corridors are most often places for intensive crop farming, which usually precludes grazing land and therefore ponds. Finally, water is easily accessible either through ground water or surface water via natural lakes, wetlands, or the stream itself, negating most needs to build artificial ponds. While rare, artificial ponds in floodplains do exist and are almost always excavated ponds that retain water through connection with ground water, not surface water.

In the context of physiographic regions, rainfall appears to have the largest impact on impoundment occurrence. For example, the High Plains region, which has an annual rainfall under 22 inches/year has the lowest density of impoundments at 0.206/km^2 while the Osage Cuestas region in the southeast has an annual rainfall of 40-46 inches/year and an average impoundment density of 3.144 (Table 3) (Natural Resource Conservation Service, 2011). Beyond rainfall, topographic factors seem to also play a role. For example, the Arkansas

Lowlands and the Wellington-McPherson Lowlands both have little topographic relief, and have substantially lower pond densities than the Smokey Hills and Red Hills with similar climate regimes but higher relief. Especially in the case for the Arkansas Lowlands, the only embankment ponds are clustered in areas that have higher relief relative to surrounding areas. The few ponds outside these areas are levee or excavated style ponds that serve as surface water storage for irrigation and confined animal feeding operations, mining and quarry operations, or recreation. Areas surrounding Wichita in western Sedgwick and eastern Butler Counties showed exceptionally high pond densities due to the high number of excavated-style recreation ponds that appear beyond the urban-rural fringe.

Change in Distribution

By 1936, Kansans had constructed 2,236 impoundments across the state (Jones, 1936). These impoundments occurred mostly in the Smokey Hill and High Plains regions, with 892 and 636 ponds, respectively. Other high concentrations existed in the Wellington-McPherson Lowlands and the Flint Hill regions surrounding Wichita. Relative to other physiographic regions, the Arkansas Lowlands was nearly devoid of impoundments in 1936, a relative low density that still exists today. The geographic median center of impoundment occurrence was located in Russell County at the center of the Smoky Hills, meaning impoundment spatial distribution was skewed to the north-central part of the state (Figure 6). The median geographic center of impoundments has since moved 211 km southwest to Lyon County in southeast Kansas.

Most artificial ponds built up to 1936 were part of state and federal efforts to both employ those hit by the Depression and ensure adequate water resources in a post-Dust Bowl Kansas (Swingle, 1970). Impoundments, mostly constructed by the Kansas Emergency Relief

Committee, were built for the purpose of stock water for cattle and preventing erosion (Jones, 1936). It appears the distribution of impoundments favored those regions that had higher concentrations of livestock and lacked adequate easy access to ground or surface water. Although the current analysis did not include pond distribution at any interval between 1936 and today, the median center of pond occurrence likely shifted continuously to the southeast as impoundments were rapidly proliferating.

Stream Fragmentation

According to the intersection with the NHD Flowline, 80,682 out of the 241,295, or 33%, of small impoundments intersect a stream, making the majority of small impoundments 'off-line'. The proportion of off-line to on-line impoundments varied spatially. The Arkansas Lowlands and the Osage Cuestas had the lowest proportion of impoundments on streams, with 22.6% and 23.2% of impoundments on-line, respectively. The Red Hills, Wellington-McPherson Lowlands, Smoky Hills, and the High Plains regions all had more than 50% of their small impoundments impounding a stream, with the Smoky Hills having the highest proportion at 64.7%. The high proportion of on-line streams in western areas of Kansas is likely due to the lack of adequate rainfall for impoundments in off-stream locations to maintain water storage. The Arkansas Lowlands was an exception however, and despite its central and western location in Kansas, the region had 77.4% of its impoundments off-line. Most off-line impoundments in this area were excavated ponds used for stock water for irrigation and livestock.

The vast majority of impoundments that actually impound a stream, 90.9%, intersect 1st order streams (Figure 7). The number of impoundments per stream order decreases exponentially as streams become higher in order. Of the impoundments on streams, 3,981, or 4.9%, impound 2nd order streams, while 813, 113, and 10 impound 3rd, 4th, and 5th order streams, respectively.

The 6th and 7th order streams were only impounded by a small impoundment once each. In general, therefore, we would expect smaller impoundments tend to impound lower order streams. The average size of an impoundment on a 1st order stream is 0.452 ha, while 2nd, 3rd, 4th, and 5th level streams are impoundment by ponds 1.346, 2.593, 2.184, and 0.874 ha in area, respectively. Many of the small impoundments on 3rd, 4th, 5th, and 6th order streams were located in western Kansas. Because of the lack of rainfall in these areas, the impoundments are usually small in surface area. Many of these impoundments on higher order streams were either small dams or larger weirs that did not substantially block stream flow, also contributing to smaller impoundment surface area. The larger proportion of small surface area impoundments on these higher order streams skewed the mean surface area for 5th, 6th and 7th order streams downward. Only one 7th order stream, the Arkansas River, was impounded by a small impoundment. This impoundment, located in Gray County, appears to have a low-height dam, allowing for medium to high flows in the Arkansas River.

The total length of stream habitat converted to lacustrine due to small impoundments is 7,498 kilometers, and as expected, regions with more impoundments had higher stream to lacustrine conversion. While the amount of converted stream habitat by impoundments is only roughly 2.5% of total stream length, the impoundments' impacts on downstream surface water flow and stream corridor connectivity affect habitat well beyond the length of the impoundment (Baxter, 1977; Bunn & Arthington, 2002; Callow & Smettem, 2009). It has been argued, however, that increased lacustrine habitat, and even greater stream fragmentation, has overall positive benefits for biodiversity, especially in intensively developed regions (Jackson & Pringle, 2010; Knutson et al., 2004; Scheffer et al., 2006). In terms of shoreline habitat created by artificially created ponds, impounding streams created 22,416 kilometers of new lake perimeter or shoreline habitat.

It is difficult to conclude whether small impoundments have had negative impacts or positive benefits on regional stream ecology. Ponds, even artificial, appear to increase regional biodiversity through the promotion of aquatic habitat and rare species (Oertli, Céréghino, Hull, & Miracle, 2009), yet this largely depends on impoundment structure, position in watershed, and the intensity and location of impoundments in relation to each other (Ebel & Lowe, 2013). Too many impoundments in a poorly planned watershed can negate these benefits by overly fragmenting the stream, promoting biological invasion, and changing flow regimes enough to significantly damage previous ecosystem function (Didham, Tylianakis, Gemmell, Rand, & Ewers, 2007). It is unknown whether the number of impoundments on Kansas streams overburdens the existing stream ecosystem enough to cause an overall negative impact. However, with the decentralized nature and intensity of impoundment construction, it appears that most watersheds in Kansas were not planned with the optimization of biodiversity in mind.

Conclusion

Small impoundments represent a substantial 20th century change to the surface water of Kansas. In 1936, Kansans had built 2,236 small impoundments dispersed mostly in the central regions of the state. Presently, Kansas has 241,295 man-made impoundments that cover a surface area of 74,880 ha (288 mi^2) and have the capacity to store approximately 1,299,483 acre/feet of water. The occurrence of impoundments estimated here far exceeds any previous Kansas inventory. While small impoundments in Kansas dominate both in occurrence and surface area, the medium to large reservoirs in the state contain 83.8% of the surface water storage, highlighting the true hydrological dominance of Kansas's large reservoirs. In terms of stream connectivity, small impoundments have impounded Kansas streams 80,862 times, with the majority, 90.9%, on first-order streams. Through the impounding of streams, nearly 7500 kilometers of original stream habitat have been converted to lacustrine habitat. The dataset produced in the study may be useful for local and state water managers with interest in documenting the occurrence of small artificial ponds on the landscape. The high occurrence of small impoundments may become more significant as Kansans continue to face water quality and quantity challenges as a result of climate change, sedimentation, and aquifer depletion.

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Figures

Figure 1. Process of creating the Kansas Small Impoundment Inventory

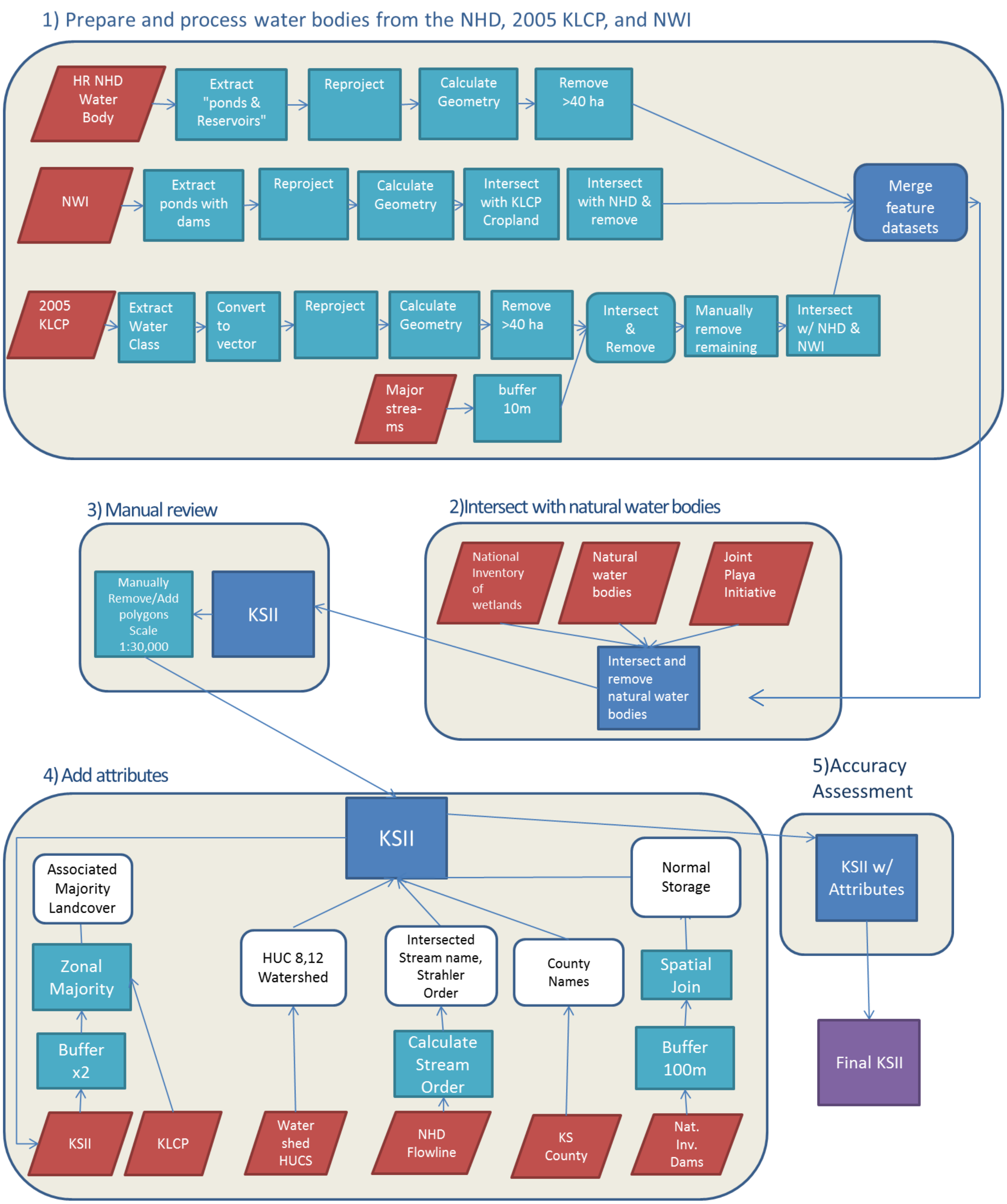

Figure 2- Spatial distribution of KSII percent error derived from the accuracy analysis.

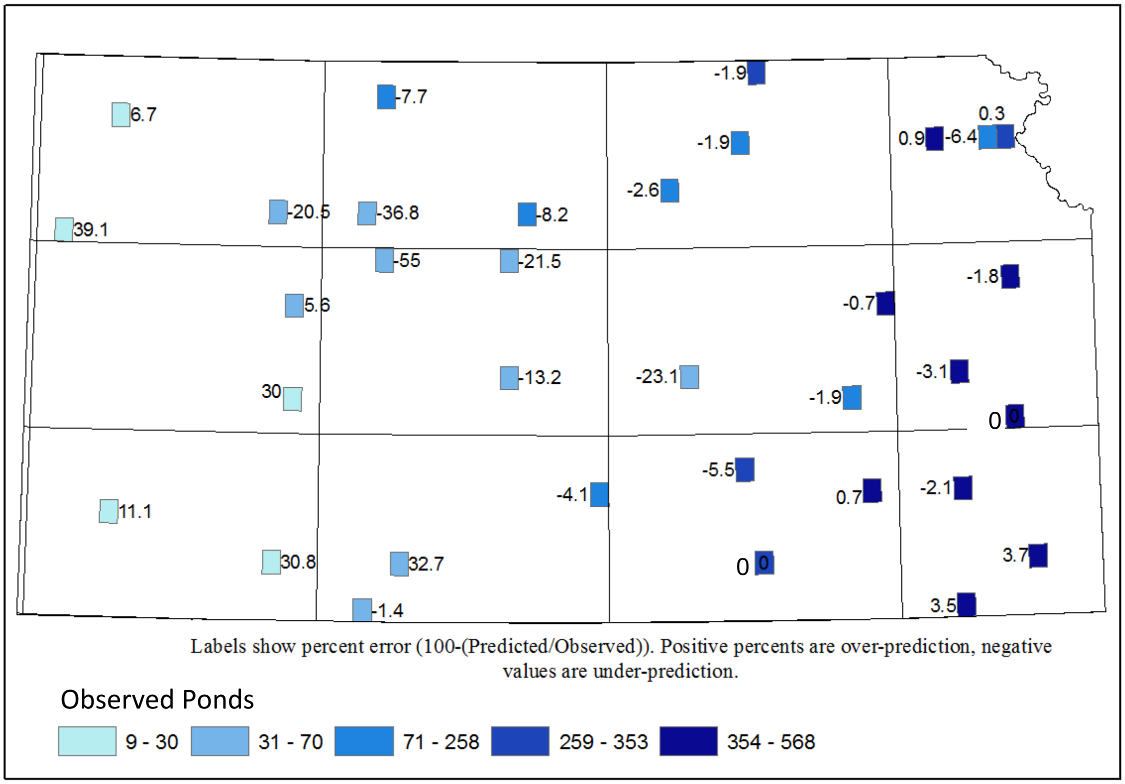

Figure 3 – Physiographic regions used in the spatial analysis.

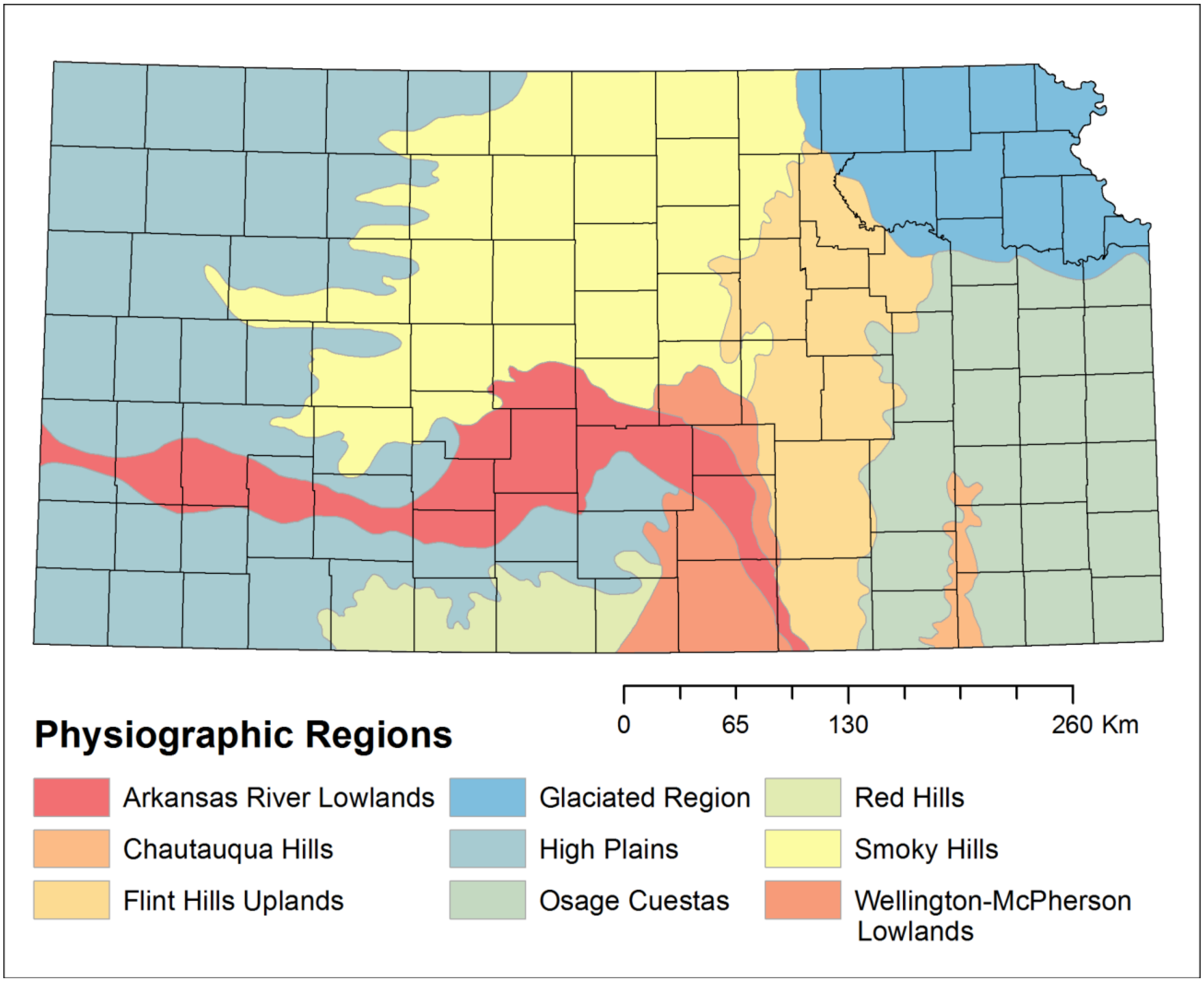

Figure 2. Distribution of Small Impoundment Occurrence by Surface Area

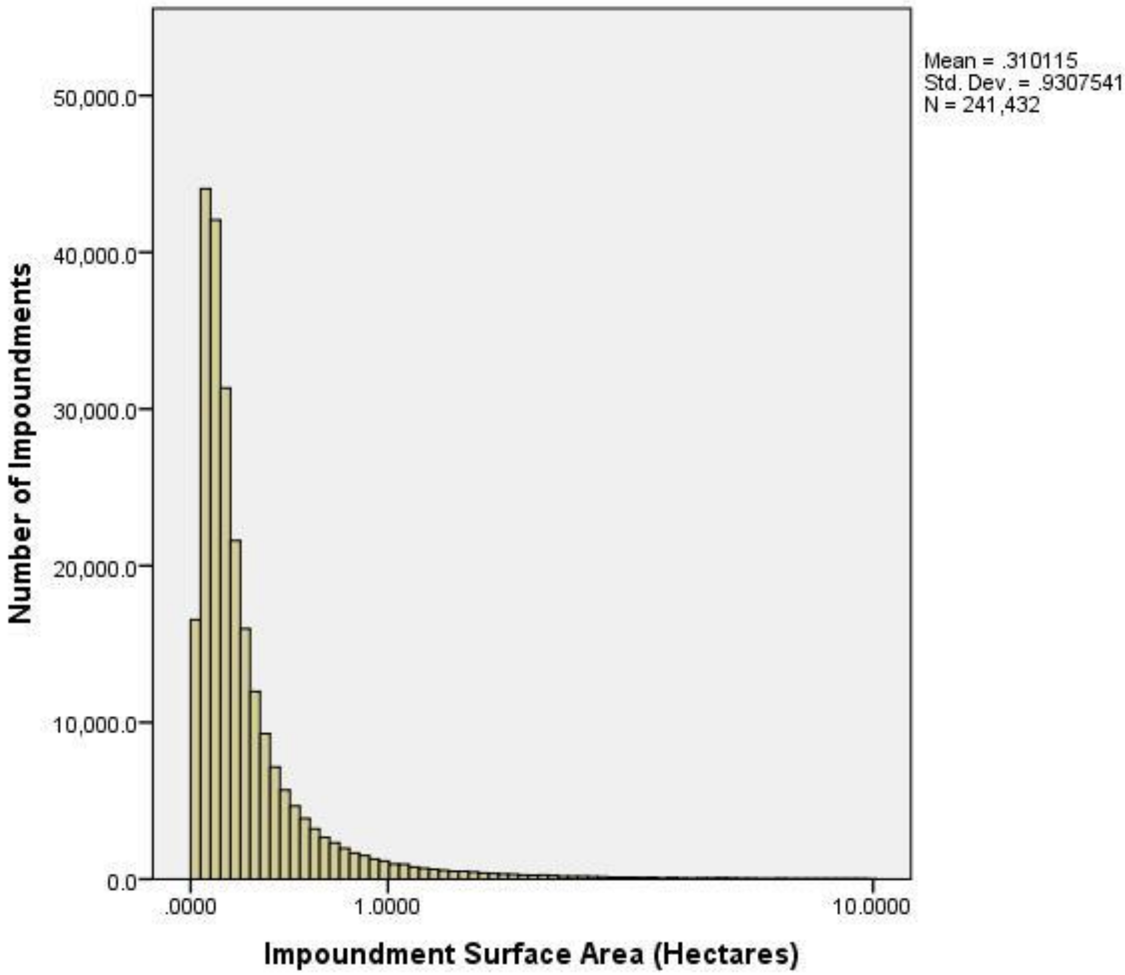

Figure 5. Kansas small impoundment density.

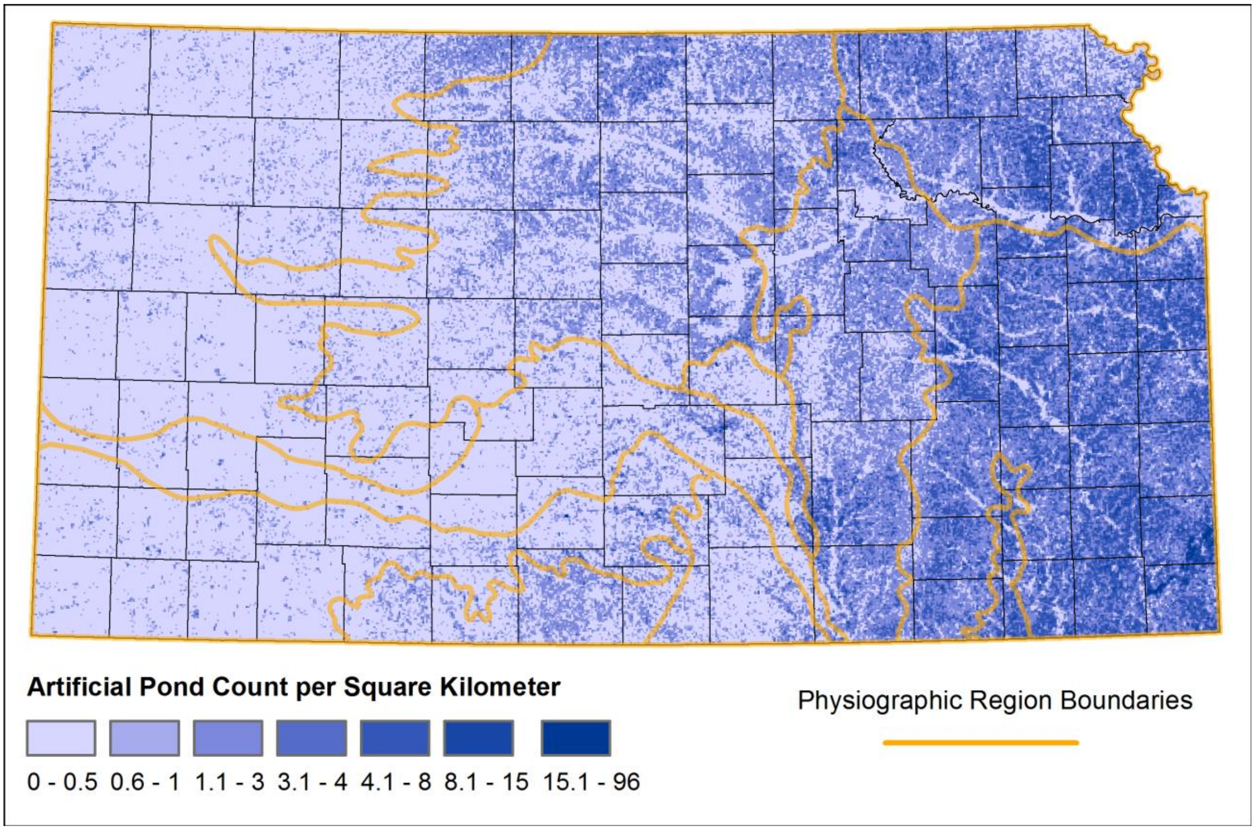

Figure 6. Digital representation of the 1936 map of Kansas small impoundments.

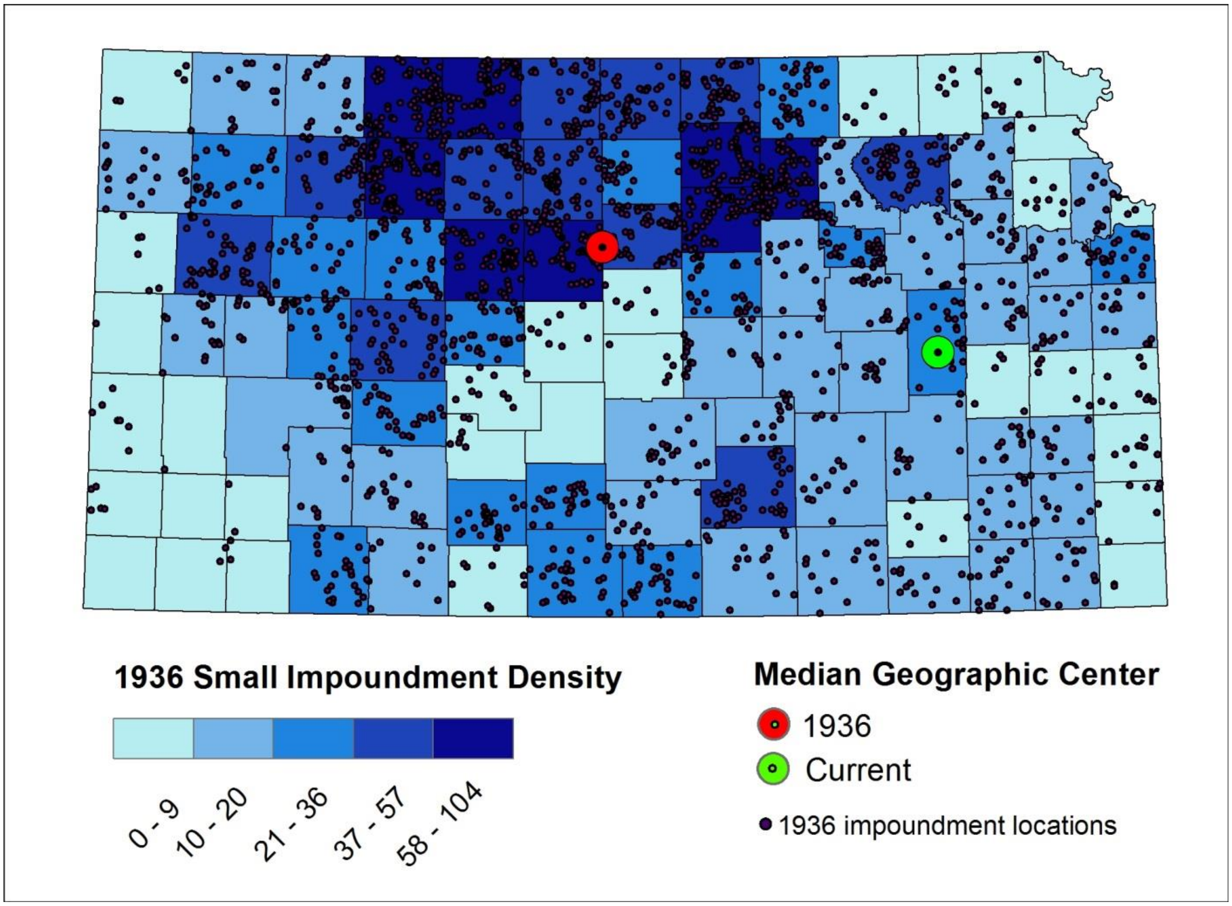

Figure 7.

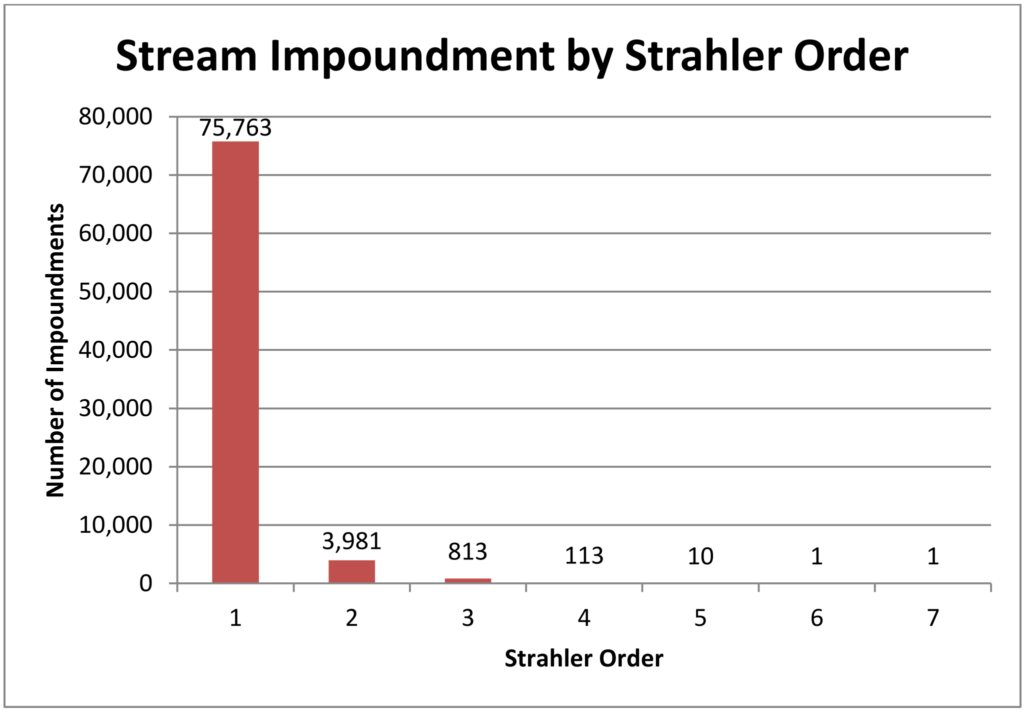
Stream Impoundment by Strahler Order
Number of Impoundments
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
75,763
3,981
813
113
10
1
1
1
2
3
4
5
6
7
Strahler Order

Table 1. Accuracy assessment by sampled 1:24,000 quad

Quad Name	Predicted	Observed	Commission	Omission	100-(Obs./Pred.)	Obs. - Pred.	Pred. – Comm.	Producer	User
Prairie View	155	168	6	19	0.92	13	149	0.89	0.96
Lamar	226	232	10	16	0.97	6	216	0.93	0.96
Meades Ranch	214	233	6	25	0.92	19	208	0.89	0.97
Midway Draw	35	44	2	11	0.80	9	33	0.75	0.94
Hill City 4 NW	36	57	5	26	0.63	21	31	0.54	0.86
Hanover West	312	318	20	26	0.98	6	292	0.92	0.94
Ulysses SW	10	9	3	2	1.11	-1	7	0.78	0.70
Dewey Ranch	16	15	3	2	1.07	-1	13	0.87	0.81
Linn SE	253	258	19	24	0.98	5	234	0.91	0.92
Netawaka	468	464	27	23	1.01	-4	441	0.95	0.94
Lancaster	219	234	8	23	0.94	15	211	0.90	0.96
Atchison West	354	353	33	32	1.00	-1	321	0.91	0.91
Utica	38	36	8	6	1.06	-2	30	0.83	0.79
Admire	429	432	10	13	0.99	3	419	0.97	0.98
Waverly SE	435	449	12	26	0.97	14	423	0.94	0.97
Ellinwood SW	33	38	6	11	0.87	5	27	0.71	0.82
Canton SW	30	39	2	11	0.77	9	28	0.72	0.93
Horse Thief	39	30	11	2	1.30	-9	28	0.93	0.72
Shaw Creek	253	258	6	11	0.98	5	247	0.96	0.98
Kincaid	491	491	22	22	1.00	0	469	0.96	0.96
Tribune 3	1	0	1			-1	0	0.00	0.00
Benton	277	293	19	35	0.95	16	258	0.88	0.93
Vilas	427	436	19	28	0.98	9	408	0.94	0.96
Severy North	417	414	14	11	1.01	-3	403	0.97	0.97
Montezuma NW	6	2	4		3.00	-4	2	1.00	0.33
Kingman	163	170	24	31	0.96	7	139	0.82	0.85
Marmaton	384	400		16	0.96	16	384	0.96	1.00
Horsethief Draw	32	23	10	1	1.39	-9	22	0.96	0.69
Ellis	27	60	4	37	0.45	33	23	0.38	0.85
Dorrance NW	51	65	1	15	0.78	14	50	0.77	0.98
McCune	472	455	27	10	1.04	-17	445	0.98	0.94
Meade	17	13	6	2	1.31	-4	11	0.85	0.65
New Salem	324	324	19	19	1.00	0	305	0.94	0.94
Coffeyville East	468	452	35	19	1.04	-16	433	0.96	0.93
Sitka SW	69	70	5	6	0.99	1	64	0.91	0.93
Baldwin City	558	568	21	31	0.98	10	537	0.95	0.96
East Kiowa	69	52	18	1	1.33	-17	51	0.98	0.74
Sum:	**7808**	**7955**	**446**	**593**					

Overall Percent Omitted : **0.076**
Overall Commission Error: **0.057**
Overall Observed/Predicted: **0.982**

Table 2. Small impoundment volume/surface area distribution

Size Class by Surface Area (ha)	Impoundment Count	Total Surface Area	Total Volume (acre/ft)
> 1 Ha	229,621	43,100	746,244
1 to 10 Ha	11,179	25156	430,978
10 to 40 Ha	393	6624	118,063
< 40 Ha	241,295	74,880	129,5285
*> 40 Ha	105[c]	65,062[c]	3,312,383[ab]
KS Federal Reservoirs	24[b]	60,019[b]	2,736,455[b]

[a]-from NID [b] from KWO [c] from NHD

*includes Federal Reservoirs

Table 3. Small impoundments per Kansas physiographic region

Physiographic Region	Region Area (km)	1936 SI Count	Current SI Count	1936 Si Count / km2	SI Count / km2	Sum SI Area (ha)	Avg SI Area (ha)	Sum SI Volume	Avg SI Volume
Red Hills	6818	60	4122	0.009	0.605	1541.3	0.374	28371.2	6.883
Chautauqua Hills	1569	12	4596	0.008	2.929	1167.7	0.254	17722.9	3.856
Arkansas River Lowlands	16624	37	4928	0.002	0.296	3264.0	0.662	44070.8	8.943
Flint Hills Uplands	19572	159	29025	0.008	1.483	9345.5	0.322	117924.2	4.063
Glaciated Region	17118	131	39305	0.008	2.296	11113.6	0.283	259871.2	6.612
Smoky Hills	43423	892	35138	0.021	0.809	9893.1	0.282	185217.7	5.271
High Plains	66704	636	13746	0.010	0.206	5438.2	0.396	140986.2	10.257
Osage Cuestas	33605	229	105658	0.007	3.144	31353.0	0.297	469902.3	4.447
McPherson Lowlands	7666	77	4738	0.010	0.618	1902.4	0.402	33340.6	7.037

Table 4. Small impoundment breakdown by Kansas counties.

County	1936 Pond Count	Current Pond Count	SI per km^2	Sum SI Area (ha)	Avg. SI Area (ha)	Total SI Volume (acre/ft)
Allen	10	4056	3.10	1014.27	0.250	15290
Anderson	6	4723	3.12	971.05	0.206	14975
Atchison	2	2209	1.97	894.29	0.405	20916
Barber	31	2516	0.86	1137.39	0.452	4718
Barton	9	1304	0.56	546.63	0.419	5401
Bourbon	8	4615	2.79	1435.63	0.311	22081
Brown	8	1760	1.19	855.37	0.486	20006
Butler	16	7012	1.87	3010.52	0.429	37968
Chase	11	2241	1.11	1190.98	0.531	15336
Chautauqua	12	4067	2.44	1210.14	0.298	19354
Cherokee	2	6292	4.11	2172.72	0.345	32721
Cheyenne	5	302	0.11	110.91	0.367	2878
Clark	10	888	0.35	281.07	0.317	2475
Clay	83	2495	1.47	554.99	0.222	9186
Cloud	69	1791	0.96	498.86	0.279	9338
Coffey	5	4892	2.89	1342.21	0.274	20533
Comanche	9	672	0.33	239.08	0.356	1690
Cowley	15	4938	1.68	1580.28	0.320	18703
Crawford	7	8145	5.29	2614.04	0.321	37130
Decatur	16	419	0.18	128.58	0.307	3290
Dickinson	13	2467	1.12	629.04	0.255	8620
Doniphan	0	1168	1.13	389.98	0.334	9121
Douglas	12	3334	2.71	947.82	0.284	16159
Edwards	7	137	0.09	82.03	0.599	1390
Elk	5	4558	2.71	1807.32	0.397	28868
Ellis	67	1166	0.50	288.33	0.247	5402
Ellsworth	6	1453	0.78	427.90	0.294	8010
Finney	15	417	0.12	255.43	0.613	4427
Ford	17	423	0.15	239.50	0.566	3551
Franklin	12	4515	3.02	1432.26	0.317	20724
Geary	34	1655	1.58	356.64	0.215	4496
Gove	21	545	0.20	195.49	0.359	4602
Graham	104	637	0.27	184.64	0.290	4597
Grant	0	125	0.08	98.35	0.787	2552
Gray	11	215	0.10	97.01	0.451	1766
Greeley	1	88	0.04	73.51	0.835	1907
Greenwood	12	6846	2.29	2451.97	0.358	35460
Hamilton	7	162	0.06	143.25	0.884	2043
Harper	32	1153	0.55	310.62	0.269	731
Harvey	11	982	0.70	513.13	0.523	2935
Haskell	2	293	0.20	170.62	0.582	4319
Hodgeman	26	385	0.17	143.04	0.372	2948
Jackson	18	5620	3.30	1498.09	0.267	35039
Jefferson	8	4369	3.03	1371.36	0.314	32075
Jewell	42	4170	1.76	802.38	0.192	15020

Johnson	22	3307	2.66	1364.64	0.413	22184
Kearny	1	193	0.09	428.06	2.218	1671
Kingman	18	1801	0.80	589.55	0.327	10790
Kiowa	26	409	0.22	178.44	0.436	3270
Labette	13	6390	3.78	1742.41	0.273	25638
Lane	24	245	0.13	122.82	0.501	2850
Leavenworth	11	4916	4.05	1374.62	0.280	32151
Lincoln	54	1539	0.82	492.33	0.320	9216
Linn	9	4683	2.98	1687.37	0.360	26473
Logan	45	253	0.09	155.01	0.613	3975
Lyon	23	6985	3.15	1925.14	0.276	28843
Marion	11	2417	0.98	703.49	0.291	9662
Marshall	6	5714	2.44	1119.80	0.196	26175
McPherson	19	2009	0.86	586.13	0.292	5466
Meade	26	240	0.09	181.26	0.755	4635
Miami	12	6305	4.12	1649.08	0.262	24197
Mitchell	22	1676	0.90	434.76	0.259	8138
Montgomery	17	5501	3.26	1242.55	0.226	19015
Morris	16	3114	1.71	843.19	0.271	10801
Morton	0	155	0.08	61.98	0.400	1608
Nemaha	6	3965	2.13	888.49	0.224	20781
Neosho	11	5890	3.94	1659.27	0.282	24803
Ness	43	595	0.21	241.47	0.406	4831
Norton	77	735	0.32	216.77	0.295	5560
Osage	12	5191	2.78	1420.41	0.274	21645
Osborne	57	2271	0.98	582.73	0.257	10908
Ottawa	65	1891	1.01	726.68	0.384	13372
Pawnee	9	318	0.16	134.00	0.421	1530
Phillips	67	2399	1.04	596.85	0.249	14170
Pottawatomie	44	3813	1.71	926.83	0.243	20286
Pratt	24	553	0.29	273.57	0.495	5530
Rawlins	15	339	0.12	111.92	0.330	2904
Reno	20	1914	0.58	798.61	0.417	5653
Republic	46	2304	1.23	540.97	0.235	10126
Rice	5	824	0.44	265.03	0.322	2622
Riley	15	2363	1.47	427.63	0.181	5659
Rooks	43	1652	0.71	537.91	0.326	10396
Rush	33	509	0.27	180.43	0.354	3376
Russell	63	1390	0.60	507.92	0.365	9508
Saline	29	2143	1.15	683.69	0.319	12507
Scott	12	123	0.07	41.60	0.338	1074
Sedgwick	41	2593	0.99	2012.81	0.776	2164
Seward	2	163	0.10	155.83	0.956	4044
Shawnee	18	4034	2.80	1382.34	0.343	25758
Sheridan	41	468	0.20	187.17	0.400	4857
Sherman	20	431	0.16	138.65	0.322	3598
Smith	45	2365	1.02	755.99	0.320	15584
Stafford	0	487	0.24	215.17	0.442	0
Stanton	5	194	0.11	91.60	0.472	2377
Stevens	2	212	0.11	126.19	0.595	3266

Sumner	15	1533	0.50	570.46	0.372	29
Thomas	28	248	0.09	117.07	0.472	3038
Trego	36	391	0.17	105.09	0.269	2288
Wabaunsee	12	3643	1.76	848.64	0.233	13165
Wallace	6	521	0.22	194.32	0.373	5043
Washington	34	3799	1.63	829.89	0.218	16365
Wichita	17	185	0.10	71.23	0.385	1848
Wilson	12	4068	2.73	926.30	0.228	13791
Woodson	10	3772	2.88	938.89	0.249	13837
Wyandotte	3	823	2.03	315.36	0.383	7376

Table 5. Small impoundment that impact streams by stream order.

Stream Order (Strahler)	Number of Impoundments (< 40 ha)	Avg Surface Area of Impoundment (ha)	Total Surface Area of Impoundment (ha)	Avg Volume of Impoundment (acre/feet)	Total Impoundment Volume (acre/feet)
1	75,763	0.452	34274.8	7.80	590,640.55
2	3,981	1.346	5359.7	24.33	96,858.66
3	813	2.593	2108.3	47.31	38,463.45
4	113	2.184	246.8	42.68	4,822.75
5	10	0.874	8.7	15.82	158.24
6	1	1.697	1.7	12.17	12.17
7	1	1.780	1.8	24.01	24.01
Off-Line	160,077	0.205	32,813.0	3.51	562,109.94

Table 6- Pearsons Product Moment Correlation between annual rainfall (inches/year) and small impoundment density

Correlations

		inches_per_year	SI_Count
inches_per_year	Pearson Correlation	1	.845**
	Sig. (1-tailed)		.000
	N	1386	1386
SI_Count	Pearson Correlation	.845**	1
	Sig. (1-tailed)	.000	
	N	1386	1386

**. Correlation is significant at the 0.01 level (1-tailed).

Chapter III

The Occurrence and Purpose of Small Impoundment Construction in Douglas County, Kansas - 1954-2012

Introduction

We have seen a tremendous increase in the number of constructed small impoundments across the US landscape over the past 100 years. Swingle (1970) estimated that the number of small impoundments increased from just 20,000 in 1934 to over 2 million in 1965. Smith, Renwick, Bartley, and Buddemeier (2002) estimated the existence of 2.6 million small artificial impoundments by the turn of the century and later Renwick, Smith, Bartley, and Buddemeier (2005) suggested the number could be closer to 9 million. While the estimates for US impoundments vary considerably, there is little doubt that small impoundments have rapidly proliferated, leaving many areas with high densities of water bodies in landscapes that had little surface water a century ago.

The stated purposes for impoundment construction vary depending on local needs but all rely on their ability to store water. We typically build large impoundments (> 40 ha) for flood control, public drinking water, recreation, power generation and irrigation. Small artificial ponds or small impoundments (< 40 ha) are usually associated with rural areas and used for water storage for livestock or crops, recreation, aesthetics, and watershed protection (Boothby, 1999). As with large reservoirs, small impoundments have become a critical component of the US surface water infrastructure in terms of numbers and utility. Their functional role, ubiquity and rapid proliferation means they have become and will continue to be inextricably linked to the US agricultural and economic landscape.

Small impoundments are diminutive in size yet impact the environmental landscape, primarily through interruption of the natural flow of water and associated suspended material. As such, many researchers recently realized that the ubiquity and rapid proliferation of constructed impoundments across the country means we may have underestimated their significance to large-scale ecological and biogeochemical cycling (J. Cole et al., 2007; J. Downing et al., 2006; J.A. Downing, 2009; J. A. Downing, 2010; Renwick et al., 2005). The slowing of water and transported material changes rates of evaporation, ground water retention, and alters the speed and location of aquatic chemical reactions (Chin, Laurencio, & Martinez, 2008; G. Winfield Fairchild & Velinsky, 2006; Graf, 1999; Verstraeten & Poesen, 2000). Impoundments can accrue 81 to 98% of all incoming sediments, keeping eroded material in the uplands and out of streams and large constructed reservoirs downstream. As such, ponds are often constructed solely for their benefits to stream water quality, especially in areas of intense agricultural development (G. Winfield Fairchild & Velinsky, 2006; Oertli, Céréghino, Hull, & Miracle, 2009). Climatically, most lakes and reservoirs are sources of both gaseous carbon dioxide (CO_2) and methane (CH_4), both well-known greenhouse gases (J. J. Cole, Caraco, Kling, & Kratz, 1994). Ecologically, the damming of streams and rivers both fragments riverine aquatic habitat and increases lacustrine aquatic habitat (Knutson et al., 2004; Markwell & Fellows, 2008).

While the large dam building culture associated with the mid- 20th century is mostly over, the construction of small impoundments has not slowed (Renwick et al., 2005). Renwick et al. (2005) documented a steady 1-3% per year rise in impoundments between the 1930s and 2000s in parts of Kansas and Ohio. Similar research in Pennsylvania found that impoundments were constructed at a rate of 5.6% per year, resulting in an 18-fold increase in impoundments from 1937-2005 (G.W. Fairchild, Robinson, Brainard, & Coutu, 2012). Not only are impoundments continually being constructed, but due to improved watershed erosion control and dam construction, those built after the 1950's have a much longer life-span, causing higher pond construction over "loss" rates in recent decades (G.W. Fairchild et al., 2012; Renwick et al., 2005). With a long sustained positive small impoundment construction rate, the trend suggests impoundment numbers will continue to increase and overcome pond loss. Therefore, the aggregated biogeochemical impacts of small impoundments will continue to increase in the foreseeable future.

A key to fully grasping any anthropogenic alteration to the earth's surface is to not only understand its occurrence and extent, but the factors that create and sustain its proliferation. In the case of small impoundments, the purpose for their construction has received little attention. Renwick et al. (2005) and G.W. Fairchild et al. (2012) both implicitly suggest that the rate of impoundment construction in recent decades appears to be, at least in part, caused by higher population densities in some rural areas, a relationship that was not seen before the 1960s. However, it is not clear why more densely populated rural areas have higher impoundment densities and how the impoundment use has changed to create this phenomenon. In fact, no analysis of impoundment proliferation has attempted to classify them based on their purpose, i.e. beyond the general distinction "pond" or "small impoundment." Detailing the purpose of an impoundment such as stock pond, watershed impoundment, or recreational use across space and time would further an understanding of the reasons for continued impoundment proliferation.

In the Midwest and much of the US, impoundments were historically associated with the rural landscape, mainly as features to maintain water for livestock. A 1955 survey of Douglas

County, Ks landowners found that 98% of impoundments were built for the purposes of storing water for livestock (Hastings & Cross, 1962). During this period, pond construction and use was likely driven by the density of livestock operations. However, the total reported number of livestock in Douglas County has been in a steady decline since the 1960s, yet the number of ponds has continued to rise (Figure 3) (USDA:NASS, 2013), suggesting that the reason for impoundment proliferation has changed in recent decades. Because the decline in livestock operations, especially cattle, and the rise in impoundment density in Douglas County reflect trends seen nationwide, the change in impoundment purpose in the county may represent a larger scale phenomenon (Smith et al., 2002; USDA:NASS, 2010).

By assessing the historic change in impoundment occurrence and usage in Douglas County, Kansas, this research will help clarify the causes of continued impoundment proliferation, especially in regions where small impoundments were historically associated with the rural landscape and livestock production. This research will specifically answer: 1) what is the current number and surface area of impoundments in Douglas County, Kansas and how has this changed from 1954 and 2) has the purpose of small impoundments changed since the 1950s and how has this possible change influenced their recent proliferation? To answer these questions, this study compares results from a 1950's survey of impoundment landowners to a current inventory, obtained through a road-side survey and aerial imagery, of impoundments and their usage.

Methodology

Study Area

Douglas County, located in northeastern Kansas, was chosen for this study due to its high concentration of impoundments and the availability of historical data on pond use. In 2012, Douglas County had a population of 112,864, mostly concentrated in the city of Lawrence. Similar to surrounding counties, Douglas has experienced not only urban growth but an increasing population growth of roughly 10% per decade in its rural or 'ex-urban' areas. Approximately 75% of the county's 291,755 acres are spread across 1,040 farms (IPSR, 2011). The county averages approximately 38 inches of precipitation per year, and average temperatures of 23.1 degrees Fahrenheit in January and 79.6 degrees in July (USDA:NRCS, 2013). In terms of climate, the higher relative precipitation makes the county more capable of sustaining impoundment storage than many other areas in the state.

Historic Pond Occurrence and Purpose in Douglas County

The historical spatial inventory of small impoundments and the estimated designation of their use was taken from Hastings's and Cross's 1962 study titled *Farm Ponds in Douglas County, Kansas, and Their Use in Fish Population*. This research, focused mostly on ponds and their value for fish production, included a 1954 inventory of impoundments (referred to as ponds by the authors) in Douglas County and the results from a 1955 survey of sampled land-owners regarding the purpose of their ponds. The 1954-55 pond occurrence and usage from their research served as a baseline with which to compare current pond occurrence and use. In particular, Hastings's and Cross's analysis on the purpose of Douglas County impoundments provides a rare insight into the historical use of ponds by landowners in Kansas.

Hastings and Cross used 1954 aerial images of Douglas County taken by the U.S. Soil Conservation Service to map the distribution and surface area of ponds in Douglas County. Hastings's and Cross's "pond" map (Figure 2) was scanned, referenced, and points were digitized into a GIS. Due to the small scale of the Hastings and Cross map, the pond locations contained some positional errors. Pond locations were corrected using the same 1954 NRCS imagery as Hastings and Cross (KDHE, 2008).

To document the purpose of Douglas County ponds, Hastings and Cross surveyed a random sample of 273 Douglas County landowners using a mailed questionnaire (Hastings & Cross, 1962). One-hundred and thirty one landowners returned the survey. Unfortunately, the raw data from these surveys no longer exists, so only their summary information could be used for this study. While the surveys contained many questions regarding pond management, use, and characteristics, only two summarized points are used for comparison in this study: 1) Water storage for livestock was the purpose of building 98.4% of ponds and was the sole purpose of 54.3% of ponds. 2) Recreation, or fishing, was the secondary use of 39.5% of ponds and the sole purpose of .8% of ponds.

Current Small Impoundment Inventory and Purpose in Douglas County, KS

The Kansas Small Impoundment Inventory (KSII) from Chapter 2 was used to analyze impoundment occurrence and surface area for Douglas County. The KSII is a composite of several datasets and has a user's and producer's accuracy of 94.2 and 92.5%. In an effort to minimize this error for Douglas County, the KSII was reviewed using 2012 National Agricultural Imagery Program (NAIP) imagery at a scale of 1:10,000. Impoundments were added to or removed from the KSII as depending on their appearance in the NAIP imagery.

To determine impoundment use, this study chose a mixture of road-side and aerial image surveying over the mailed landowner survey used by Hastings and Cross (1962). This approach was chosen due to control over samples size and location, ease of implementation, and repeatability. Road-side classification of ponds was the preferred approach but aerial imagery was necessary in cases where the view of the pond and surroundings was obscured or in cases where older imagery was needed for addition information. Aerial imagery was used in conjunction with the roadside survey for 29% sample ponds and exclusively for 35% of the samples.

Sample locations were chosen through a stratified random approach. Douglas County was separated into 11 sections using USGS 24k Quads. Survey routes were constructed by picking three random road segments in each of the 11 sections. Adjacent roads were selected until the three survey routes were of equal length and totaled ~25 kilometers for the full 24k quads (i.e., quads lying completely within the county boundaries) and ~15 kilometers for the partial quads. To select impoundments to sample, the sample roads were buffered by 200m. Impoundments from the KSII that intersected the buffer were extracted (Figure 3). With this approach, 249 impoundments were selected to be sampled.

With this approach, as opposed to the land-owner survey approach, it was only possible to reliably classify ponds into four categories: stock water, recreational, mixed-use/unknown, and other. The "stock water" classification includes any impoundments that appear only to serve the purpose of providing water to livestock. The "recreational" category includes impoundments used for both recreational and aesthetic purposes. Any impoundments that appeared to not have any dominant use (in other words, it had a clear mix of activities) or did not have enough distinguishing characteristics to be defined as "stock", "recreational", or "other" were classified as "Mixed-use/Unknown". The "other" category was used for non-conventional pond uses such industrial, irrigation, or waste storage.

The criteria used to classify impoundments took into account features of each impoundment itself and contextual information from surrounding features. Impoundments designed and/or used for recreation and aesthetics (fishing, small boating, etc.) can be identified by dam placement, pond accessories (e.g. docks, boats, aerators), groomed landscaping, and the absence of livestock and livestock associated features (Figure 3). Alternatively, water supply impoundments for livestock are usually placed in pastureland and will have signs of livestock presence such as fences, actual livestock, livestock trails, and a trampled shoreline (Figure 4). To be classified as either dominant stock water or recreation, the impoundments needed to have the exclusive characteristics of that category (Figure 5). If an impoundment had a mixture of stock pond and recreation pond characteristics, it was labeled as “Mixed-use/Unknown”. For example, if an impoundment appeared in obvious pastureland (indicating a stock pond), but also featured a dock (recreational/aesthetic), the impoundment was classified as “Mixed-use/Unknown”. If a pond had a clear purpose beyond stock water, aesthetic or mixed use, it was classified as “Other”. Also noted during the survey was the dam type of the impoundment (i.e., embankment, excavated, or levee) and if the impoundment appeared to be dilapidated/eutrophic.

Many of the impoundments classified as “Mixed-use/Unknown” were impoundments dominantly used for livestock but lacked signs of cattle because the land had not recently been used for grazing. Often the grass was well grown (indicating lack of grazing) and there were no clear signs of livestock, such as patchy grass or livestock trails. In these cases, 2010 NAIP imagery was used after-the-fact to look for signs of cattle within the field. If cattle were present in 2010, the impoundment was classified as a stock water pond.

Results and Discussion

Douglas County Impoundment Occurrence: 1954 to 2012

Using 1954 aerial imagery, Hastings and Cross (1962) mapped 1,316 impoundments (Figure 2). This estimate appears correct after comparing and correcting their inventory using 1954 aerial imagery. According to their area measurements, 1,281, or 97.3%, of ponds were < 1 acres in surface area, with 68.8% being below 1/4 acres. Only four impoundments were larger than 4 acres in surface area (not including Lone Star Lake, the only major Douglas County reservoir during this time).

From 1954 to 2012 the number of small impoundments in Douglas County increased 150% to 3,342 (Figure 7) (Table 1). The high increase in impoundments over the time periods is consistent with other reports of pond proliferation in Kansas (Buddemeier, 2004). Out of the 1,316 impoundments seen in 1954, only 484, or 36.7 %, remained in 2012. This high loss of impoundments coupled with high overall growth means that as impoundments are lost through eutrophication or changing land-use, new impoundments are built to replace them, but not necessarily in the same location. It is not known how many of the impoundments that persisted through 2012 were dredged in order to increase the impoundment longevity.

As with the surface area to occurrence distribution of impoundments in 1954, the majority of impoundments in 2012 (85.9%) are < 1 acre in surface area. Interestingly, as seen in Figure 8, the size distribution of impoundments has shifted slightly to larger sizes. The proportion of impoundments < 0.25 acre in surface area is 22% lower than in 1954, while the proportion is greater in all other size classes, meaning that over time, impoundments have increased in size. It is not clear if this is an actual increase in impoundment surface area or by measurement error. As noted by Hastings and Cross, the two years before the 1954 aerial imagery was flown were relatively dry years which may have caused surface area measurements to be smaller than typical. Assuming no measurement error, improved availability of resources such as earth-movers, public funds and technical support for dam building seen after the 1950s may have allowed land-owners to build larger impoundments (Rasmussen, 1962; Renwick et al., 2005).

Change in Impoundment Use

One hundred three of the 249 impoundments surveyed for this study (~ 41.3%) were predominantly used for the purpose of maintaining water for livestock (Table 2). Of these impoundments, 75% had visible livestock in, near or in the same field as the pond. The remaining impoundments were clearly used for stock water because of their location in a recently grazed field, proximity to a barn, and/or signs of livestock (i.e., trails). Sixty-seven impoundments surveyed, or 27.7%, were used predominantly for recreation. The most frequent characteristic of recreational ponds was some type of landscaping surrounding the pond, such as well-groomed grass with close proximity to housing. Pond amenities such as a dock, boats, or feeders were present in 40.9% of impoundments classified as recreational. Impoundments that had a mixture of stock and recreational characteristics or had no defining features constituted 30.5% of sampled impoundments. Only three impoundments were classified as 'other' - two impoundments for industrial use and one lagoon.

As mentioned previously, it is difficult to decisively compare the values from Hastings and Cross to the sample results found here due the inability of the road-side/imagery sampling approach to reliably classify impoundments having multiple uses. However, from this comparison, we can infer that recreation as the sole or dominant use of an impoundment is a substantially more important factor in pond construction than in 1954. In 1954, recreation was the sole purpose of 0.8% of impoundments compared to 2013, where 27.7% of ponds appear to be used solely or primarily for recreation. In 1954, water for livestock was a purpose of all but 1.6% of impoundments. In 2013, at least 28.9% of impoundments ("recreational" + "other") appeared to not have any association with livestock. This proportion may be higher than 28.9% if we consider the likelihood that many impoundments classified as "Mixed Use/Unknown" were not used for stock water. Overall, we can conclude that impoundment use as a means to store water for livestock is no longer as dominant as it was in the 1950s. This decrease in stock water ponds appears to be associated with changing land-use priorities. Reported livestock in Douglas County has steadily declined since the mid 1960s (USDA:NASS, 2013), making it appropriate to assume livestock-related landscape features, such as stock water ponds, have since become increasingly unnecessary.

In Douglas County, the increase in recreational impoundments may be associated with expansion of 'exurban' areas. While definitions of exurban vary, it is usually associated with traditionally rural areas with increasing population density, close proximity to an urban center, and a relatively high percentage of daily work commuters with relatively high incomes (Berube, Singer, Watson, & Frey, 2006). With an increasing rural population density and within commuting distance of three major urban centers (Lawrence, Kansas City, and Topeka), much of Douglas County may be described as exurban. Because inhabitants of the exurban area have more land, and water is considered a valuable aesthetic improvement to the landscape, many exurban land-owners likely constructed or maintained previously existing impoundments for recreational and aesthetic use (USDA:NRCS, 1997). Indeed, many, if not most, of the aesthetic/recreation impoundments in this survey appeared near housing developments consistent with the 'exurban' landscape. Also, as described in Chapter 2, many of the high impoundment density areas in Kansas are especially prevalent near but not within urban centers. These findings of the exurban-driven impoundment proliferation may be significant beyond Douglas County considering that the exurban landscape occupies five to ten times more area nationwide than the urban or suburban and has been growing about 10-15% per year (Theobald, 2001).

The roadside survey and aerial imagery method for determining impoundment usage did have some major drawbacks and similar future studies may consider a different approach. First, some impoundment uses are difficult to detect via simple visual cues from the roadside or through aerial imagery. For this reason, this study likely underrepresents or misclassifies impoundments for nutrient and sediment retention (i.e. watershed impoundments) which have little to no discernible visible characteristics outside of their landscape position. As such, most watershed impoundments were included in the “Mixed-use/Unknown” classification, obscuring their significance as a purpose of impoundment use. Because much federal and state money goes into small impoundment construction as a means for erosion and nutrient control, their significance is likely higher than stated here. Second, sampling within a certain distance of the road (200 meters in this case) may bias sampling toward aesthetic or recreation ponds as these structures are often near buildings or houses which tend to be closer to the road. However, 48.7 percent of all Douglas County impoundments are within 200 meters of the public road network, meaning impoundments in general tend to occur near roads. To address these drawbacks, a similar future study may want to consider a random landowner survey similar to the approach of Hastings and Cross (1962).

Conclusion

Douglas County experienced a 153% increase, from 1,316 to 3,342, in the occurrence of its constructed small impoundments. As impoundment numbers increased, the size of impoundments (by surface area) shifted from mostly <0.25 acre in size to slightly larger sizes >0.25 acres. Of the 1,316 impoundments present in 1954, only 484, or 36.7 %, remained in 2012, meaning the majority of impoundments built before 1954 have been lost through sedimentation or changing land-use. While stock water ponds were overwhelmingly dominant in the 1950s, by 2013 only 41% seemed to be dominantly for the purposes of maintaining stock water. Impoundment uses appear to have shifted away from stock water ponds to more recreational and aesthetic ponds that are now the dominant purpose of at least 26.9% of impoundments. This rise is recreational/aesthetic impoundments may be tied to the increase in ‘exurban’ land-use. If so, exurban land-use, through the construction of recreational/aesthetic impoundments, could be driving a significant part of the recent increases in impoundment densities experienced in other areas of the US.

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Tables and Figures

Figure 1. Reported Livestock vs. Number of Impoundments: Douglas County 1930-2012

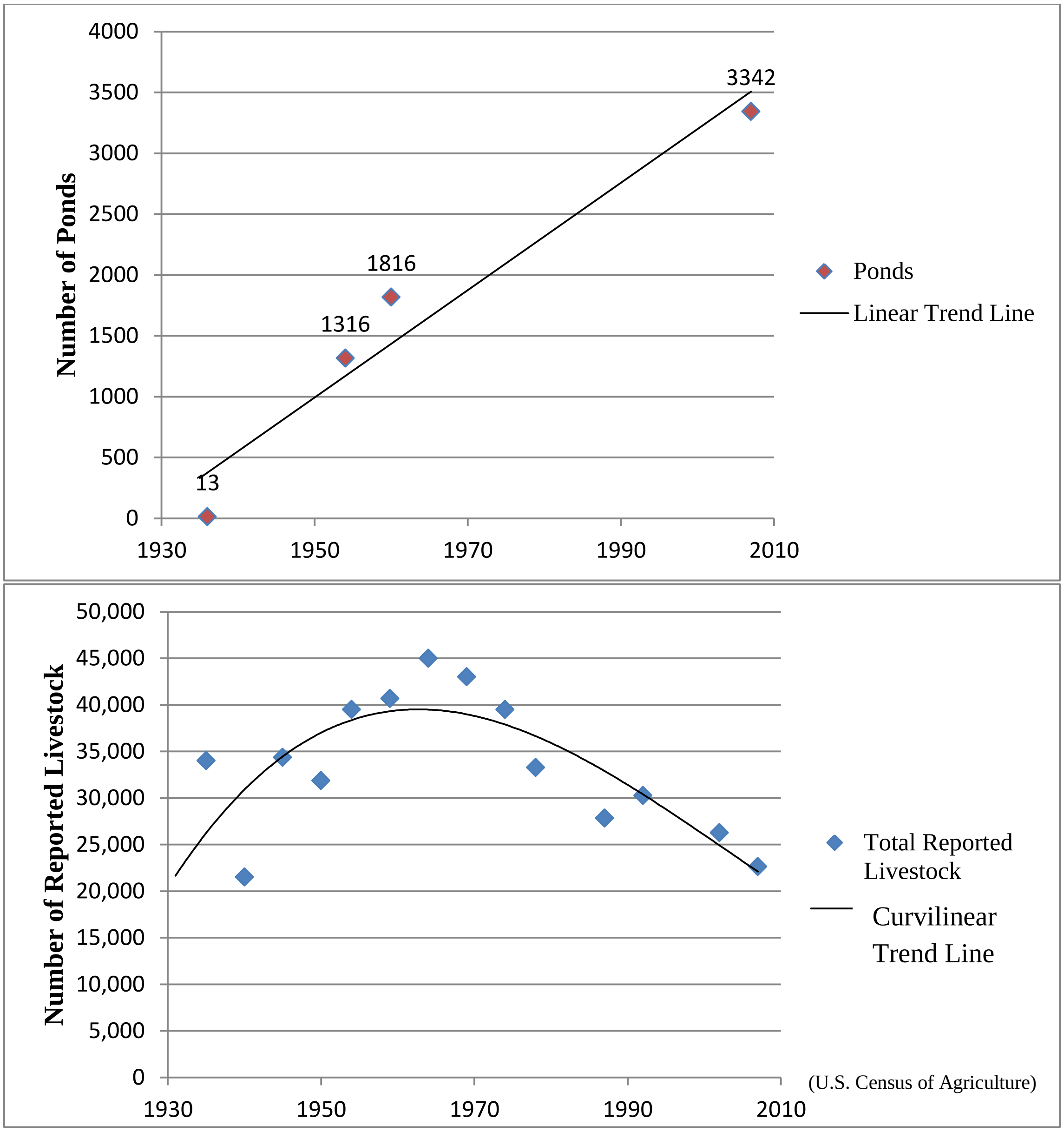


Figure 2. Map of 1954 Douglas County small impoundments taken from Hastings and Cross (1962)

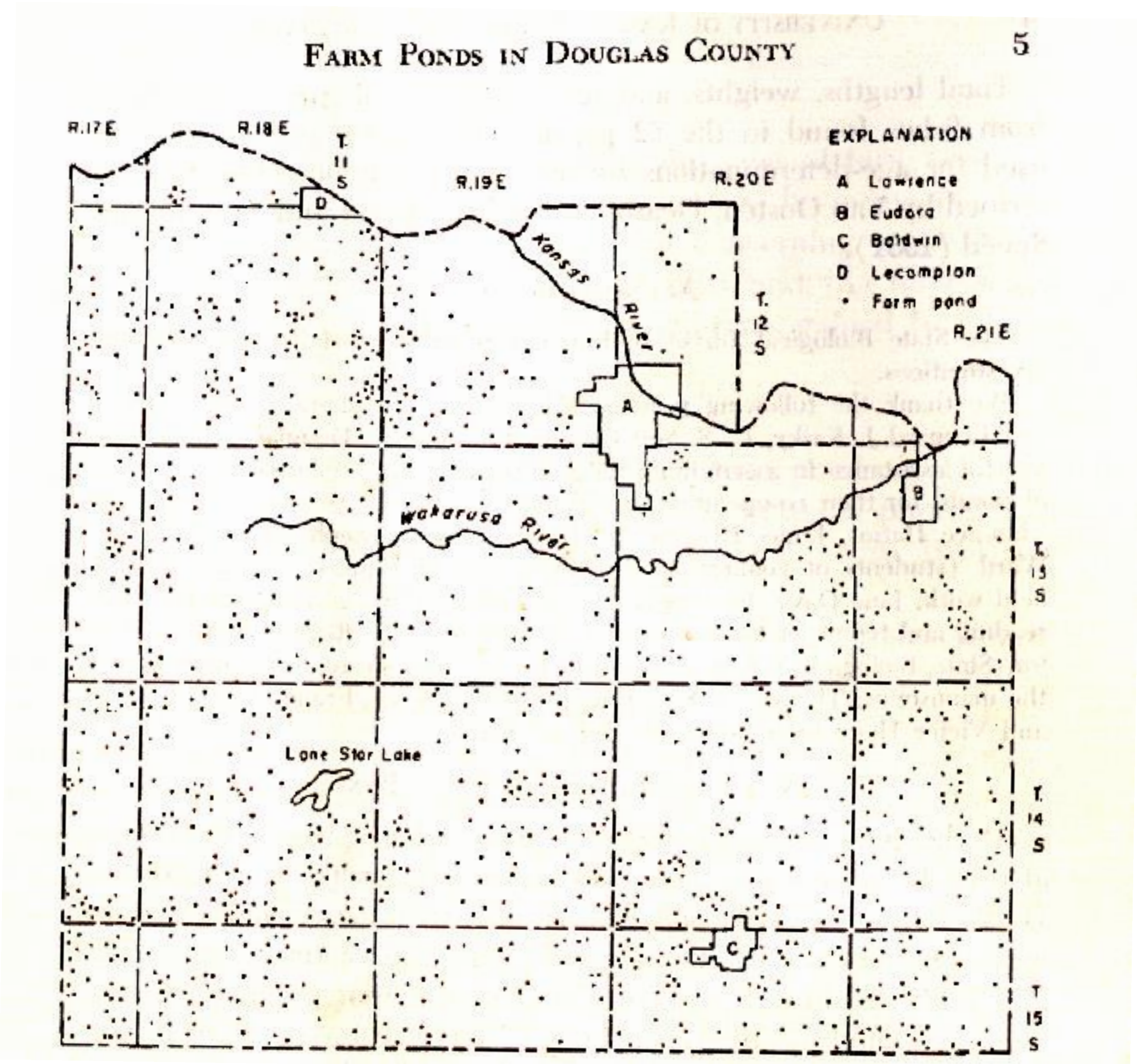


Figure 3.

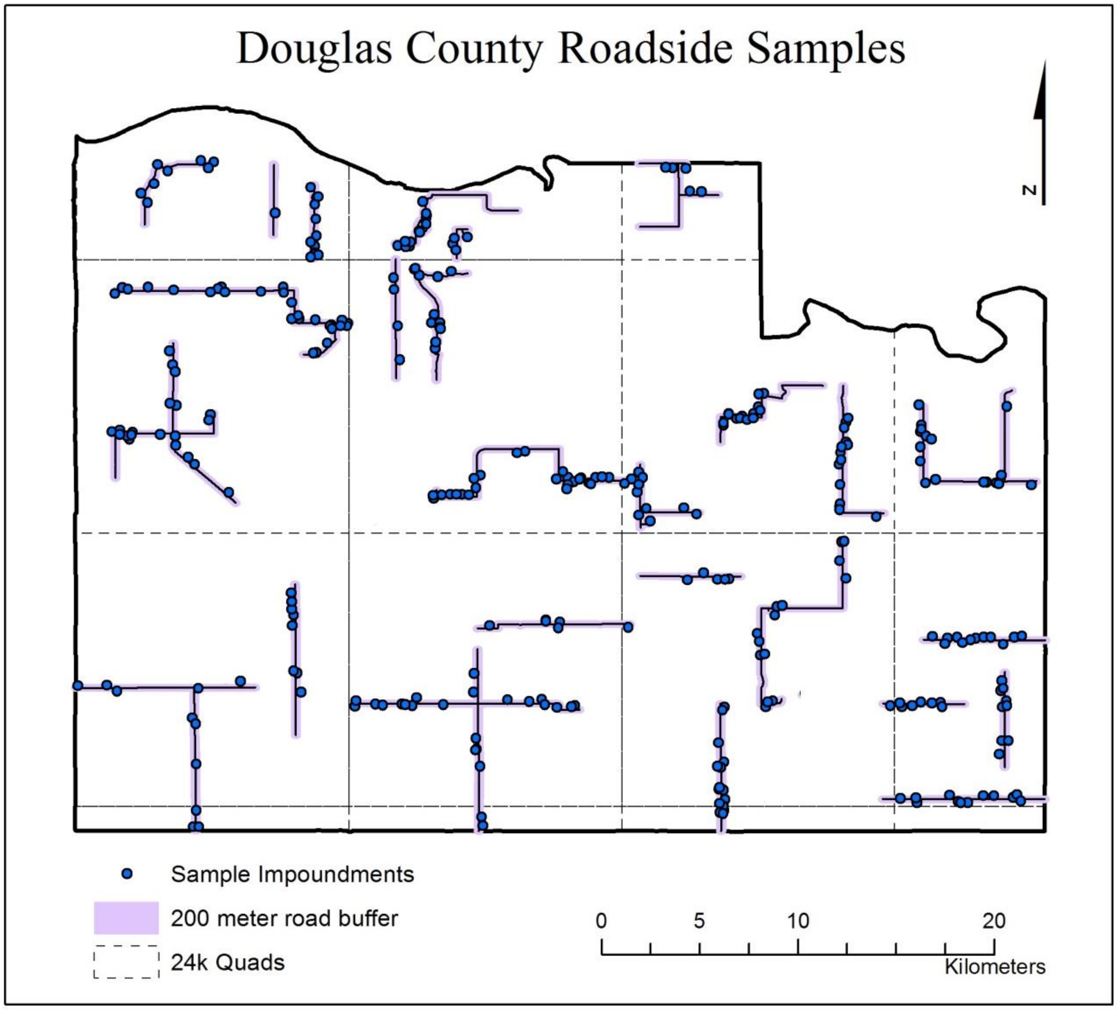

Douglas County Roadside Samples
N
Sample Impoundments
200 meter road buffer
24k Quads
0
5
10
20
Kilometers

Figure 4. Typical "Recreational/Aesthetic" impoundment. Location: Near Baldwin City

Figure 5. Typical small impoundment for livestock (i.e. "farm pond").

Figure 6. Small impoundment classification schema.

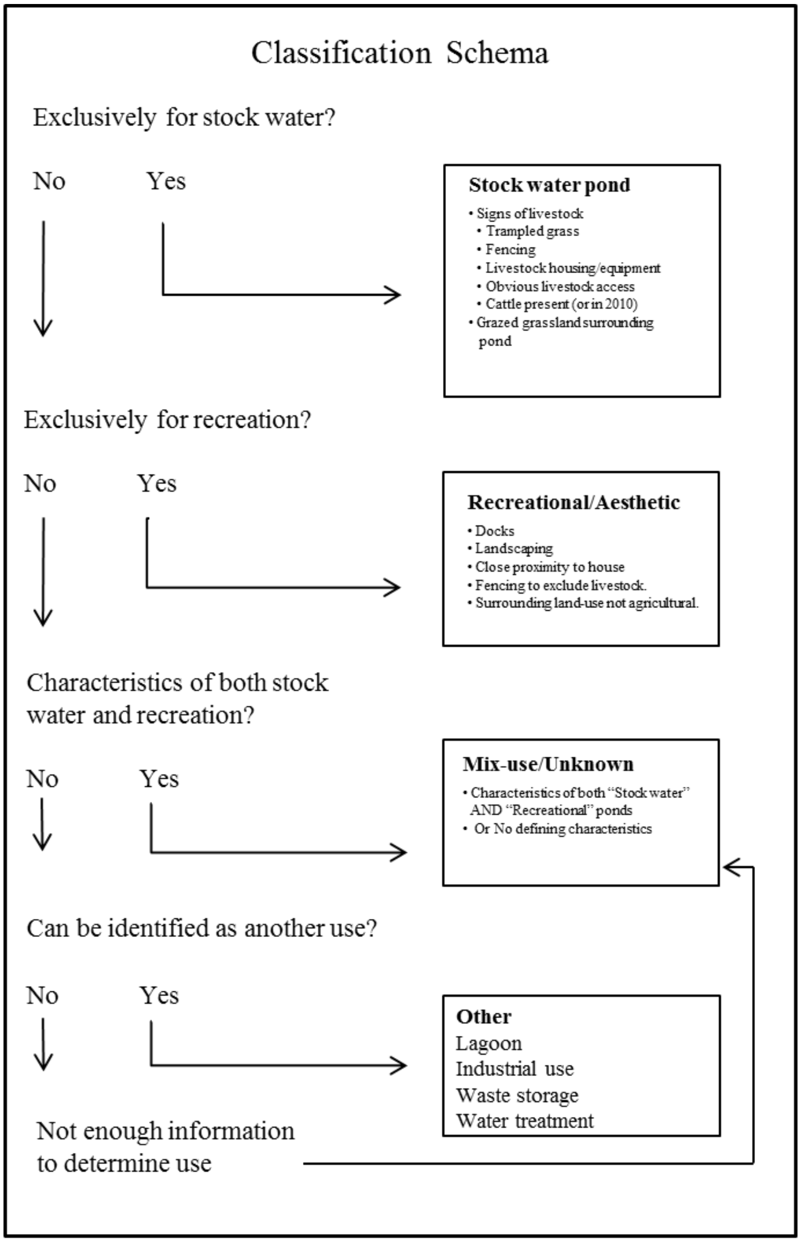


Figure 7.

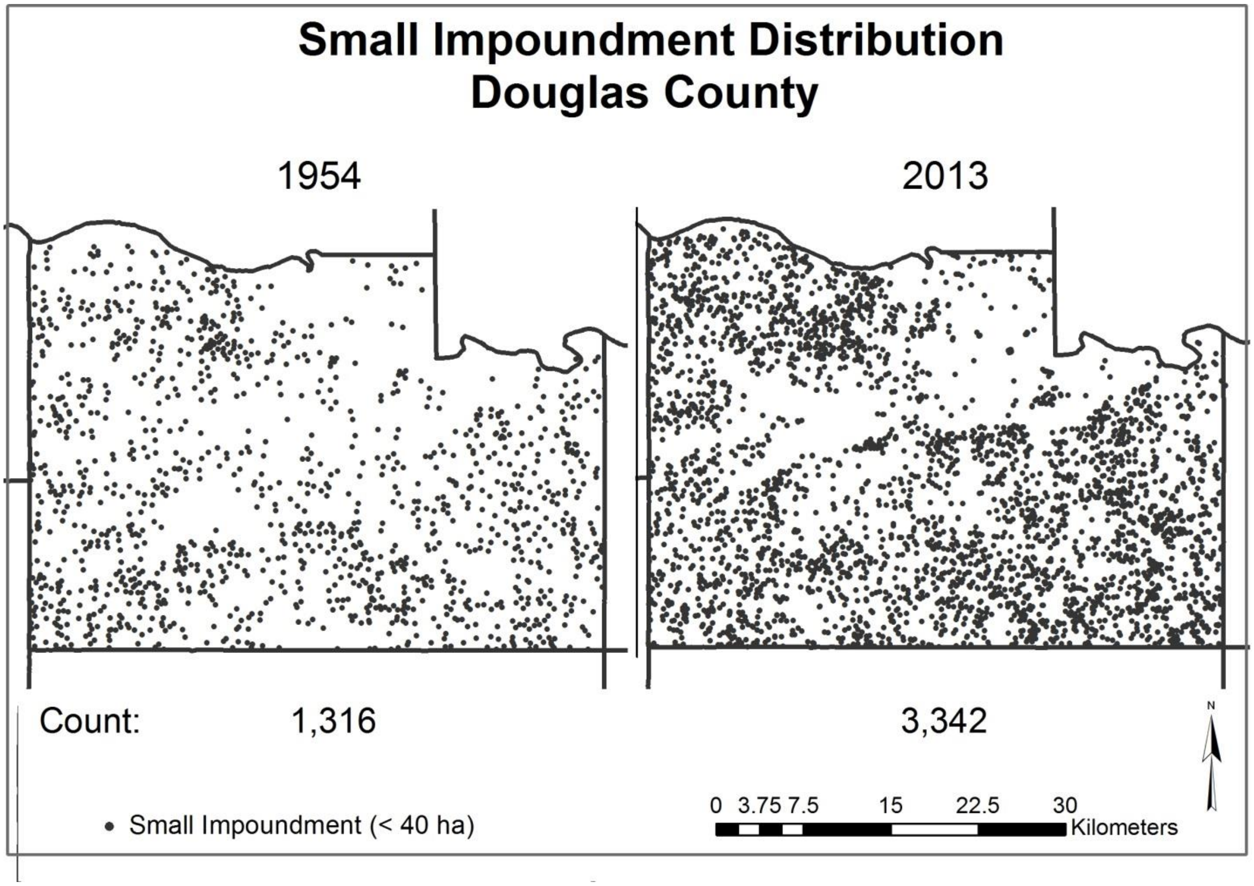
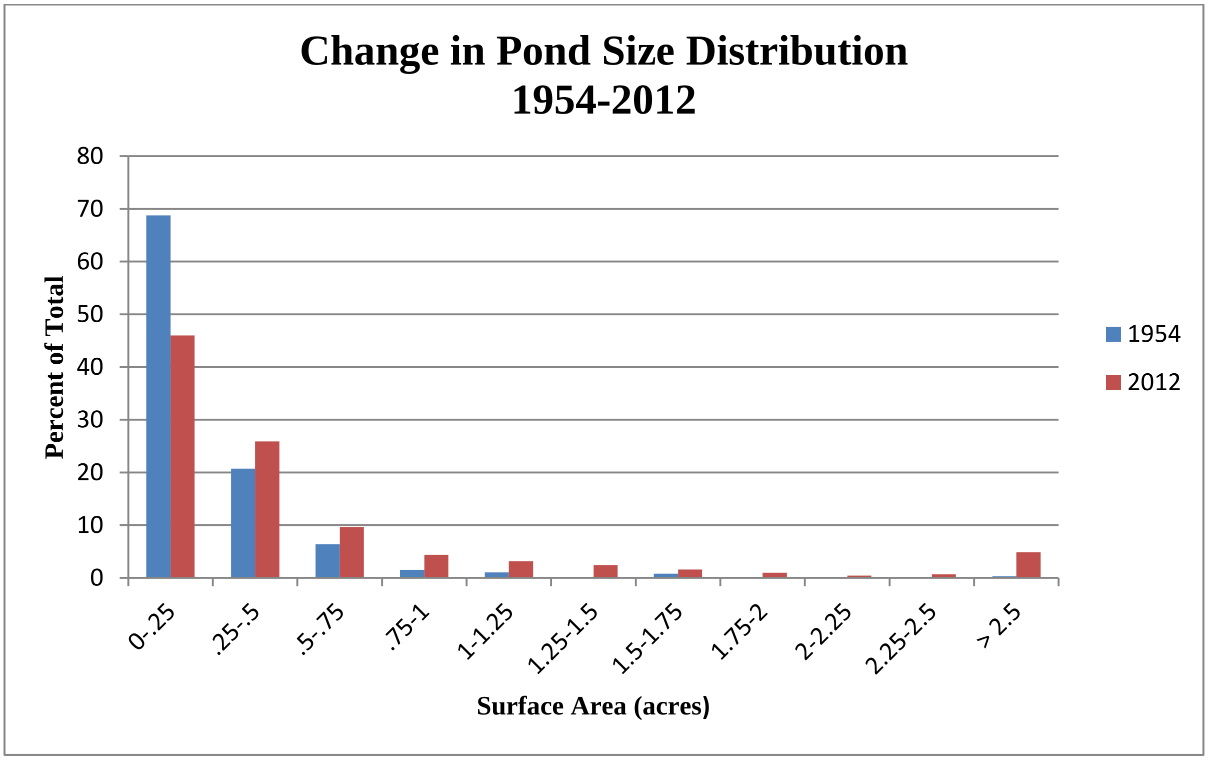

Small Impoundment Distribution
Douglas County
1954
2013
Count:
1,316
3,342
N
0 3.75 7.5 15 22.5 30
Kilometers
Small Impoundment (< 40 ha)

Figure 8.



Change in Pond Size Distribution
1954-2012
Percent of Total
80
70
60
50
40
30
20
10
0
0-.25
.25-.5
.5-.75
.75-1
1-1.25
1.25-1.5
1.5-1.75
1.75-2
2-2.25
2.25-2.5
> 2.5
Surface Area (acres)
1954
2012

Table 1. Change in size distribution of small impoundments from 1954 to 2012.

Size Range	1954		2013	
(acres)	Number of Ponds	Percent of Total	Number of Ponds	Percent of Total
0-.25	906	68.8	1536	46.0
.25-.5	272	20.7	864	25.9
.5-.75	84	6.4	322	9.6
.75-1	19	1.5	146	4.4
1-1.25	13	1	106	3.2
1.25-1.5	3	0.2	82	2.5
1.5-1.75	11	0.8	53	1.6
1.75-2	3	0.2	33	1.0
2-2.25	1	0.1	15	0.4
2.25-2.5	0	0	23	0.7
> 2.5	4	0.3	162	4.8
Total	1316	100.0	3342	100.0

Table 2. Douglas County Impoundment Survey Results

		Count	Percent of Total
Pond Use	Dominant Recreation	67	26.9%
	Dominant Livestock	103	41.4%
	Mixture/Unknown	76	30.5%
	Other	3	1.2%
Type	Embankment	226	90.8%
	Excavated	19	7.6%
	Levee	4	1.6%
	Dilapidated/Silted	37	14.9%
	Total Impoundments Surveyed:	**249**	

Chapter IV

Conclusion

"The tremendous increase in (small) reservoir construction beginning in the twentieth century is an *<u>unfolding</u>* *experiment as to how the human capture of hydrological flows alters ecological systems and the human systems coupled to them."* Ignatius and Stallins (2011)

Summary

The high proliferation of impoundments in the 20th century coupled may be one of the most profound, yet ignored, anthropogenic changes to the natural landscape (Downing, 2010; Smith, Renwick, Bartley, & Buddemeier, 2002). Particularly in Kansas, we have taken a landscape once remarkably deficient in surface water and created one of the more reservoir dense and impounded landscapes in the US (Graf, 1999; McDonald, Rover, Stets, & Striegel, 2012; Smith et al., 2002). Existing water bodies in Kansas, which number over 200,000, are almost entirely the result of human development (Callihan, 2011; Stene, 1946), and the rate of construction has not declined, even as the large dam building culture of the mid-20th century has ended (Renwick, et al. 2005).

This thesis sought to add to a very recent and growing body of literature concerned with the documenting small impoundment occurrence and describing their impact to the hydrologic and ecological landscape. Particularly, this research focused on the state of Kansas, a large region with a high concentration of small impoundments. The research in Chapter 2 inventories their occurrence, describes their spatial distribution and proliferation over time, and makes some attempt to quantify their significance to regional hydrology and ecology. In an attempt to understand the drivers of impoundment proliferation over time, Chapter 3 quantified both the change in their occurrence and their usage over a 60 year period in Douglas County, Kansas.

The results of Chapter 2 showed that the 20th century construction of small impoundments constitutes a substantial change to the surface water of Kansas. In 1936, Kansans had built 2,236 small impoundments dispersed mostly in the central regions of the state. Now, Kansas has 241,295 small impoundments that cover a surface area of 74,880 ha (288 mi^2), greater than all 24 Federal Kansas reservoirs combined. While the small impoundments in Kansas dominate both in occurrence and surface area, the medium to large reservoirs in the state contain 83.8% of the surface water storage, highlighting the true hydrological dominance of Kansas's large reservoirs. In terms of hydrologic and stream ecological impacts, small impoundments have impounded Kansas streams 80,862 times, with the majority 90.9% on first order streams. Through the impounding of streams, nearly 7500 kilometers of original stream habitat have been converted to lacustrine habitat.

Chapter 3 highlighted the changing use of small impoundments in Douglas County, Kansas over time and, in doing so, exposed some potential reasons they have continued to proliferate in parts of Kansas and the US. From the results, the number of small impoundments in Douglas County increased 153% from 1954 to 2012. Of the 1,316 impoundments present in 1954, only 484, or 36.7 % of the original, remained in 2012, indicating that 85% of current impoundments were built after 1954. While stock water ponds were overwhelmingly dominant in 1950's, by 2013 only 41% appeared to be mainly for the purposes of maintaining stock water. Over time, impoundment uses appear to have shifted away from stock water ponds to more recreational and aesthetic ponds that are now the dominant purpose of at least 26.9% of impoundments. It is speculated that the rise is recreational/aesthetic impoundments is tied to the increase in ‘exurban’ land-use and in driving recent impoundment proliferation in Kansas and possibly other regions of the US.

Further Research

The research and writing of this thesis uncovered many potential avenues to further understand both how impoundments are proliferating and how they impact the landscape. Only a few ideas will be highlighted here.

First, the few analyses done to estimate the significance of impoundments in Chapter 2 in no way gives justice to the myriad of chemical, hydrological, ecological, and climatic impacts that a landscape with an increasingly high density of impoundments may experience. For example, a very important area of potential research, especially in Kansas, is how small impoundments impact the flow of sediment throughout the landscape. Some studies have calculated the sediment trap capacity of individual small impoundments, but little research has considered the large-scale storage capacity of many small impoundments (Brainard & Fairchild, 2012; Dendy, 1974; Renwick, Smith, Bartley, & Buddemeier, 2005). In Kansas, it would particularly valuable to quantify the volume of sediment that small impoundments prevent from flowing downstream into the region’s large and expensive federal reservoirs.

While this study made some attempt to quantify the stream ecological impact of Kansas small impoundments, there are many unanswered questions, especially in how an increasingly impounded landscape negatively or positively effects regional ecology. For example, Kansas contained very few non-stream water bodies before human settlement, so how has the recent proliferation of small impoundments affected the mobility of aquatic and semi-aquatic biota that thrive in lacustrine conditions? Also, much research has focused on the effect of large impoundments on stream biota, chemistry, and geomorphic characteristics, but we have very little understanding of these sample ecological principles in regards to small constructed impoundments (Ebel & Lowe, 2013). For example, how does the deceleration and reduced variability of stream flow caused by small impoundments impact the natural biota of Kansas streams? Altered flow regimes caused by small impoundments may be particularly important in Kansas's ephemeral streams where biota may be more sensitive to subtle changes in stream flow.

Finally, of most interest to the author are the current factors that continue to drive the proliferation of small impoundments. In particular, while the research in this thesis provided evidence of a relationship between the 'exurban' activities as a possible factor in impoundment construction, a statistical causal relationship could be established on a large-scale. If the exurban areas are driving the proliferation of impoundments, we must consider the long-term consequences of this type of anthropomorphic change, which may provoke some interesting questions in environmental ethics in land-use planning. For example, if a high concentration of exurban impoundments prove to cause negative downstream effects on the area's stream biota, how do we weigh the importance of aesthetic and recreational ponds, which some may argue have little functional value, over regional biodiversity or stream function?

No matter the drivers of impoundment proliferation, we must continue to explore the ecological, climatic, hydrologic thresholds or ability of any given region to sustain high densities of impoundments. Currently, small impoundments are built in a decentralized nature with little to no foresight into regional watershed planning. Without this knowledge, the non-planned, iterative, rising number of impounded streams by small impoundments may eventually overwhelm a watershed's ecosystem through changes in stream water flow. As impoundment numbers appear to continuously increase, proper insight into their impacts will help prevent this case of "run-away" growth of impoundments.

Significance

Kansas is currently facing both quality and quantity problems that restrict our ability to use water as a resource and degrades regional habitat. Small impoundments in Kansas directly and indirectly affect these water quality and quantity impairments through biogeochemical interactions and sediment retention. Because small impoundments influence the processes that impair water in Kansas, quantifying their development, distribution, and overall impact will lead more informed decision making regarding the future of water in the State. The Kansas Small Impoundment Inventory developed here is currently the most comprehensive representation of Kansas small artificial water bodies.

Beyond value to the state, the provided insight into the temporal change in impoundment use will add to the current knowledge gap about the causes of impoundment proliferation. Since the US is experiencing growth in impoundment numbers and these impoundment have large-scale, but mostly unknown, biogeochemical impacts, it would be prudent to not only fully understand their extent, but the factors causing their proliferation.

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