Interbasin Transfers and Water Risk in the United States

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ABSTRACT

Some parts of the U.S. have strained or insufficient local water supplies to meet the demands of population, industry and agriculture located in the region. Some areas with insufficient water supply have long implemented measures to address the shortfall through transferring water from other basins. New York City obtains almost 97% of its water and Los Angeles over 90% from interbasin transfers (IBTs).

With climate change affecting precipitation and temperature patterns across the U.S., coupled with growth in population and the economy leading to changes in demand, planning for risks to water supplies is critical to ensuring continued supply of water for all U.S. regions. Assessment of areas of high and low water risk can provide insights into potential changes in availability for existing supply, and aid in decision making for mitigating forecasted risks to local water supply. Implementation of IBTs historically has been one approach for addressing water supply risks.

The overarching goal of this research was to examine the role of IBTs for water resource supply and management in the U.S. Specific objectives were as follows:

1. Quantify the number of IBTs that exist at a defined hydrologic unit code (HUC) level in the U.S. and examine the distribution of IBTs and potential causes associated with any observed clustering of IBTs.

2. Characterize and classify IBTs, and examine the development drivers for a subset of IBTs in the U.S through sampling in different climate regions of the U.S.
3. Examine the water risks in the U.S. by county, considering both current and future conditions and accounting for natural water importation through streams and rivers, and consider the role of IBTs in mitigating these risks.

As part of the first objective, the definition of what constitutes a “basin” was required to assess man-made transfers that cross those basin boundaries. There are several definitions utilized by different states, with no federal definition. The most recent inventory of IBTs was conducted by the USGS in 1985 and 1986 using the HUC4 level. To build a new inventory of IBTs in the U.S., the National Hydrography Dataset (NHD) was utilized, combined with the Watershed Boundary Dataset (WBD). Man-made transfers across basin boundaries at the HUC6 level were considered to be interbasin. Geographic Information Systems (GIS) analysis showed that as of 2016 there were 2,161 IBTs crossing HUC6 boundaries in the U.S. These were located across the country, although over 50% of those identified were located in Florida, Texas or North Carolina. Some clustering of IBTs was observed in various states and analysis of the clustering suggested a variety of reasons for IBT construction, including population, drainage and agricultural factors. However, the flow volumes associated with the IBTs identified could not be evaluated due to a lack of available data at both the state and federal level.

The second objective expanded upon this analysis, examining a subset of 109 (5%) of the identified IBT reaches within the various climate regions of the U.S. To characterize and classify the IBTs each was labeled as being near irrigated agricultural land, near cities, or rural for those not near either cities or irrigated land. IBTs in proximity to both cities and irrigated agricultural lands were given the designation city+irrigated agriculture. Selection of IBTs for this analysis was based on the approximate proportional distribution of the total number of IBTs within each climate region and included representation of IBT clusters identified as part of the first objective. The results of the analysis showed that there have been four major drivers behind the construction of IBTs in the U.S.: irrigation for agriculture, municipal and industrial water supply, commercial shipping or navigation, and drainage or flood management. The most common factor for IBT construction has been to enable drainage or flood management. IBT development for agricultural needs has also been prevalent. The majority of IBTs examined were constructed between 1880 and 1980, with peaks in construction occurring between 1900-1910 and 1960-1970. The case studies examined showed that drivers of IBT development evolved through history, reflecting the changes in U.S. and regional economies, populations and needs.

To examine the risks associated with the U.S. water supply a new Water Risk Index (WRI) was developed, building upon and advancing a prior risk analysis developed by Roy et al. (2012). The Roy et al. work utilized risk factors that focused upon local precipitation, demand and evapotranspiration, without examining the natural flow of water between counties. To produce the WRI the analysis utilized the 2015 USGS Water Use Report data and projected water use in 2050, assuming only municipal and domestic water demand and thermoelectric power water withdrawal demand would change over time as per Roy et al. (2012). To calculate the flow volumes for each county the Water Supply Sustainability Index (WaSSI) developed by the USDA Forest Service (Sun, 2008) was used. The WaSSI model allowed for the analysis to include changes in climate and related hydrology as well as the evolving water demand. The WRI calculated water supply risk for each county in the contiguous U.S. The WRI calculation includes comparisons of water withdrawal to local flow volume, the drought susceptibility during summer for both the present and future, the projected growth in water demand, and the proportion of groundwater use relative to total water demand. This risk index provides a scaled value system that provides context to each individual risk factor included. The results of this showed that while some counties are regarded as high or very high risk, there are significantly fewer than those identified by the Roy et al. (2012) analysis. A maximum of 36 counties were identified as high or very high risk within the scenarios examined as part of the WRI analysis, in comparison to over 400 in the previous analysis. The highest risk areas are located in the west, with most counties determined to be at very high risk located in California. Most of the counties with negligible risk are located in Montana and Wyoming, as well as Colorado west of the continental divide.

This research provides insights into locations within the U.S. that may have high risks to their water supplies, and into the role that current or potential IBTs can have to mitigate those risks. In addition, the methods developed can help support planners to identify low risk locations to examine for their potential to support IBT water supply solutions while accounting for the downstream impacts such diversions may cause. To ensure that the U.S. maintains a consistent and secure water supply all options must be considered for their viability, including the potential for moving water from where it is plentiful to areas it is not.

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Chapter 1 : Introduction

1.1 Water Resources and Development

Since the earliest recorded histories of civilization, water has been a central part of human existence. Many of the earliest empires, such as Egypt, Babylon and Rome, started upon rivers that were used to farm lands through irrigation and cities such as Petra used clever engineering to awe visitors with the unlikely sight of water cascading through a city in the middle of a desert (Mithen, 2012).

Globally importance of water to populations hasn't changed from those times. Major cities are often located on the shores of rivers, and this is particularly true in the U.S. Early U.S. cities were by necessity coastal, with settlers arriving from the sea, and in the first 100 years of movement of population to the North American Continent the colonizers built along the coastline, mostly in proximity to inlets and natural harbors (University of Groningen, 2005). The earliest population centers during this colonial period were commercial ports in the north, with Boston, Philadelphia and New York reaping the benefits of trade across the Atlantic (Roth, 1918). Of the five most populous cities in the U.S. in 2017 (Census Bureau, 2018), all were founded on rivers, with three located on the ocean; New York, Los Angeles and Houston, and one on the Great Lakes; Chicago. The final city, Phoenix, was founded on land that had previously been settled and still bore the design of irrigation canals built by the Hohokam tribe over 400 years prior (Arizona Experience, 2018).

Since the early settlements though, the human relationship with water has changed. New industries exerting water demand such as electrical power generation combined with a growing population have driven human needs for water ever higher.

While New York and Los Angeles were founded on rivers, the rapidly increasing demand for water strained the ability of the local sources to provide it. New York City grew from a population of 60,000 to 200,000 between 1800 and 1830, with brackish water and quality problems plaguing the city during this period both in surface and groundwater supplies (National Research Council, 2000). The solution for New York was a simple idea at the time; they could import the water through man-made means, moving water in a similar fashion to the Romans millennia ago. However, the implementation was both expensive and difficult to engineer during this period of history. The Croton River Project was the first project of this scale since the Roman Empire and the arrival of water in Manhattan on July 4th, 1842 was a celebrated event (National Research Council, 2000). The city of New York today imports about 90% of its water from the Catskill and Delaware watersheds, even further away than the Croton River Project, (NYS DEC, 2017), while Los Angeles imports more than 90% of its water from multiple sources including the Colorado River, over 200 miles away (Ashoori et al., 2015).

With the knowledge of the importance of water to the economic health and prosperity of not just cities, but entire states, the allocation of this natural resource is a contentious issue in many water-stressed areas of the world, including the U.S. This may be seen in the landmark compact formed among seven U.S. states in 1922 to share the water of the Colorado River among these arid western states (National Research Council, 2007).

However, the compact was unable to prevent friction between California and Arizona about the right to make use of the Colorado River according to their individual interpretations of the compact. After 25 years of impasse, the U.S. Supreme Court was required to make the final decision regarding the allocation of water for the two states (USBR, 2008).

Issues about water resource allocation have not been only in the western U.S. For example, North Carolina and Virginia long discussed the Lake Gaston Water Transfer desired by Virginia, with final resolution in 1998 (Cox, 2007). Also, Georgia, Florida and Alabama have had a long-standing negotiation over the flow of water resources among them, with a Supreme Court case still pending in 2018 after referral back to a court appointed special master (King, 2018).

Many of the U.S. water allocation disputes stem from the desire of each state to increase its use of a natural resource. However, the ability of watersheds to provide the desired withdrawals is under question, with drought and other climate impacts being felt across the country (Christensen et al., 2004; EPA, 2016; Frederick and Major, 1997; Hamlet and Lettenmaier, 2007; White et al. 2006). For the states in the Lower Colorado River Basin, for example, the Colorado River compact was adjusted to account for the potential critical drop in the level of Lake Mead, reducing the allocation permitted for each of the states downstream based on the lake's level (USBR, 2007). With potential constraints on the existing water supply and a growing population, the risk to U.S. states to continue to provide adequate water supplies needs to be assessed and considered in decision making processes, as well as examining the potential solutions for those areas demonstrated to be at risk.

1.2 Interbasin Transfers

Water resource allocations in the U.S. are dependent in many areas on interbasin transfers (IBTs), and new IBTs may be needed to meet future water demands. The knowledge base for IBT infrastructure is lacking, however. Some large scale IBTs are well known, such as the Catskill and Delaware Aqueducts, which supply the city of New York; the Central Arizona Project, which conveys Arizona's allocation from the Colorado River across the state for uses including both agriculture and the city of Phoenix; and the Los Angeles Aqueduct, providing water to the city of Los Angeles. However, IBTs in general are not well documented.

The U.S. Geological Survey (USGS) conducted examinations of IBTs in the U.S. in the mid 1980s by surveys, with one study examining the east (Mooty and Jeffcoat, 1986) and one examining the west (Petsch, 1985). The lack of IBT knowledge provides a challenge to water resource planners on multiple fronts. Water flow modelling in particular is difficult without the knowledge of diversions that move water from donor basins to recipient basins as this impacts downstream watersheds in both basins (Emanuel et al., 2015). Additionally, it is important to discover what the water risks are in the U.S. and the drivers of demand to help understand locations that may face pressure to implement diversions to alleviate water shortages, as well as regions that may be suitable as donors. This will be impacted by the evolving demands of the U.S. population as it grows.

This dissertation examines IBTs in the contiguous U.S., providing information for water planners regarding the number and location of IBTs, the factors driving the construction of IBTs, and risks to the U.S. water supply and the potential role of IBTs to help mitigate these risks. Through analyzing these topics, water resource planning can be conducted effectively and ensure that changes in climate and demand are less likely to have severe impacts on local or regional water supply.

1.3 Research Objectives

This research had three individual objectives to meet the overall goal of examining the role of interbasin transfers for water resource supply and management in the U.S.

1. Quantify the number of IBTs that exist at a defined hydrologic unit code (HUC) level in the U.S. and examine the distribution of IBTs and potential causes associated with any observed clustering of IBTs.
2. Characterize and classify IBTs, and examine the development drivers for a subset of IBTs in the U.S through sampling in different climate regions of the U.S.
3. Examine the water risks in the U.S. by county, considering both current and future conditions and accounting for natural water importation through streams and rivers, and consider the role of IBTs in mitigating these risks.

These three objectives were chosen to provide information regarding IBTs and water risk in the U.S. Through knowledge of IBTs, it is possible for water resource planners to account for the existing movement of water throughout the U.S. and make improved projections regarding areas of high water supply risk, identify existing IBTs that may not provide sufficient supply due to changing climate and demands, and, with knowledge of why IBTs were built, determine locations that may face pressure to expand or construct IBTs.

1.4 Dissertation Structure

This dissertation consists of five chapters, of which the three central chapters either have been or will be submitted for publication in peer-reviewed journals. Chapter 2 of the dissertation contains an inventory of IBTs in the contiguous United States, providing an update on the 1985-1986 work by the USGS. The analysis makes use of tools and databases that have been developed during the intervening years to map the location of IBTs and also provide some potential reasons for the spatial distribution of the identified IBTs. Chapter 3 expands upon this by sampling a subset of the IBTs identified in Chapter 2, to provide information regarding when the IBT was built and the driver, or drivers, that resulted in the IBT's construction. The analysis examines these factors by U.S. climate regions defined by the National Oceanic and Atmospheric Administration (NOAA) to aid in understanding the role of climate as a factor in the history of IBT construction. Chapter 4 builds upon a previous water risk index developed by Roy et al. (2012). The new analysis utilizes a water balance model from the U.S. Forest Service (Sun, 2008; U.S. Forest Service, 2018) to produce a water risk index that accounts for natural importation of water from upstream watersheds, rather than solely examining local demand and precipitation factors as was done by Roy et al. The water risk index examines factors that include both current and projected future conditions under different growth and climate scenarios. Chapter 4 also includes a mapping of calculated water risk by county for the

U.S. with an overlay of the IBTs identified by the work in Chapter 2, to provide insight into areas that are identified as high water risk. Such areas may have their supplies supplemented by existing diversions, as well as diversions that may by impacted by water supply risk. The mapping also indicates areas of low water risk that could be examined as potential donors for higher risk counties. The final chapter summarizes the findings of the studies and discusses the implications and limitations of the results, and provides recommendations regarding potential follow-up research.

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Chapter 2 : Inventory of Interbasin Transfers in the United States

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2.1 Abstract

Interbasin Transfers (IBTs) are man-made transfers of water that cross basin boundaries. These transfers are used to distribute water resources according to supply and demand. The objectives of this work were to quantify the number of IBTs that exist in the United States and to examine the distribution of IBTs and potential causes associated with any observed clustering of IBTs. Defining “basin” was important to enable determination of which transfers qualify as “interbasin”. A variety of definitions are employed by states, with no federal definition. The most recent national studies of IBTs were conducted by the U.S. Geological Survey in 1985 and 1986 using USGS Hydrologic Unit Code (HUC) definitions of basins. To build a 2016 inventory of IBTs in the U.S., and to identify where they most commonly occur, the USGS National Hydrographic Database (NHD) was utilized in conjunction with the Watershed Boundary Dataset (WBD). Transfers across HUC6 basin boundaries were considered interbasin. Geographical information analysis with the NHD and WBD databases revealed that there are a total of 2,160 man-made waterways crossing HUC6 basin boundaries in the U.S. IBTs are somewhat concentrated: Florida, Texas and North Carolina account for over 50% of the total identified IBTs. For some states, identified IBTs are locally clustered. Analysis of these clusters suggests a variety of reasons that IBTs have been built, including population, drainage and agricultural factors.

2.2 Introduction

Since the invention of the aqueduct, civilizations throughout history have utilized man-made conveyances to move water to where it was needed (Mays 2007). In the millennia that have passed since the earliest examples of water transfer, humanity has expanded across the globe and developed many uses for water, including power generation, navigation, and others.

Interbasin Transfers (IBTs) are a subset of water transfers, being defined as the transfer of water through a man-made conveyance across a basin boundary. These can occur with both surface water and groundwater, although basin delineations for each differ. Surface water basins are defined through topographic features, which determine the direction of water flow within a basin, in contrast to groundwater basins which are defined by geologic features that yield complex flow processes within them due to varying porous media properties. Many well known surface water IBTs exist in the United States, such as the Catskill and Delaware Aqueducts, which supply the city of New York; the Central Arizona Project, which distributes Arizona's allocation from the Colorado River across the state for uses including both agriculture and the city of Phoenix; and the Los Angeles Aqueduct, providing water to the city of Los Angeles. The city of New York, for example, imports approximately 90% of its water from the Catskill and Delaware watersheds (NYS DEC, 2017), while Los Angeles imports more than 90% of its water from multiple sources (Ashoori et al., 2015), showing that this form of supply can be essential for cities. The long reach of urban water infrastructure has been documented, with 10% or more of large cities worldwide moving water across basins (McDonald et al. 2014), and examination of

U.S. cities has shown that over 15% of the U.S. population can be considered “at risk” for water scarcity (Padowski and Jawitz, 2012). Thus, to understand the water supply landscape in the U.S. it is essential that IBTs are considered during planning, ensuring supplies can meet evolving demands.

For the United States there are inherent challenges in classifying IBTs due to the scale of the country, resulting in basins being defined at multiple levels and in different ways by some states, and no federal agency that maintains a database of man-made transfers of water, either inter- or intra-state. The most recent national study of IBTs in the U.S. was conducted by the U.S. Geological Survey (USGS) via a survey methodology (Petsch, 1985; Mooty and Jeffcoat, 1986). The studies examined the existence of IBTs through investigation of man-made water transfers across boundaries defined by the USGS called Hydrologic Unit Codes (HUCs). Petsch (1985) examined the western coterminous U.S. and found 111 IBTs, of which 21 had been constructed in the decade prior to the study. Of the 111 HUC4 regions examined in the study, only 39 exported water. Mooty and Jeffcoat (1986) found more IBTs in the eastern coterminous U.S., 145 in only 95 HUC4 regions examined, although a higher proportion of the HUC4s had exports. The volumes of water transferred were also examined and although there were fewer IBTs identified in the west, the total volume transferred was higher.

There have been studies of IBTs within individual states and basins. Examination of state standards and information revealed several definitions of what constitutes an IBT. In Nevada a state system called the Hydrologic Area (HA) is used instead of the USGS HUCs (NDWR, 2013). Both Oklahoma and New York State use the USGS HUCs when defining IBTs, but use different levels to do so. Oklahoma considers IBTs to be man-made water transfers across HUC12 boundaries (Mills, 2016) while New York State considers an IBT to be transfers across HUC8 boundaries (NYS DEC, 2012).

The Ohio River Valley Water Sanitation Commission (ORSANCO) investigated IBTs leaving the Ohio River Basin (ORSANCO, 2014). This study examined the flows exiting and entering the Ohio River basin at the HUC8 level.

Other studies have examined factors such as environmental considerations, economic justifications and the potential for IBTs in regional water management. For example the interactions between IBTs and the Clean Water Act (Schroeder and Woodcock, 2011) and the effects of IBT connectivity on fish biodiversity (Grant et al., 2012) provide insights into the environmental impacts of IBTs. Economic, water-quality-based modelling has been conducted with a focus on IBTs (Karamouz et al. 2010), to investigate the feasibility of transfer projects using optimization models with the objective of maximizing net benefits. Potential and existing water rights conflicts between states (Cox, 2007) have also been examined. In the case of North Carolina and Virginia, the conflict was concerning the Lake Gaston Water Transfer, which North Carolina opposed, though it was finally completed in 1998, after years of controversy.

Management of regional water resources with IBTs, taking into account climate forecasts, is another aspect that has been explored (Li et al., 2014). The distribution of water from regional transfers has also been tracked utilizing stable isotope comparisons in the water supply, to identify if non-local water sources are present at the end use location (Good et al., 2014).

Despite these investigations of topics related to existing IBTs, a national inventory of IBTs present in the U.S. has not been conducted since the USGS studies of 1985-1986, likely due to the difficulties associated with the survey approach previously utilized, or other labor-intensive investigative approaches. However, with the development of technological advancements, several new tools are available in approaching the mapping of water in the United States. The USGS National Hydrographic Database (NHD) and its evolution have been documented (Moore and Dewald, 2016), and the importance of access to open data on water on a large scale is now well recognized (Bales, 2016). The range of applications for the NHD data has been widespread, e.g., in modeling streamflow and water quality sensitivity (Johnson et al., 2015), and in integrated GIS (Geographic Information System) and water resource modelling (Martin et al., 2005) utilizing a variety of methods (Tavernia et al., 2013; Payne and Woessner, 2010). Volumetric flow data for each reach are not currently available directly through the NHD. While this provides a barrier in examining the impact each IBT has on the basins involved in each transfer, knowledge of IBT locations provides information that can be used to search for flow data for specific reaches and basins.

The objectives of this work were to quantify the number of IBTs that exist at a defined HUC level in the United States, and to examine the distribution of IBTs and potential causes associated with any observed clustering of IBTs. Geographical information analysis was employed with use of the USGS National Hydrographic Database.

2.3 Methodology

2.3.1 HUC System

The HUC system was created by the USGS and defines drainage basins across the U.S. (Seaber et al., 1987). These basins are divided and then further subdivided into several successively smaller levels (see Table 2-1). Each HUC level consists of two digits appended to the two digits of the HUC that they are enclosed within, up to the largest HUC classification. The first level of classifications, known as HUC2 in relation to the two-digit code associated with them, are called regions, of which there are 21 including Alaska, Hawaii, Puerto Rico and other outlying Caribbean islands. The subdivisions of these regions are known as HUC4 subregions. This is due to the two-digit subdivision identifying number being appended to the two-digit regional identifier, resulting in a four-digit unique identification code. These subdivisions can then themselves be divided, with a further two-digit unique identifier being applied, resulting in a six-digit HUC known as HUC6. The USGS has subdivided these areas even further, resulting in up to 16-digit codes being available to define an area.

Table 2-1 Example of the USGS Hydrologic Unit Code (HUC) Basin Idenfication System

Name	Level	Digits in Code	Average Size (km^2) (approx.)	Number of HUCs (approx.)	Example Name	Example Code
Region	1	2	460,000	21	South Atlantic-Gulf Region	03
Subregion	2	4	43,500	222	St. Johns	0308
Basin	3	6	27,440	370	St. Johns	030801
Subbasin	4	8	1,810	2,200	Upper St. Johns	03080101
Watershed	5	10	588	22,000	Crab Grass Creek	0308010104
Subwatershed	6	12	104	160,000	West Branch of Crab Grass Creek	030801010404

In their efforts to inventory IBTs in the contiguous U.S., Petsch (1985) and Mooty and Jeffcoat (1986) requested survey data in the form of HUC8 information (Level 4 in Table 2-1). The surveys requested other details, including transfer volumes, but provided results referencing only HUC4 levels of information (Level 2 in Table 2-1).

For the inventory effort reported here, the HUC6 level was chosen as the basin size for IBTs. By choosing this classification level, more detailed results were obtained concerning the state of IBTs in the U.S. than was available from the 1985-1986 investigations (Petsch, 1985; Mooty and Jeffcoat, 1986). Additionally in the U.S. there are fewer than 350 HUC6 boundaries, so IBTs can be analyzed with higher spatial resolution than examination of HUC 2 or HUC 4 levels. While examination at even more focused spatial resolutions, such as HUC 8 or HUC 10, is technically feasible through this methodology, the HUC 8 level alone has in excess of 2,200 boundaries in the U.S. This would impact the ability to draw comparisons with the 1985-1986 investigations and potentially identify many additional flows across boundaries that would need to be investigated manually. Additionally, the average size of a HUC 4 is comparable to a HUC 6, whereas HUC 2 boundaries are an order of magnitude larger in area than HUC 4 boundaries and HUC 8 areas are an order of magnitude smaller than HUC 6 areas. This means that comparison of IBT numbers at other scales would make meaningful comparisons of results difficult.

2.3.2 National Hydrography Database

Data from the National Hydrographic Database (NHD) and the Water Boundary Dataset (WBD) (USGS, 2016a) were utilized to construct Geographic Information System maps for analysis. The NHD is a digital database containing a variety of surface water features that can be displayed and edited using GIS software. Each feature is encoded with data including a geographic location, allowing for an accurate map of surface water features in the U.S. to be constructed. The WBD provides the geographic locations and boundaries of HUCs, between HUC2 and HUC12, for the entire U.S., along with Puerto Rico and Caribbean Islands. The NHD data are available in both high resolution, nominally at a 1:24,000 scale, and medium resolution, 1:100,000 scale. In some areas the high resolution data can be at a higher scale than 1:24,000. This is due to submission of data by USGS partners, which provides a densified network of data in some instances.

The NHD has both individual state datasets and a national dataset. The state datasets were utilized for this work to facilitate processing, considering the large quantity of data within the national dataset formed by aggregating the state data. The files contain information on all surface water features in the respective states, forming a geometric network. The datasets are contained as layers of data within a geodatabase file, with each layer containing specific types of features, and some features appearing in multiple layers. Table 2-2 shows some of the layers that are included within the NHD and the features that are associated with them.

Table 2-2 National Hydrography Database Layers, Features and Descriptions (USGS, 2016c)

Layer Name	Features	Description
NHDFlowline	Artificial Path, CanalDitch, Coastline, Connector, Pipeline, StreamRiver, Underground Conduit	Features that make up the linear surface water drainage network, including flow direction
NHDWaterbody	Estuary, Ice Mass, LakePond, Playa, Reservoir, SwampMarsh	Regions that represent areal hydrographic waterbody features
NHDPoint	DamWeir, Gaging Station, Gate, Lock Chamber, Rapids, Reservoir, Rock, SinkRise, SpringSeep, Waterfall, WaterIntake/Outflow, Well	Point data concerning the locations of hydrographic landmark data
NHDLine	Bridge, DamWeir, Flume, Gate, Levee, Lock Chamber, Non Earthen Shore, Rapids, Reef, SinkRise, Sounding Datum Line, Tunnel, Wall, Waterfall	Linear hydrographic landmark features that are used for cartographic representation
NHDArea	Area of Complex Channels, Area to be Submerged, BayInlet, Bridge, CanalDitch, DamWeir, Flume, Foreshore, Inundation Area, Levee, Lock Chamber, Rapids, Sea Ocean, Spillway, StreamRiver, Submerged Stream, Wash, Water Intake/Outflow	Areal hydrographic landmark features

As this study focused on the transfer of surface water through man-made waterways, the NHD flowline data layer was utilized as a comprehensive directory of surface water flows. The features within this layer are defined in Table 2-3.

Table 2-3 Definitions and Descriptions of Features in the NHD Flowline Layer (USGS, 2016c)

Feature Name	Definition	Description
Artificial Path	Surrogate for general flow direction within NHDWaterbodies and NHDArea	This is a simulated line which represents water flow through larger water features that appear in the Waterbody and Area layers. This includes CanalDitch and StreamRiver features if they are of a large enough size to be present in the NHDArea layer. This feature can therefore be naturally occurring or man-made.
CanalDitch	An artificial open waterway which is for transportation of water, irrigation or drainage of land, to connect two or more water bodies, or to serve as a waterway for watercraft.	A man-made waterway of any size that is not featured in the NHDArea layer. This type of waterway could be utilized for a variety of purposes.
Coastline	An artificially generated line indicating the contact point between inland water bodies and the open sea	A representation of where the sea meets the coast, calculated by the National Ocean and Atmospheric Agency (NOAA)
Connector	A known, but non-specific, invisible connection between two nonadjacent network segments	This feature is used when there is a connection between two or more waterbodies that cannot be seen. This can include groundwater connecting lakes or pipes passing through a dam.
Pipeline	Closed conduits with pumps, valves and control devices that convey water.	An enclosed conveyance used to physically move liquids or gases, in this instance water
StreamRiver	Natural waterways including streams, rivers, sloughs and creeks	These are all natural surface water flows that are not also featured within the NHDWaterbody or NHDArea layers
Underground Conduit	A set of naturally occurring subsurface drainage channels formed from dissolution of soluble rock in Karst terrain, or terrain similar to Karst but formed in non-soluble rocks (e.g. melting of permafrost or ground ice), collapse after mining, or through outflow of liquid lava beneath solidified crust	This type of feature is a relatively rare occurrence and consists of waterways located beneath ground level; in caves or caverns that have been formed through either natural means or through the collapse of man-made subsurface structures.

Of the features listed in Table 2-3, only the "CanalDitch" and "Pipeline" features are always man-made. "Artificial Path" features are usually natural features, but could be man-made, requiring any instances of this feature crossing a basin boundary to be investigated further. The remaining features are naturally occurring and therefore do not need to be considered. Figure 2-1a and b present a schematic illustrating the various occurrences of the types of features listed within Table 2-3.

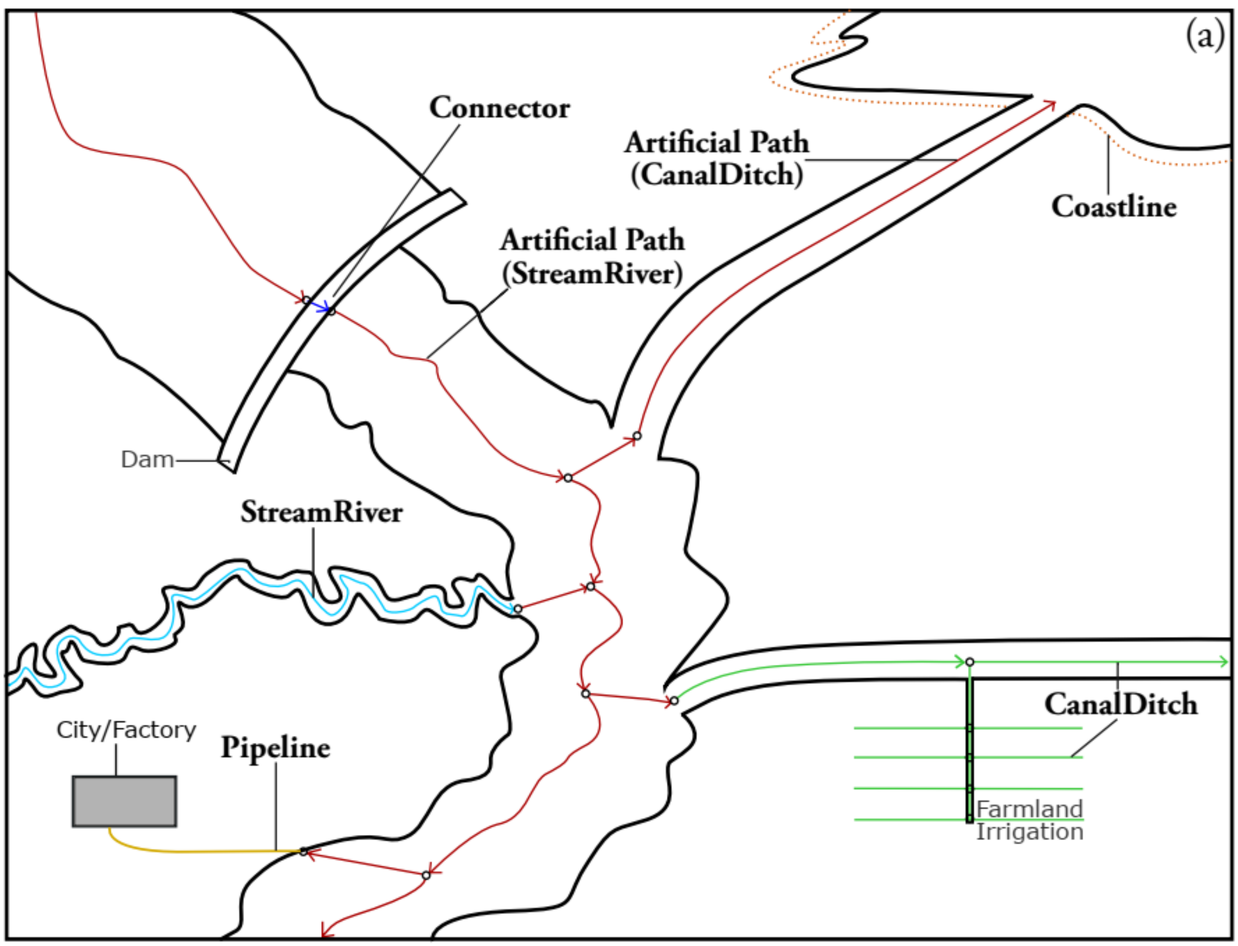

Figure 2-1a - Hydraulic and Hydrologic features (indicated in bold) in the National Hydrographic Database Flowline Layer, (a) surface and near surface features

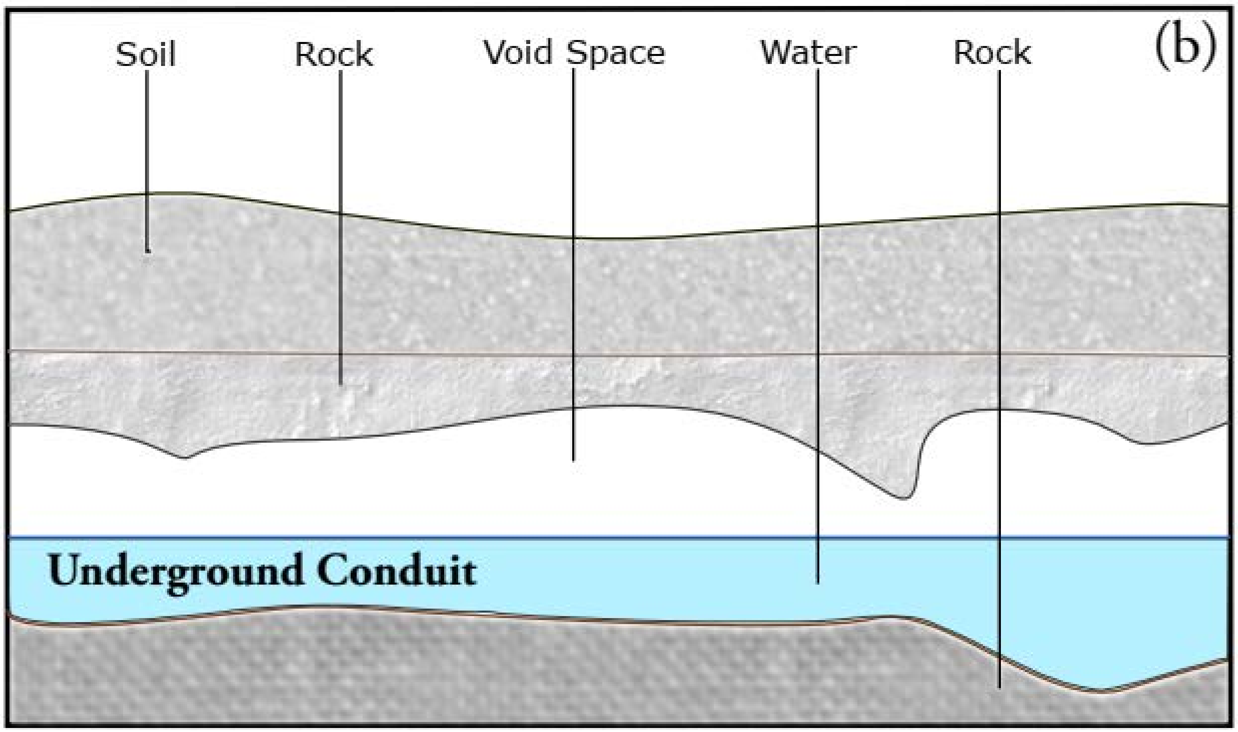

Figure 2-1b: Hydraulic and Hydrologic features (indicated in bold) in the National Hydrographic Database Flowline Layer, (b) underground conduit feature (USGS, 2016c)

While flow direction data are included for the flows within the NHD, volumetric flow data are not available for linking to the layer. Each part of the geometric network has a unique identification code, called a Reach Code, but a volumetric flow database for reaches is not available through the USGS. To provide such data, each reach would need to be investigated individually through various state and local agencies, and private entities. Investigation of reaches with regard to volumetric flow data is further complicated as most small scale, and some larger scale, waterways are unnamed within the NHD, meaning that the only tool that can be used to search for identified IBT information is the geographic co-ordinates provided within the NHD. Procuring data on the volumes of water transferred in all of the IBTs would be a large-scope, labor-intensive effort and was not feasible to do as part of this work.

2.3.3 IBT Qualification Criteria

In this work, for a reach to qualify as an IBT two major criteria were required to be satisfied:

1) The reach must be confirmed as a man-made waterway or conveyance, as per the NHD or other investigations
2) The reach must begin within one HUC and end in another, i.e. if the start and end point of a reach is in the same HUC, even if it crosses a basin boundary along its length, it will not qualify as an IBT.

Reaches that cross basin boundaries with seas, oceans and the Great Lakes were not considered to be IBTs. As the Great Lakes are their own HUC6 basins, any man-made use of their waters, or outflows into them, would be considered an IBT. This could skew results towards states and especially cities that rely on these sources for their water needs, even though they border these bodies of water. As the seas and oceans do not have a HUC code, flows that enter or exit through this type of boundary cannot be interbasin as they do not traverse from one defined basin to another. The southern coastline of Connecticut is therefore not considered a boundary for IBTs, as while the coastline is the boundary between the Connecticut Coastal and Long Island HUCs, the outflows from Connecticut immediately enter the Long Island Sound which is connected directly to the North Atlantic Ocean. This work therefore considered flows across the boundary between the Connecticut Coastal and Long Island HUCs to be flows into the ocean and therefore not IBTs.

2.3.4 Data Acquisition

The NHD data were downloaded via the USGS NHD website (USGS 2016b). The website allows selection of the type of download, and by selecting the link for data based on state boundaries an FTP site is reached (USGS, 2016a). From this site, the High Resolution folder was selected, followed by the Geodatabase (GDB) folder. The zip files for each state were downloaded from this folder and decompressed into individual data folders for each state. The NHD data files downloaded contained both NHD data and WBD data. Additionally a national level map was downloaded from the U.S. Census Bureau at the highest available resolution, 1:500,000 (U.S. Census Bureau, 2015), which was added to all maps to reflect the locations of the states in contrast with the WBD and state NHD data.

2.3.5 ArcGIS Map Creation

The program ArcGIS was used to create maps of IBTs using the following steps.

For each state the relevant HUC6 data layer and the NHDFlowline layers were added to the maps. The layer frame coordinate system utilized was the North American Datum (NAD) 1983 to ensure that all layers inserted displayed correctly for the entirety of the U.S. Once the NHDFlowline layer was inserted into the map, the editor toolbar was used to enable editing of the NHDflowline layer. As the only features in the NHDFlowline layer that could be IBTs are Artificial Paths, CanalDitch or Pipeline, all other feature types were deleted. This was due to the size of some files negatively impacting performance of the data processing. This process is made simpler by performing a sort on the FType field of the attributes table, which states the type of feature for each reach.

Once the extraneous data were deleted, the “select by location” tool in ArcGIS was utilized. The selection method was the default “select features from” with the NHDFlowline layer selected as the target layer. The source layer was selected as the WBDHU6 layer and the spatial selection method for target layer features was set as “are crossed by the outline of the source layer feature”. This method selected all reaches within the remaining NHDFlowline data, which were then extracted by right-clicking on the NHDFlowline layer and choosing to export the data. This action created a new layer from the selected features, which was placed in the map. The new layer had the same fields as the original NHDFlowline data, but used numeric codes in lieu of text for some fields, including the FType field. A value of 336 in the FType field represents a CanalDitch feature, 428 represents Pipelines, and 558 represents Artificial Paths.

The new layer also required further cleaning of the data extracted from the NHDFlowline layer. The state data extended past the borders of the state to ensure complete data capture within it; however, this could have resulted in some reaches being selected that are not within the state under examination. Those results were therefore deleted by selecting them and then employing the same process used to delete fields in the original NHDFlowline layer. Following this each reach was individually examined to ensure that they started and ended in separate HUCs. Those that did not satisfy this criterion were also deleted.

The Artificial Path features, FType number 558, were then individually examined to verify whether they were man-made or natural features. Some of these features are named within the NHD, for example the Mississippi River or Central Arizona Project Aqueduct, allowing an Artificial Path feature to be immediately retained or deleted. Both network location and geographic location were then examined to enable accurate identification of those reaches that are man-made. In terms of network location, if the reach connected at both ends to a man-made feature, such as a canal, then the Artificial Path would also be considered to be man-made. For geographic examination, as each reach is labelled with its coordinate location, the identify feature could be used to discover the exact location within the U.S. in degrees, minutes and seconds. Once the location was determined, a map search via both Google Maps™ and MapQuest™ was conducted. Examination of the feature and surrounding area provided insight as to the nature of the reach and further search and investigation into named waterbodies or waterways enabled a determination to be made in regards to the origin of the artificial path. Those determined to be man-made were then retained and those that were either undefined features or features determined to be naturally occurring were deleted.

Once this methodology had been completed for the contiguous U.S., and for Alaska and Hawaii, the individual data files created with the state IBTs were all added into a single map file and the Merge function was used to create a single file containing all the identified IBTs.

This file was then used with the U.S. map layer from the Census Bureau and the national WBD to form a national map of all IBTs. To analyze the data further, these files were also put into the GIS ArcPRO software and the kernel density tool was utilized. The parameters for this operation included the layer containing all IBTs in the contiguous US as the input polyline feature with all other values at their defaults. For the Environments, the output coordinate system was set as the same as the IBT layer, with all other values at the default. This provided a map of the density of IBT occurrences per square mile, which was then converted to per square kilometer, and then the USGS Small-scale Dataset of Cities and Towns of the United States was added (USGS, 2014). To isolate the locations of the largest cities, any with populations of under 200,000 were eliminated and the remaining cities added to the map as a new layer.

2.4 Results and Discussion

2.4.1 IBTs by State

A total of 2,160 IBTs were found to exist within the contiguous United States. Table 2-4 provides the total number of IBTs by state, as well as a breakdown of the types of flows that are IBTs within each state. For states with no IBTs the type is listed as Not Applicable (N/A). Although not part of the contiguous U.S., results from both Alaska and Hawaii were also obtained, and are included in Table 2-4.

Table 2-4 U.S. Interbasin Transfers by State, with Breakdown, in 2016

State	Number of IBTs	Type		
		Canal/Ditch	Pipeline	Artificial Path (Large Canal/Ditch)
Alabama	6	4	0	2
Alaska	1	0	1	0
Arizona	69	49	11	9
Arkansas	71	69	1	1
California	110	70	29	11
Colorado	53	34	18	1
Connecticut	0	N/A	N/A	N/A
Delaware	8	6	0	2
District of Colombia	0	N/A	N/A	N/A
Florida	610	573	0	37
Georgia	12	9	0	3
Hawaii	0	N/A	N/A	N/A
Idaho	16	13	3	0
Illinois	6	4	0	2
Indiana	122	91	30	1
Iowa	0	N/A	N/A	N/A
Kansas	1	1	0	0
Kentucky	20	9	10	1
Louisiana	74	44	2	28
Maine	0	N/A	N/A	N/A
Maryland	23	20	3	0
Massachusetts	4	0	4	0
Michigan	22	22	0	0
Minnesota	56	52	4	0
Mississippi	8	4	0	4
Missouri	1	1	0	0
Montana	43	37	3	3
Nebraska	44	32	5	7

Table 2-4 U.S. Interbasin Transfers by State, with Breakdown, in 2016 (continued)

State	Number of IBTs	Type		
		Canal/Ditch	Pipeline	Artificial Path (Large Canal/Ditch)
Nevada	17	6	10	1
New Hampshire	1	1	0	0
New Jersey	3	1	0	2
New Mexico	20	4	16	0
New York	18	6	7	5
North Carolina	168	160	0	8
North Dakota	4	3	0	1
Ohio	5	1	0	4
Oklahoma	14	11	3	0
Oregon	12	8	4	0
Pennsylvania	4	1	3	0
Rhode Island	0	N/A	N/A	N/A
South Carolina	12	7	0	5
South Dakota	3	2	1	0
Tennessee	2	1	0	1
Texas	388	327	25	36
Utah	52	33	17	2
Vermont	0	N/A	N/A	N/A
Virginia	21	19	2	0
Washington	19	19	0	0
West Virginia	0	N/A	N/A	N/A
Wisconsin	4	4	0	0
Wyoming	14	6	8	0
TOTAL	**2160**	**1763**	**220**	**178**

The five states with the most IBTs and their respective breakdowns are shown in Table 2-5.

Table 2-5 Five U.S. States with the Most Interbasin Transfers, with Breakdown, in 2016

State	Number of IBTs	Type		
		Canal/Ditch	Pipeline	Artificial Path (Large Canal/Ditch)
Florida	610	573	0	37
Texas	388	327	25	36
North Carolina	168	160	0	8
Indiana	122	91	30	1
California	110	70	29	11

The total number of IBTs in the contiguous U.S. was determined to be 2,160 for the HUC6 level, with one additional IBT identified in Alaska. Cross referencing this result with HUC4 boundaries, to compare with the earlier USGS studies, a total of 1,344 IBTs were determined to exist at that level. This is far in excess of the 256 total conveyances determined to be IBTs in the two prior inventory studies of the eastern and western United States conducted by the USGS in 1985 and 1986 (Petsch, 1985; Mooty and Jeffcoat, 1986). This also shows that 817 additional reaches were identified as IBTs by moving from the HUC 4 level to the HUC 6 level.

While the present study examined the total number of IBTs, both across the contiguous U.S. and by state, the results do not indicate the relative sizes of these transfers. The results are therefore skewed towards states and areas that have large numbers of IBTs, rather than states which have large IBT transfers by volume. For example, while Florida has the most identified IBTs, New York State may transfer a larger total volume of water despite having less than 3% of the number of IBTs in Florida. This would be due to very large scale IBTs that supply New York City with its drinking water. As mentioned in the methodology, flow data are not available for linking to the NHD utilized to produce this analysis and there are limited identification data available to aid in contacting the various state and local agencies and private entities that may possess information regarding the volumes transferred by each IBT. Thus, there is some uncertainty regarding the importance of each individual transfer and which states and basins are most impacted by the transfer of water, both in terms of those that import water and those that export water, internally and externally.

Due to the survey methodology employed in the 1985-1986 USGS IBT inventories (Petsch, 1985; Moody and Jeffcoat, 1986), many of the reaches identified as IBTs in the present study would not have appeared previously due to their small size and local nature. In particular the multitude of “CanalDitch” type features in Florida were not defined in the previous studies. Additionally the prior USGS studies examined IBTs as a whole feature, rather than examining individual reaches. Long-distance IBTs that cross multiple basin boundaries are counted multiple times with the approach employed in the present study, e.g., the Central Arizona Project has three reaches that are each classified as individual IBTs. In the previous work, the Central Arizona Project was counted as a single IBT, from start point to end point. While acknowledging these differences in methodology, the number of IBTs identified in the present study provides more resolution and a much clearer picture of water transfers across basin boundaries in the U.S.

2.4.2 U.S. IBT Distribution

Figure 2-2 shows the areas of the U.S. where the occurrences of IBTs are most spatially dense.

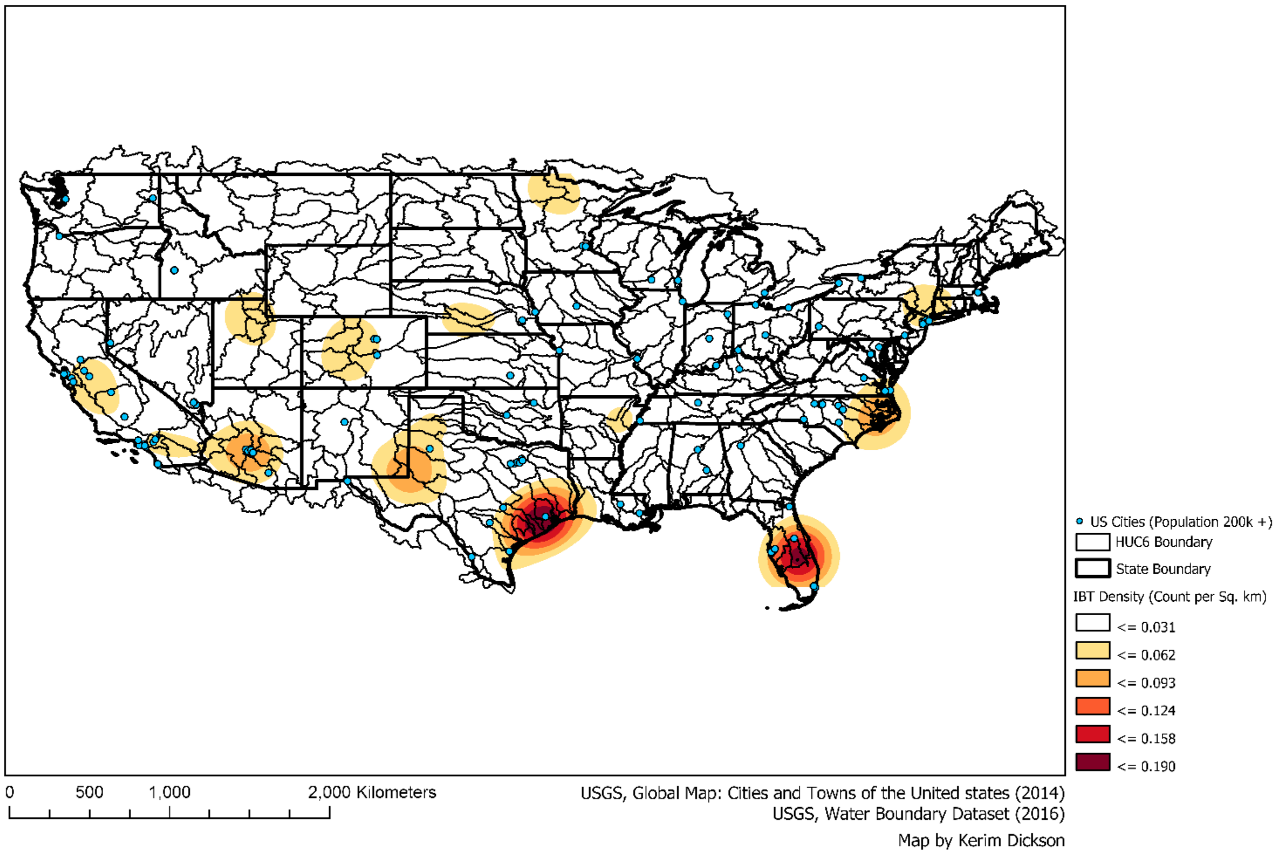

Figure 2-2 Interbasin Transfer Densities and Major Cities in the Contiguous United States in 2016

To further examine the areas with the most transfers occurring, Table 2-6 shows the HUCs with the most transfers in and out of them.

Table 2-6 U.S. HUCs with Greater Than 60 Transfers Into or Out of their Borders, in 2016

HUC6 Number	HUC6 Name	Number of Transfers
030901	Kissimmee	260
030902	Southern Florida	225
030801	St. Johns	210
031001	Peace	197
030802	East Florida Coastal	168
120402	Galveston Bay – Sabine Lake	154
031002	Tampa Bay	120
030201	Pamilco	109
121004	Central Texas Coastal	95
030202	Neuse	80
030102	Albmarle-Chowan	67
080203	Lower White	66
121001	Lavaca	65
120903	Lower Colorado	64
180400	San Joaquin	64
071200	Upper Illinois	61
120200	Neches	61

The density map in Figure 2-2 and Table 2-6 show that two regions dominate in terms of both numbers and densities of IBTs: Central Florida and Southeastern Texas. As previously mentioned, these hotspots only represent concentrations of IBT transfers, and not necessarily locations of the largest transfers by volume. Table 2-7 shows the breakdown of the ten basins with the most transfers into them and also the basins with the most transfers out of them. There are many HUCs that have similar numbers of transfers in and out, although these are not representative of the potential total volume of water into, or out of, any given HUC.

Table 2-7 Ten U.S. HUCs with the Most IBTs Transferred In and the Most Transferred Out, in 2016

HUC6 Number	HUC6 Name (State)	Transfers Out	HUC6 Number	HUC6 Name (State)	Transfers In
030902	Southern Florida (Florida)	120	030901	Kissimmee (Florida)	167
030801	St Johns (Florida)	112	031001	Peace (Florida)	105
030802	East Florida Coastal (Florida)	98	030902	Southern Florida (Florida)	104
030901	Kissimmee (Florida)	93	030801	St Johns (Florida)	97
031001	Peace (Florida)	91	120402	Galveston Bay - Sabine Lake (Texas and Louisiana)	80
031002	Tampa Bay (Florida)	72	030802	East Florida Coastal (Florida)	69
120402	Galveston Bay - Sabine Lake (Texas and Louisiana)	72	030201	Pamilco (North Carolina)	55
030201	Pamilco (North Carolina)	53	031002	Tampa Bay (Florida)	47
121004	Central Texas Coastal (Texas)	53	071200	Upper Illinois (Illinois, Indiana, Michigan and Wisconsin)	47
120200	Neches (Texas)	44	121001	Lavaca (Texas)	42

For the Southeastern Texas hotspot, one explanation for the number of IBTs is the City of Houston. The city has been growing consistently over the past century, from a town with a population of approximately 78,800 in 1910 to over 2.1 million in 2010. In just the span from 2000 to 2010 the city grew by about 7.5%, with almost 150,000 additional people (HPDD, 2014). Additionally a significant amount of land, almost 195 km^2, is used for agriculture, specifically growing hay, in the area surrounding the City of Houston (Purdue University CNCPP, 2012).

In Central Florida, many of the IBTs appear to be short drainage conveyances, most likely created to avoid flooding caused by a combination of frequent storms and high groundwater tables. Additionally, the cities of Tampa and Orlando add significant water demands, with tourism and theme park attractions that are not present in most parts of the U.S. exacerbating demands. Of the 25 largest theme parks in the world, 7 are in Orlando; with approximately 72.6 million visitors to these attractions in 2014 creating a water burden larger than local population figures would indicate (TEA and AECOM, 2014). Florida is also a significant producer of citrus, with over 3,050 km^2 dedicated to oranges alone within the state, and other warm weather and tropical crops, such as avocados, which add a further water burden across the state (Purdue University CNCPP, 2016a).

Cities and large-area irrigated agriculture often show correlation with the locations of IBT clusters as identified by Figure 2-2. The City of Phoenix in Arizona, and the cotton grown to the south (NOAA, 2015) of it are located within another density hotspot. A dense line of IBTs create another hotspot leading directly to the City of Los Angeles from the Colorado River. Further north in California another hotspot is located in the Central Valley, a region of intensive agriculture with products that are distributed nationwide (HCNR, 2014). Additional hotspots are near to the cities of Sacramento, San Francisco and San Jose. New York City is responsible for the hotspot in the Northeast of the U.S..

The hotspot covering northeast North Carolina and southeast Virginia has no major cities central to the area, but has the cities of Chesapeake and Norfolk on the northern border of the hotspot, in Virginia, and Durham and Raleigh on the western border within North Carolina. The center of the hotspot covers some areas that produce the largest agricultural exports from the state of North Carolina (Stout, 2012) including over 300 km^2 of cotton and over 200 km^2 of corn (Purdue University CNCPP, 2016b). Both cotton and corn are relatively water intensive crops and can require almost 765,000 m^3 and over 815,000 m^3 of water per square kilometer respectively (Mohammadi-Kanigolzar et al., 2014).

It is also apparent that while Indiana has a large number of IBTs, and as demonstrated by Table 2-5 has one basin with more than 60 transfers into and out of it (071200, Upper Illinois), it does not show up on the density map of IBTs. This is likely due to the spread of the individual IBTs, reducing their density per square kilometer. As a result, while the area has many IBTs, the maps indicate that they are further apart.

Climate does not appear to be a significant factor initially, with Central Florida, Southeastern Texas and Indiana having very high quantities of IBTs despite being within locales that have relatively high annual precipitation rather than being arid. However, the previous USGS surveys of IBTs (Petsch, 1985; Mooty and Jeffcoat, 1986) indicate that while the numbers of IBTs identified in the Eastern U.S. may be higher, the arid conditions of the Western U.S. result in larger volumes of water transfer. Additionally, several waterways that have been constructed in the east are for navigation purposes, to facilitate shipping, rather than for the need of water transfer, which provides more perspective on factors governing IBT construction and locations.

As 90% of total water withdrawals in the U.S. are used for public water supply, irrigation and thermoelectric power (Barber, 2014), clusters of IBTs may be expected in areas near cities and agricultural lands. As this analysis shows, water transfers do indeed appear to cluster near urban areas, such as Houston, Phoenix, Los Angeles, and New York, and those where irrigation for agriculture is prevalent, such as California's Central Valley, Western Texas and Central Florida. This leads to the hypothesis that the largest water users tend to have an impact upon the transfer of water between basins.

2.5 Summary and Conclusions

The objectives of this work were to identify IBTs that exist in the U.S. and to examine the distribution of IBTs and potential causes of any observed clusters.

Utilizing the USGS National Hydrography Database and the Water Boundary Dataset a map of IBTs in the U.S. was created through use of GIS software. This map identified the locations of 2,160 IBTs in the U.S., which were further analyzed to provide a density map of IBTs. The map showed that there are several hotspots across the U.S., with the densest clusters occurring in Texas, around the City of Houston, and Florida, around Orlando.

This was a significant increase in IBTs in comparison to the USGS inventory of IBTs in 1985-1986 (Petsch, 1985; Mooty and Jeffcoat, 1986) which defined a total of 256 IBTs, although at a HUC4 level, as opposed to the HUC6 level used in this work. The regions of highest IBT density in the U.S. coincide with areas of high population, and large-area, water-intensive agriculture, although each hotspot had unique factors that could have also contributed to IBT construction and location.

Many avenues of exploration remain for expanding upon this body of work. While the present study analyzed the quantity of IBTs nationally and by state, it did not evaluate the volumes of water transferred by each identified IBT. Additionally this work only examined reaches that qualified as IBTs under the definition employed; further investigation could be conducted into those IBTs that cross state or international lines that may not be immediately apparent from the analysis conducted here. Future work on this topic may also include closer examination of the various factors that promote the construction or maintenance of specific IBTs and identification as to which of the factors is most important in the construction of those IBTs. Furthermore, analysis could be conducted regarding the areas of the U.S. most likely to require IBTs in the future, given the factors that have driven IBT construction heretofore.

2.6 Acknowledgements

This work was supported by a Steinbrenner Institute U.S. Environmental Sustainability Ph.D. Fellowship to Kerim Dickson. The fellowship program is supported by a grant from the Colcom Foundation and by the Steinbrenner Institute for Environmental Education and Research at Carnegie Mellon University. Additional support for the study was provided by a College of Engineering Dean's Fellowship to Kerim Dickson, and by the Hamerschlag University Professorship of David Dzombak.

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Chapter 3 : Drivers of Interbasin Transfers in the United States: Insights from Sampling

This chapter, written by Kerim E. Dickson and co-authored by Dr. David A. Dzombak has been submitted to the Journal of the American Water Resources Association

3.1 Abstract

Interbasin Transfers (IBTs) are man-made transfers of water that cross basin boundaries. In an analysis of 2016 data we identified 2,161 reaches crossing USGS HUC6 boundaries in the U.S. The objectives of this study were to characterize and classify IBTs, and examine the development drivers for a subset of 109 (~5%) of the IBT reaches through examination of samples from different climate regions of the U.S. The IBTs were classified as being near irrigated agricultural lands, near cities, or rural IBTs not near cities or irrigated land. IBTs near both cities and irrigated agricultural land were designated as city + irrigated agriculture. The 109 samples were selected based on approximate proportional distribution to the total number of IBTs within each climate region, and with representation of areas having a high density of IBTs. These showed that in the U.S. there are four major drivers for basin transfers: irrigation for agriculture, municipal and industrial water supply, commercial shipping or navigation, and drainage or flood management. The most common was drainage or flood management, though IBTs at least partially driven by agricultural needs were also prevalent. Historically the majority of the case study IBTs were constructed between 1880 and 1980, with peaks in development between 1900-1910 and 1960-1970. The samples also showed that the drivers of IBT development evolved over time, reflecting changes in regional economies, populations, and needs.

3.2 Introduction

Interbasin Transfers (IBTs) have been within the realm of human capabilities for millennia, moving water to meet the needs and desires of civilizations (Mays et al., 2007). The reasons for IBTs have always been linked to the users, to meet their diverse needs including drinking water supply, irrigation for agriculture, power generation, shipping, and others (Aron et al., 1977). Since the advent of the capability to transfer water, technology has progressed to allow humanity to move water over much larger distances and terrain constraints to meet the supply needs of ever-evolving demands.

Advances in technology now allow high resolution tracking of surface water features across the U.S. (Moore et al., 2016), with the U.S. Geological Survey (USGS) National Hydrography Dataset High Resolution (NHDHR) providing a multitude of information on streams, canals, pipelines and other features at a 1:24,000 resolution or better (USGS, 2016a). In previous work we examined the locations of IBTs within the U.S. using the NHDHR, defining them as man-made transfers across the USGS defined Hydrologic Unit Code (HUC) boundaries at the HUC6 basin level (Dickson and Dzombak, 2017). This study identified 2,161 reaches across the U.S. that qualified as IBTs. While the study provided an inventory and mapping of where IBTs occur in the U.S, it did not examine the reasons for their locations, or provide information regarding their construction dates. The types and relative importance of drivers for the development of such transfers are not well understood.

Specific well-known IBTs have been thoroughly examined due to their size, length, or populations served, such as the Central Arizona Project (CAP) in Arizona (Hanemann, 2002; Wilson, 2002; Kleiman, 2016) and the Los Angeles (L.A.) Aqueduct in California (Kahrl, 1982; Pincetl et al., 2016; Water and Power Associates, 2018), but many smaller

IBTs are relatively unknown and have not been studied. For many IBTs, knowledge of their construction and purpose is limited to local sources, with no national context.

No general analysis of the drivers for the development of IBTs in the U.S. has been performed heretofore. The construction of the L.A. aqueduct was in response to the population growth of the city, after attempts to cut consumption were insufficient for the city to continue with existing water sources (Brown, 2013). As the CAP moves Arizona's allocation from the Colorado River through three counties, it provides water to several users with the original driver being irrigation for over 4,000km^2 of agricultural land and also providing water for both municipal and industrial use in Phoenix and Tucson (Zuniga, 2000). In total about 39% of Arizona's water supply is through transfer from the Colorado River (Jacobs et al., 2005). Without analysis of IBT drivers more broadly, however, it is not possible to have an understanding of what led to IBT development across the U.S. Such knowledge is needed, for example, to help identify areas of pressure on water resources that may be addressed through the construction of new transfers.

Many studies have examined IBTs regarding a diverse variety of topics such as environmental considerations, economic justifications and the potential for IBTs in regional water management. Examples include interactions between IBTs and the Clean Water Act (Schroeder and Woodcock, 2011), effects of IBT connectivity on fish biodiversity (Grant et al., 2012), and the economic feasibility of IBTs utilizing optimization models with maximization of net benefits as the objective (Karamouz et al., 2010). Other works have also examined the drivers of future water withdrawals in general (Worland et al., 2018).

This work examines, through case studies, specific IBTs in the U.S. with the aim of understanding the drivers behind the construction of IBTs and the factors that influence the drivers, such as proximity (or lack of proximity) to population centers and agricultural lands that require irrigation. The factors that determine water supply needs clearly are drivers for many IBTs as approximately 90% of water withdrawals in the U.S. are utilized to produce electric power, to irrigate farmland or to provide public supply (Barber, 2014). Other drivers for IBT development are possible, however, and were examined here. We also examined the temporal aspect of IBT development in the U.S., to see if IBTs have been developed continuously or only during specific time periods.

While cities like L.A. and New York City (NYC) rely on receiving 90% or more of their public supply from IBTs (Ashoori et al., 2015; NYS DEC, 2017), it is not obvious that other population centers can exert this same driving force on IBTs in other climate regions, as L.A. and NYC are the largest population centers in the U.S (Li et al., 2015). However, as 10% or more of large cities worldwide move water across basins (McDonald et al. 2014), and examination of U.S. cities has shown that over 15% of the U.S. population can be considered “at risk” for water scarcity (Padowski and Jawitz, 2012), there is both clear precedent and need for water transfers to supply major populations within the U.S.

Electric power demand is highest in cities, and water demands for electric power production are significant. Thermoelectric power production is the largest source of U.S. water withdrawal (Barber, 2014). As power production is intrinsically linked to population centers, most thermoelectric power production withdrawals occur in similar areas as public supply withdrawals (Li et al., 2011). Thus, electric power production is a driver of water transfers.

A sampling approach was chosen for this work as examination of factors from cases across the U.S., in a variety of climate regions and proximity to features which may exert significant demands, will enable generalizations to be drawn for other IBTs that were not examined. The sampling approach provides external validity, defining the domain where the results can be generalized, while the examination of the driving factors for the IBTs derived from multiple sources provides internal validity, establishing causal relationships, and reliability to the results (Yin, 2009).

The objectives of this study were to characterize and classify IBTs, linking IBTs to land uses occurring in the vicinity, and to examine development drivers for a subset of IBTs in the U.S through samples in different climate regions of the U.S. The samples included investigation of IBT construction dates and the original reasons for development, providing insight into the current status of IBTs.

3.3 Methodology

3.3.1 U.S. Interbasin Transfer Dataset

To identify IBTs that could be selected for sampling, the inventory of IBTs in the continental U.S. as of 2016 developed by Dickson and Dzombak (2017) was utilized. The dataset provides the locations of over 2,100 IBT reaches across the U.S., allowing selection of samples by climate region and also by proximity to selected features, such as cities and irrigated agricultural land. The IBT dataset was created with use of the USGS

National Hydrography Database (USGS, 2016a), state boundary files (US Census Bureau, 2015a), and the Watershed Boundary Dataset (USGS, 2016b), utilizing Geographic Information System (GIS) analysis (Dickson and Dzombak, 2017). IBTs were identified at the HUC6 basin level. An average HUC6 basin has an area of approximately 27,500km^2, approximately equivalent to the area of a circle of radius 100km.

3.3.2 Classification of U.S. Interbasin Transfers by Climate Region

The continental U.S. spans a wide range of geographic and climatic conditions. The National Oceanic and Atmospheric Administration (NOAA), in association with the National Centers for Environmental Information, have identified nine climatically consistent regions within the contiguous U.S. (NOAA, 2018). These are shown in Figure 3-1. Each climate region consists of multiple states that share climatic conditions.

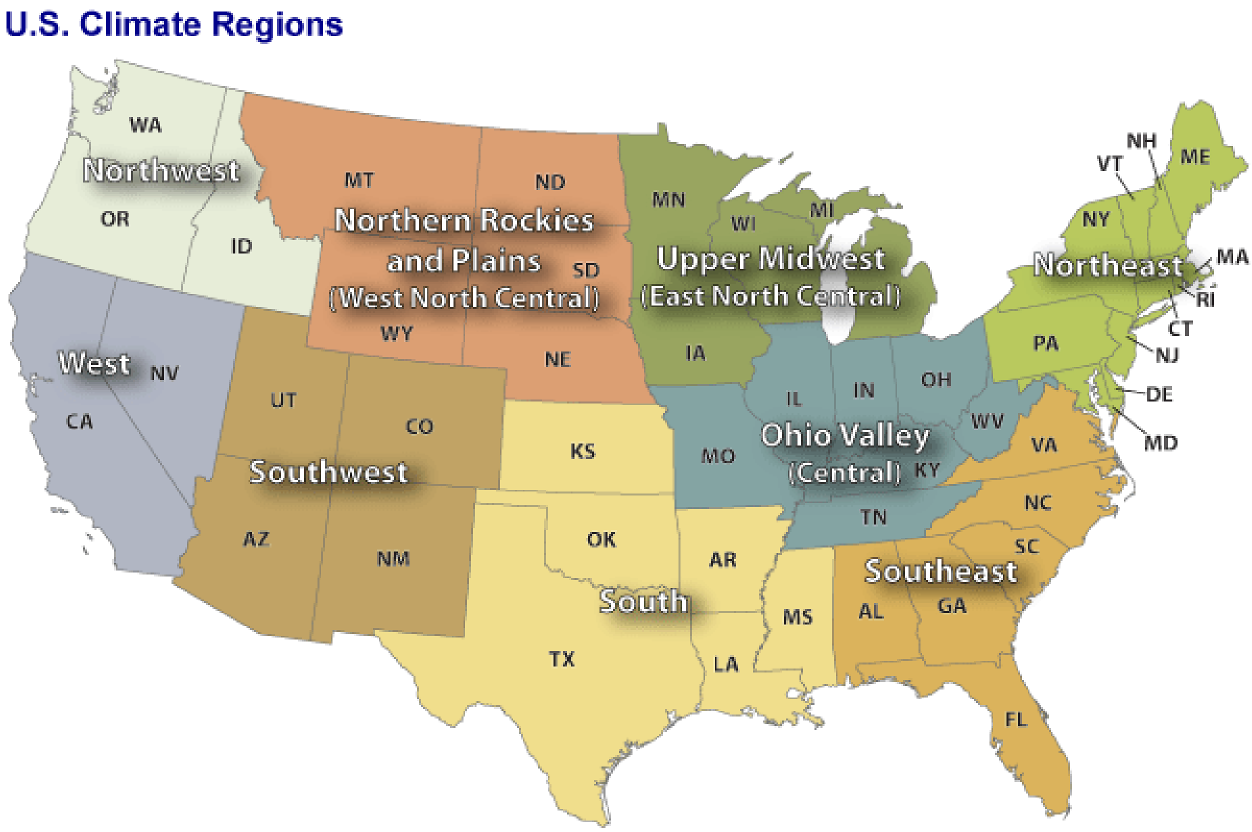

Figure 3-1 Climate Regions of the Continental United States (Source: NOAA, 2018)

Using the NOAA climate region scheme, a climate region was designated to each IBT in the dataset. This approach was chosen to enable evaluation of a possible climate link to abundance and scarcity of water resources in the U.S. Other organizational choices such as political or state boundaries were considered, however, historically these boundaries have evolved coincident with the IBT development. Furthermore, organization by climate region provides a level of regional aggregation that enables insight at a defined multi-state scale.

3.3.3 Defining Types of Water Users Related to U.S. Interbasin Transfers

IBTs are likely to be associated with major water uses. Most water withdrawals in the U.S. take place for uses connected to thermoelectric power generation, public water supply, and irrigation for agriculture (Barber, 2014). The types of water users that have governed the development of IBTs in the U.S. were defined in a specific manner for this study

3.3.3.1 City

Defining what constitutes a city can be difficult as there are multiple definitions, with no standard either federally or internationally (US Census Bureau, 2015b; United Nations, 2016). Population size is often seen as a part of the definition of a city, however many other factors, such as economic role and land extent, also play significant roles in defining a city. City types internationally are often described as primary, secondary, and tertiary based on differences in population and economic factors (Roberts and Hohmann, 2014). These city types have overlap due to differences in national or regional populations and their specific role in the nation or region. City types may have overlap, in the case of large, highly populated countries like the U.S. where some large cities in states may be secondary to even larger-scale cities, such as L.A. or NYC. However, primary cities are always defined as being in excess of 200,000 population.

In the U.S. a mid-sized city has been defined as a city with a population of between 100,000 and 300,000 (Rochester, 2002). As public water supply and thermoelectric power water are known to be significant sources of water withdrawal in the U.S. (Barber, 2014), and as scale for both of these water uses relates to population, city population was considered likely to be a driving factor for IBT development. Note that public water supply includes both indoor use, such as human use, and outdoor use, such as lawn irrigation.

Based on these definitions, for this work population centers of 200,000 people or more were selected as the classification for a city. This was to ensure all primary cities were captured, as well as being the midpoint for the definition of a mid-sized city in the U.S, according to population. City data were obtained through the USGS small-scale dataset of cities and towns of the U.S. which included data from the 2010 census (USGS, 2014) for the population. All towns and cities below 200,000 in population were then removed from the dataset.

3.3.3.2 Irrigated Agriculture

To define irrigated agricultural lands the 2012 Census of Agriculture (USDA, 2015) data were utilized to examine counties in the U.S. for the proportion of land devoted to irrigation. The data were downloaded from the U.S. Department of Agriculture (USDA, 2015) to a spreadsheet and then combined with GIS data for counties, including their boundaries, also available through a download from the USDA (USDA, 2017). This was achieved using the “join” function within the ArcGIS software (ESRI, 2017) which allows two sets of data to be merged given a matching set of data in one column, which in this case was the Federal Information Processing Standards (FIPS) code present in both datasets, allowing the spreadsheet data to be mapped geographically. The downloaded information in the spreadsheet did not contain data regarding the percentage of land irrigated in each county. It did contain, however, data on the acres of land in farms as percent of land area in acres and the acres of irrigated land as percent of land in farm acreage. Thus, a new column of data was calculated by multiplying these two values and dividing the result by 100, providing the percentage of irrigated land as a proportion of total land area by county. The result of this approach is seen in Figure 3-2.

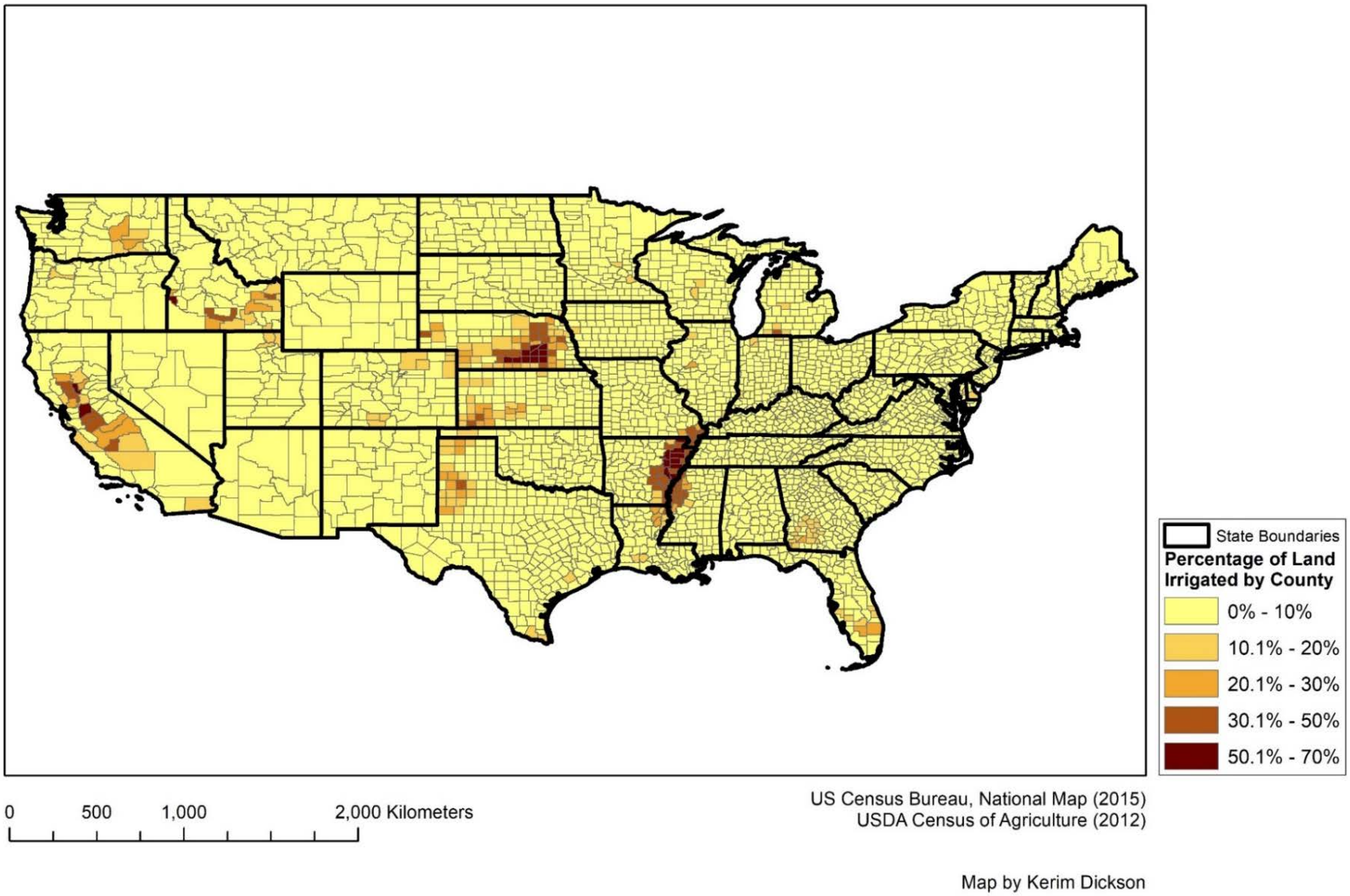

Figure 3-2 Proportion of Irrigated Agricultural Land for Each County in the United States

Figure 3-2 shows that much of the U.S. is lightly irrigated, with less than 10% of land in most counties irrigated. For this work, counties with greater than 10% of their area irrigated were considered to be highly irrigated and thus classified as irrigated agricultural land.

3.3.3.3 City + Irrigated Agriculture

Some IBTs can be in proximity to both the city and irrigated agriculture features defined above. In such cases the classification of “city + irrigated agriculture” was used. This classification was used to show regions in the U.S. that have coexisting population centers and irrigated agricultural land. These IBTs could not be classified as being near a single feature and could not be classified in both categories without resulting in a double count.

3.3.3.4 Rural

Some IBTs may not be in proximity to locations defined as either city or irrigated agriculture. The classification “rural” was used for areas that are not within range of either a city or irrigated agriculture, as previously defined.

3.3.4 Sample Selection

To utilize the classification definitions established, ArcGIS was utilized to select IBTs in a circular zone of radius 100km around identified cities and irrigated agricultural land. This range was selected based on the average size of an HUC6 being approximately equal to a circle of radius 100km, so that the nearest basin boundaries to the feature would be captured. Each state was then grouped and exported as a separate data layer for each defined climate region.

To create the circular zones around cities and agricultural lands, the geoprocessing tool “Buffer” in ArcGIS was used. For cities, a linear unit of 100 km was entered in the tool, utilizing the “Planar” method and the “All” selection for the “Dissolve” option, which ensured any overlap between city circular (buffer) zones were merged together. This method was then repeated for the counties with greater than 10% of their area covered by irrigation, with the additional option of “Side Type” set to “Full”.

Once the buffer zones were created in ArcGIS, the “Select by Location” function was used to select IBTs that were within the respective zones. The data regarding the IBTs within the buffer zone for cities and the buffer zone for irrigated agriculture were extracted as their own data layers. IBTs present in both data layers were then removed from each of the previously created layers and entered as their own unique city + irrigated agriculture layer. The remaining unselected IBTs were then extracted as the rural layer. The definitions for each of the four IBT classifications are restated in Table 3-1.

Table 3-1 Interbasin Transfer Classifications and Definitions

Classification	***Definition***
City	IBTs within 100km radius of population centers of 200,000 or more
Irrigated Agriculture	IBTs within 100km radius of a county with 10% or more of their land irrigated
Rural	IBTs outside of a 100km radius from a population center of 200,000 or more and a county with 10% or more of their land irrigated
City + Irrigated Agriculture	IBTs within 100km radius of both a population center of 200,000 or more and a county with 10% or more of their land irrigated

The IBTs were then extracted within each climate region to provide a list of IBTs in the four classifications. While some IBTs are longer than 100km and may have multiple reaches identified that could be classified differently, despite being part of the same IBT, these are infrequent and the IBTs affected are well known, such as the Central Arizona Project and the State Water Project in California.

To ensure that sufficient samples were selected to enable general conclusions a representative IBT from at least three of the four IBT types were chosen for each climate region in the U.S. This also facilitated examination of the impact of climate on the factors associated with the construction of IBTs, and the temporal evolution in drivers for IBT construction. A total of 5% of the 2161 reaches identified as IBTs by Dickson and Dzombak (2017) were examined to provide a robust sample set, with a minimum of three IBTs selected in each climate region.

The number and types of IBTs selected for examination within each region are provided in Table 3-2.

Table 3-2 Number of Samples Selected by U.S. Climate Region

Climate Region*	***Number to study per class****				***Total***
	City	**Irrigated Agriculture**	**Rural**	**City + Irrigated Agriculture**	
Northwest	0	1	1	1	3
West North Central	1	2	2	0	5
East North Central	0	1	2	1	4
Northeast	2	1	1	0	4
West	1	2	1	6	10
Southwest	4	4	5	0	13
South	6	15	3	5	29
Central	1	4	1	2	8
Southeast	5	15	10	3	33
Total	**20**	**45**	**26**	**18**	**109**

* As defined by NOAA (2018); see Figure 3-1
** The values chosen as part of the methodology are based on the results of IBT type identification provided in Table 3-3 within Section 3.4.1.

The values in Table 3-2 were selected to be approximately proportional to the total number of IBTs in each climate region. Areas that have been identified as having a high density of IBTs (Dickson and Dzombak, 2017) were examined for potential case studies to help evaluate whether IBT clusters were the result of a specific driver in some locations. The identified IBT clusters by climate region are shown in Figure 3-3.

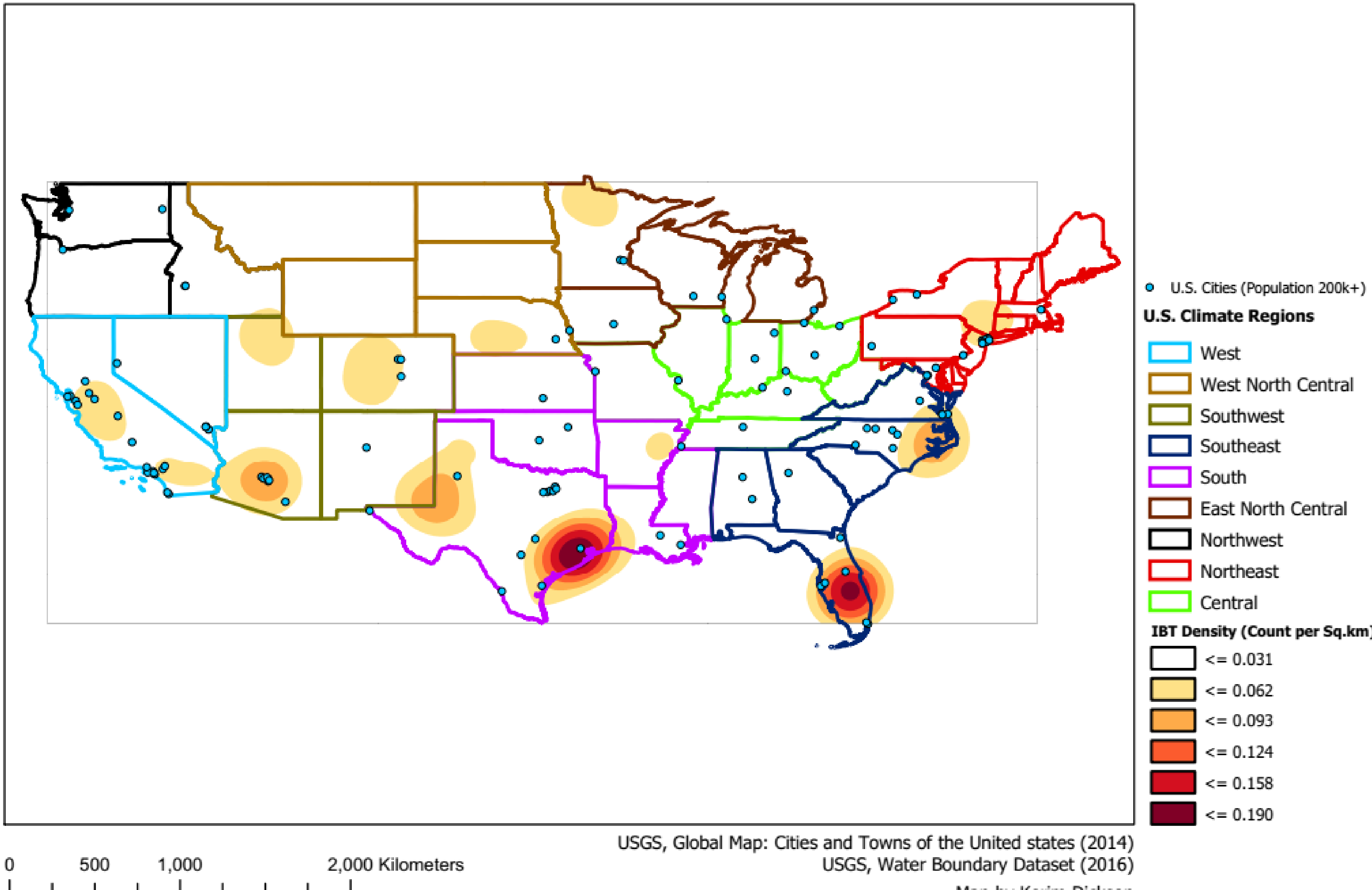

Figure 3-3 Interbasin Transfer Density in the U.S. and U.S. Climate Regions. Data Soure: Dickson and Dzombak (2016)

3.3.5 Driver Identification

To identify the drivers associated with the sampled IBTs a mixture of methods were employed. The IBT names assigned within the NHD and the geographic locations were utilized to find reports regarding the initial construction, mainly from historical sources rather than archival peer reviewed literature. These included both government agencies, such as the Army Corps of Engineers and the Bureau of Reclamation, and private organizations, such as Ohio History Central and Erie's History and Memorabilia. For some IBTs information was not available through databases and reports, so interviews were conducted with sources within these groups or local organizations to assist in defining what drove construction of IBTs and when construction started. The full list of IBTs selected for examination and the sources utilized in identifying the driver associated with each is included in Appendix A.

3.4 Results and Discussion

3.4.1 Classification of IBTs

IBTs within each climate region were classified as city, irrigated agriculture, city + irrigated agriculture, or rural. This provided the data shown in Table 3-3, indicating the geographic features near IBTs in each climate region.

Table 3-3 Number and Type of Interbasin Transfers by U.S. Climate Region

Climate Region*	***Numbers in region***				***Tota l***
	Cit y	**Irrigated Agriculture**	**Rural**	**City + Irrigated Agriculture**	
Northwest	0	37	8	2	47
West North Central	0	45	60	2	107
East North Central	1	10	64	7	82
Northeast	19	27	13	2	61
West	14	8	11	93	126
Southwest	57	75	59	4	195
South	116	297	62	83	558
Central	32	69	7	48	156
Southeast	57	424	198	150	829
Total	**296**	**992**	**482**	**391**	**2161**

* As defined by NOAA (2018); see Figure 3-1

As Table 3-3 shows, the majority of IBTs are located in the Southeast and South climate regions, with almost 65% of IBTs occurring in these regions. For both regions, IBTs occurring near irrigated agriculture made up over 50% of the total IBTs. However, the second most common IBT classification for each region differed, with IBTs near cities being more common in the South climate region and rural IBTs more common in the Southeast. Both regions also had a significant number of IBTs classified as city + irrigated agriculture.

Some climate regions exhibited skew towards specific IBT classifications, particularly in the north and the west of the U.S. The Northwest, West North Central and East North Central climate regions showed their relatively sparse population with only one IBT identified as being near a city, and 11 out of 236 IBTs being city + irrigated agriculture. The West climate region had almost 75% of IBTs constructed near both irrigated agriculture and cities, showing the proximity between population centers and agriculture in this region.

3.4.1.1 Northwest

The Northwest climate region consists of three states: Washington, Oregon and Idaho. The region is relatively sparsely populated, with only four population centers of 200,000 or more. IBTs in this region are also relatively sparse, with only eight identified IBTs in the rural classification, and none that are near cities only. The region has high annual rainfall in the western, coastal areas, and also areas of low annual rainfall in the eastern parts (Wieczork and Lamotte, 2010). Thus, this region has some heavily irrigated lands, reflected by over 75% of the identified IBTs being in proximity to irrigated agriculture.

3.4.1.2 West North Central

The West North Central climate region consists of five states: Montana, Wyoming, North Dakota, South Dakota and Nebraska. This region is relatively sparsely populated, with only two population centers of 200,000 or more, both in eastern Nebraska. The region has a relatively high number of IBTs, with 45 near irrigated agricultural lands and 60 in rural areas, mostly located in Nebraska. The lack of concentrated population in this region is reflected in only two IBTs being identified as either near a city or near both a city and irrigated agriculture

3.4.1.3 East North Central

The East North Central climate region consists of four states: Minnesota, Iowa, Wisconsin and Michigan. This region is also relatively sparsely populated, with six population centers of 200,000 or more. At least one population center is within each state in the region. Only eight IBTs in this region were classified as either city + irrigated agriculture or near a city, and 10 were classified as near irrigated agricultural land. The relatively small number of IBTs near irrigated agriculture reflects that in this climate region there are only 10 counties identified as heavily irrigated. Most IBTs (78%) in this region are rural IBTs, reflecting the lack of population centers and limited land area that is irrigated for agriculture.

3.4.1.4 Central

The Central climate region consists of seven states: Missouri, Illinois, Indiana, Ohio, West Virginia, Kentucky and Tennessee. This region is more heavily populated with 12 cities of larger than 200,000 people. With the greater population, more IBTs were identified in this region, with 69 near irrigated agriculture, 32 near cities, and only seven classified as rural. An additional 48 were near both agricultural lands and cities.

3.4.1.5 Northeast

The Northeast climate region consists of many, mostly smaller, states: Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire and Maine. The region in general is moderately populated, although New York City and its surroundings are very densely populated. Only 19 IBTs were identified as being in proximity to cities only, with a further

13 rural IBTs, 27 near irrigated agriculture and only two classified as city + irrigated agriculture. This region has relatively high annual rainfall for nearly all areas (Wieczork and Lamotte, 2010).

3.4.1.6 West

The West climate region consists of only two large states, California and Nevada. California is the most populous state in the U.S. It also is highly agricultural (USDA, 2018) and has relatively low annual rainfall across much of the state (Wieczork and Lamotte, 2010). Seven counties have more than 30% of their land irrigated, two of which have greater than 50% of land irrigated for agriculture. Nevada, however, has no counties with irrigated agricultural lands and only two areas with population centers: Reno and Las Vegas. Due to this mix of population and agriculture, only eight IBTs were near irrigated agriculture and 14 near cities, with 93 being city + irrigated agriculture. 11 IBTs were classified as rural, with the majority of those in Nevada.

3.4.1.7 Southwest

The Southwest climate region consists of four states: Arizona, Utah, Colorado and New Mexico. This region has relatively low annual rainfall (Wieczork and Lamotte, 2010) and as a result has a significant number of IBTs (195). In most cases agricultural lands and population centers are distant from each other in this region, leading to only four multiclass IBTs. 75 IBTs in the region were near agricultural lands only, 57 near cities, and 59 were classified as rural.

3.4.1.8 South

The South climate region consists of six states: Texas, Oklahoma, Kansas, Arkansas, Mississippi and Louisiana. It has the second largest number of IBTs (558) of the U.S. climate regions. This region contains several major cities, particularly within Texas, Louisiana and Oklahoma, although population outside of the cities is sparse. There is significant agricultural land in Arkansas, with a large amount of irrigated land in the country near the Mississippi River (see Figure 3-2). Due to relatively low annual rainfall (Wieczork and Lamotte, 2010), there is also a significant amount of irrigated land in northwest Texas and west Kansas. This mix is reflected by the identification of 62 rural IBTs, 116 IBTs near cities, 297 near irrigated agriculture, and 83 classified as city + irrigated agriculture.

3.4.1.9 Southeast

The Southeast climate region consists of six states: Alabama, Florida, Georgia, South Carolina, North Carolina and Virginia. This region has the largest number of IBTs (829) of the U.S. climate regions. Most of the population is concentrated in Florida, which has almost double the population of any other state in this region. Irrigated agricultural lands are concentrated mostly in central and southern Florida, with some in the southwest of Georgia (see Figure 3-2). In Florida there are a great many IBT reaches, resulting in over 400 irrigated agriculture reaches and 150 classified as city + irrigated agriculture. An additional 57 reaches are classified as city IBTs and 198 are rural IBTs.

3.4.2 Drivers of Interbasin Transfers in the U.S.

Information regarding the date and specific purpose for the construction of each IBT was obtained for each sample. The sources of information utilized to identify the dates of construction and purpose for each sample are provided in the Supporting Information. The NHD reach codes associated with each IBT sample are also provided within the Supporting Information, which allows for further examination of the samples including flow direction within the water network. Five drivers of IBT construction were identified in this study based on the purposes for which the sample IBTs were found to be originally constructed. These are listed in Table 3-4.

Table 3-4 Identified Drivers and Definitions

Driver	*Definition*
Municipal and Industrial	IBTs constructed for municipal water supply, industrial uses such as mining and manufacturing, and power generation including both thermoelectric and hydroelectric generation
Agriculture	IBTs constructed to provide water to agricultural lands
Drainage/Flood Management	IBTs constructed to facilitate drainage of land for any other use, prevent flooding of land, or to prevent changes in drainage patterns of rivers
Commercial Shipping/Navigation	IBTs constructed to enable commercial shipping operations for any purpose, including industrial and agricultural goods, or to enable recreational craft passage
Hunting and Trapping	IBTs constructed for the original purpose of hunting and trapping game
Dual Purpose	Dual purpose is utilized in instances where both the Municipal and Industrial driver and the Agriculture driver was discovered to be the original purpose of construction

The frequency of occurrence of the various drivers of IBT development among the 109 samples examined is shown in Figure 3-4. The figure shows that the most common driver in the U.S. for interbasin transfer is for drainage or flood management purposes, with 35 instances of basin transfers constructed for this purpose among the 109 sampled IBTs. Notably 23 of these were in the Southeast climate region, predominantly Florida.

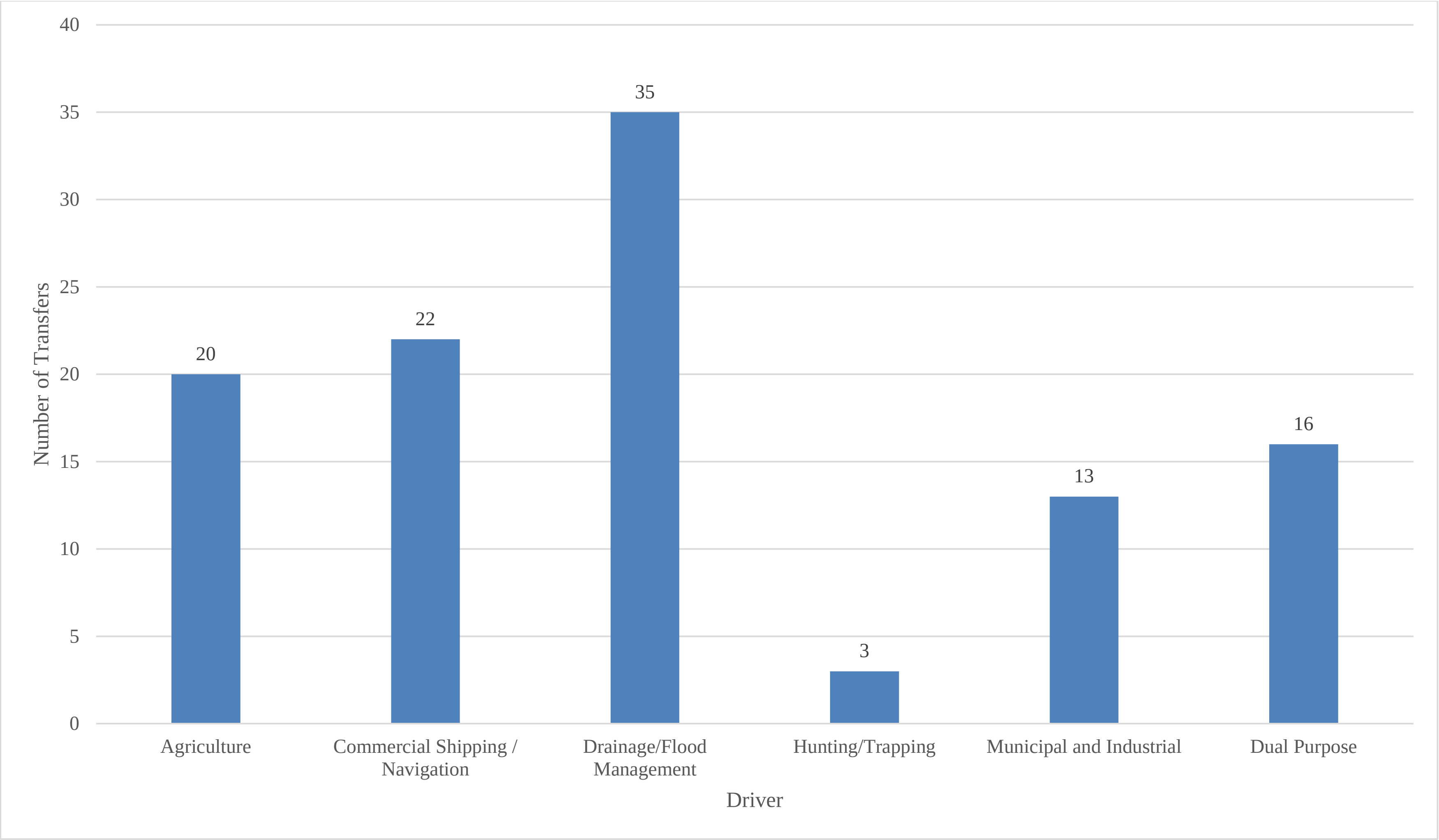

Figure 3-4 U.S. Interbasin Transfer Sample Drivers – Frequency of Occurrence Among 109 IBT Sample. See Table 3-4 for definitions of drivers

While Figure 3-4 indicates that commercial shipping and navigation driver is the next most common driver, IBTs that are at least partially for agriculture are more frequent, with 20 built solely for use in agriculture and a further 16 built for dual purposes, both municipal and industrial use and for agriculture. Similarly, IBTs used only for municipal and industrial purposes totaled 13, but as noted an additional 16 IBTs were dual purpose.

Commercial shipping and navigation is shown, however, to be a very important driver, with 22 of the sampled IBTs being constructed for that purpose. From Figure 3-4 it is clear that there are four major drivers of IBTs in the continental U.S.: agriculture, commercial shipping and navigation, drainage or flood management, and municipal and industrial purposes. Hunting and trapping was not found to be a common driver and was limited to three instances, all occurring in one small part of Louisiana, within the South climate region.

The samples examined also provided information on the relationship of drivers and IBT classification. Of the 109 IBT reaches examined, 20 were classified as city IBTs and the original development drivers associated with those IBTs reflected their proximity to populations. Only one sample classified as a city IBT had an agricultural purpose, with the remaining 19 samples mainly for municipal and industrial supply (seven), drainage or flood management (five), or commercial shipping or navigation (four). The remaining three reaches were part of the Central Arizona Project which provides water over very large distances and was initially constructed for both municipal and industrial supply and agricultural supply.

Reaches classified as near irrigated agricultural lands represented 45 of the samples. Only 13 of these reaches were identified as originally driven by agricultural needs. An additional 18 reaches had drainage or flood management drivers, commonly linked to the creation of arable or pasturable land. Three additional IBT reaches were at least partially driven by agricultural needs as well, with their driver being both municipal and industrial supply and agricultural supply. Six of the reaches were for commercial shipping or navigation, in some instances for moving agricultural products. Two IBTs classified as irrigated agriculture were constructed to meet municipal and industrial needs, but these are outliers, with one bypassing irrigated lands to deliver water to a city and the other related to mining occurring near agricultural land. The remaining three IBT samples classified as near irrigated agricultural lands were for hunting and trapping.

Eighteen of the sampled IBT reaches examined were classified as city + irrigated agriculture. This proximity to multiple features resulted in most transfers being constructed, although the major purpose was for drainage or flood management. Eight of the IBTs were identified as being for this purpose, with five for dual purpose, two for municipal and industrial purposes and two for agriculture.

The remaining 26 samples examined were classified as rural IBTs. The lack of dense population centers and significant agricultural water needs is reflected by the drivers for rural IBTs, with 11 of the reaches constructed for commercial shipping or navigation purposes and another four for drainage or flood management. However, four of the rural IBTs were for agricultural purposes and two were for municipal or industrial supply. While five rural reaches were for dual purpose, three were part of the Central Arizona Project, moving water towards Phoenix and Tucson from Lake Havasu, and another was a reach constructed before the U.S was even founded, providing water only on a very local scale, reflective of its rural classification.

3.4.3 Interbasin Transfer Drivers by Climate Region

Drivers in each climate region were found to be closely aligned, with most regions having one or two major drivers for the majority of the case-study IBTs within their boundaries.

3.4.3.1 Northwest

Three IBTs were examined in this region, each located in different parts of Oregon. Two of the IBTs were found to be driven by agricultural needs, with the remaining sample originally constructed for drainage or flood management.

3.4.3.2 West North Central

Five IBTs were examined in this climate region. The initial development of four of the sample IBTs were driven by agricultural needs, while the one that was classified as near a city was for drainage or flood management.

3.4.3.3 East North Central

Four IBTs were examined in this region. Three of the IBTs were constructed for drainage or flood management purposes, while the fourth was constructed for agricultural purposes.

3.4.3.4 Central

Eight IBTs were examined for this region and commercial shipping and navigation was found to be the dominant driver, with five of the IBTs built for this purpose. Two more were built for drainage or flood management purposes.

3.4.3.5 Northeast

Due to the small number of IBTs in this region only four samples were examined, two near New York City to examine the importance of a large population center on local drivers with the other IBTs being rural and agricultural types. Only two counties in this region have more than 10% of their lands irrigated and this was reflected by the drivers identified. The two samples near New York City were constructed to address municipal and industrial needs, while the other two were constructed for commercial shipping or navigation purposes.

3.4.3.6 West

In total 10 IBT samples were performed and the only drivers identified in this region were linked to agriculture or municipal and industrial supply. Two of the IBTs examined were for agriculture only, three were for municipal and industrial supply only, and five were dual purpose, specifically for supplying both agriculture and municipal and industrial water.

3.4.3.7 Southwest

Thirteen IBT reaches were examined as case studies and these were constructed to meet agricultural needs, municipal and industrial demand, or both. Six of the examined IBT reaches were for the Central Arizona Project, all of which were driven by both agricultural and municipal and industrial needs. However, four other IBT reaches were also driven by this purpose, meaning that 10 out of 13 IBT reaches in this region were for dual purpose, with two of the remaining three for irrigated agriculture and the other reach was developed for municipal and industrial use.

3.4.3.8 South

The large number of IBTs in this region led to performance of 29 case studies. A relatively wide range of IBT drivers was found, with three major drivers accounting for over 75% of IBTs constructed. Nine IBTs were constructed to provide water for agriculture, seven for municipal and industrial needs, and six for commercial shipping or navigation. One small cluster of three IBTs in Louisiana had the unique driver of hunting and trapping, which was not identified in any other region or state. Three other IBT reaches were for drainage or flood management purposes.

3.4.3.9 Southeast

Although 33 case studies were conducted in this region, only two drivers were found for the IBTs constructed; drainage or flood management, and commercial shipping or navigation. Of the IBTs examined for case studies, eight were for commercial shipping or navigation, although within South Carolina and Alabama all five case studies were for this purpose. In the remaining four states 21 out of 24 case studies were for drainage purposes. This driver was particularly prevalent in low-elevation Florida, but also in wetland areas of North Carolina.

3.4.4 History of Interbasin Transfer Construction in the Contiguous U.S.

IBTs have been constructed in the U.S. since before its formation as a country, with one case study IBT having a construction date of approximately 1717. However, the general indication from the case studies is that IBTs were predominantly constructed between the late 1800s and 1980. This is shown in Figure 3-5, which does not include the Hunting and Trapping Driver as only three were constructed, all between 1900 and 1910.

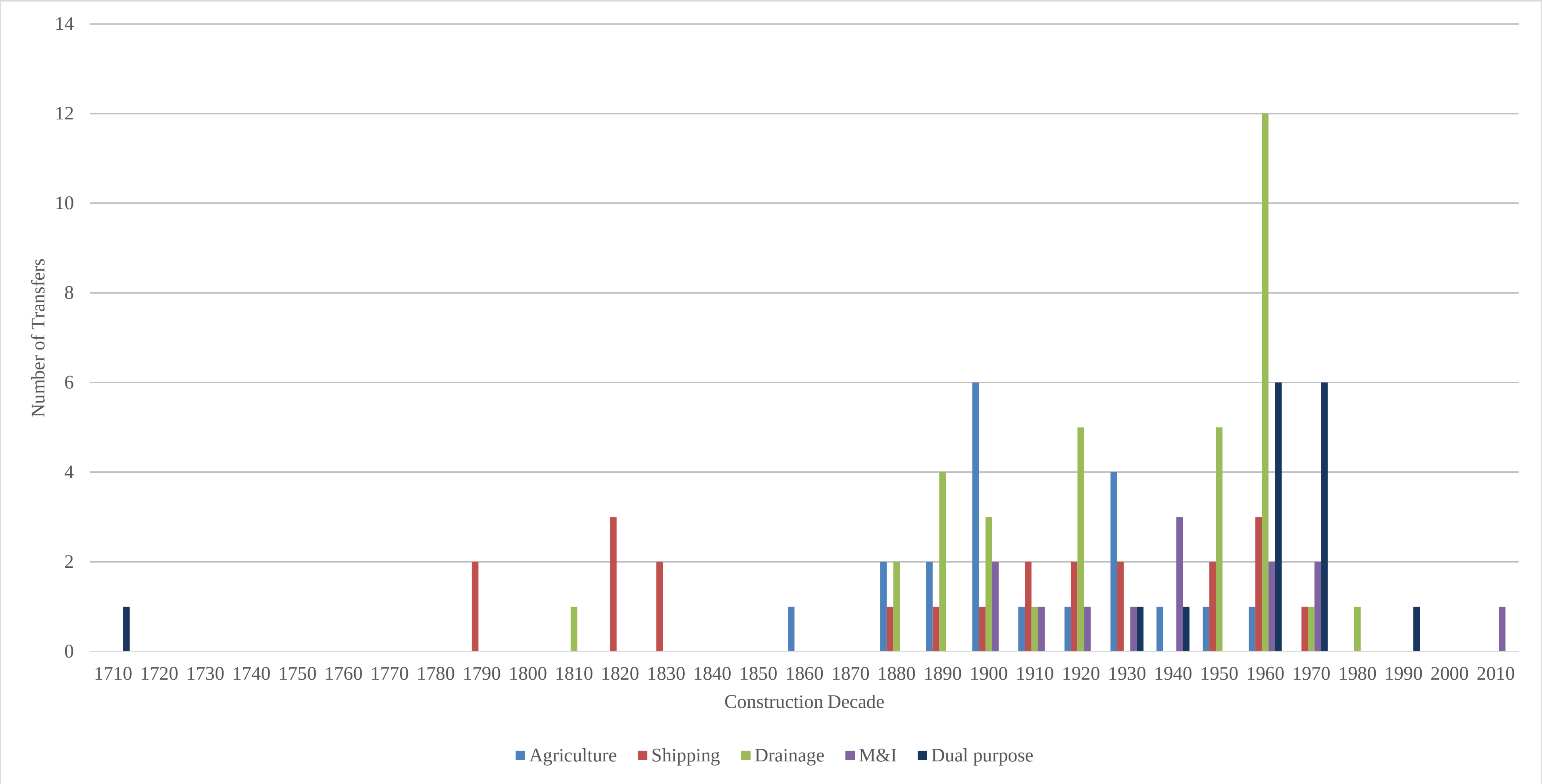

Figure 3-5 U.S. Interbasin Transfer Construction Periods by Driver for 109 IBT Samples. See Table 3-4 for definitions of drivers

Of the 109 case studies investigated, 96 were discovered to have been constructed within the 100 years following 1880. Two decades stand out within this period: 1900-1910, during which a total of 15 IBTs were constructed; and the 1960s, in which 24 IBTs were built. The 1920s and 1970s also had strong IBT construction numbers, with 9 and 10 respectively, and 8 each in the 1930s and 1950s.

Development of agricultural IBTs was particularly prevalent between 1880 and 1910. Ten of the 20 IBTs for agricultural purposes were constructed within this three-decade span with a further four built in the 1930s. Many of these were built in Texas and Nebraska, taking advantage of major rivers to irrigate lands nearby, though outside of the basin of origin. In Texas, the main source utilized was the Rio Grande River, with many irrigation districts founded and canals built between 1900 and 1910. For Nebraska, the Platte River was utilized as a source for several transfers for agricultural purposes. The spike in construction in the 1930s coincides with a major drought, known as the “Dust Bowl” which severely impacted agriculture in the U.S. (Adams County, 2015; Hornbeck, 2012; National Drought Mitigation Center, 2018). No agricultural IBTs have been constructed in the U.S. since 1970.

Shipping and navigation was a more intermittent driver historically, with five IBTs constructed for this purpose between 1820 and 1840, but no others as part of the case studies until 1880. However, between 1880 and 1980 shipping was a consistent, though small, factor in the construction of the IBTs studied, with one or two built every decade except the 1940s.

IBT construction for drainage or flood management was especially prevalent during two separate periods in U.S. history from analysis of the case studies. Between 1890 and 1930, 12 of the 26 case studies were constructed for drainage or flood management purposes. An additional 11 were constructed between 1950 and 1970, with the majority of those in the 1960s. All case study IBTs constructed in the 1960s for the purposes of drainage or flood management were located in Florida. This can be attributed to a combination of agricultural needs, with significant needs for lands to grow sugar after a Cuban embargo (Landry, 2002), and residential needs, with large numbers moving into the state, over 130,000 people per year, starting in the 1950s and continuing to the end of the 1990s (Smith, 2005).

Municipal and industrial use as a driver of IBT development was not seen in early U.S. history, but became prevalent between 1900 and 1950. Several of the projects built during this time period were to supply water to cities and enable continued growth, with two examples being New York City, which began importing water from the Catskill and Delaware watersheds in the periods 1900-1910 and 1910-1920 respectively, and Tulsa in Oklahoma, which began importing water in the 1920s. Three IBTs constructed in the 1940s for municipal and industrial purposes can be linked to the Second World War and its aftermath, due to population movements towards the Pacific coast and wartime military bases (Rhode, 2018).

Dual purpose IBTs, constructed for both municipal-industrial and agricultural purposes became more common from 1960-1980, with 12 such IBT reaches constructed. However, most of these IBT reaches were part of two larger transfer projects: California's State

Water Project and Arizona's State Water Project. The few remaining dual-purpose IBTs built during that period were also in California.

While construction of IBTs across the contiguous U.S. took place in 18 of the 30 decades from 1710 to 2010, the times of construction varied dependent upon region. This clustering reflects times when states were initially being populated, shifts in that population and the evolution of human needs within specific parts of the country.

The earliest basin transfers were focused in two regions, with five of the seven IBTs (canals) constructed up to 1840 either in the Southeast climate region, specifically North Carolina, South Carolina, and Georgia, or in the Central climate region, specifically Ohio. In the period 1900-1910 the South and Southwest climate regions experienced significant IBT development, with 10 out of the 15 constructed in this period occurring in these two regions. More than half of the case studies from that decade were in the South climate region, specifically Texas and Louisiana.

IBTs were developed in many regions from 1910 to 1940, with six climate regions represented among the 21 case study IBTs constructed in this period. The West North Central climate region saw most of its IBTs constructed within this timeframe, with four out of the five examined built during that three-decade span.

The 1950s and 1960s had much of the IBT construction occurring in the South and Southeast regions, while in the 1970s most reaches were constructed in the Southwest region, specifically for the Central Arizona Project which has six reaches crossing basin boundaries. The remaining four IBTs from this period were all located in the South Climate Region.

Only three case-study IBTs had construction dates after 1980. Notably, these occurred in three of the four most populous regions, and specifically within the most populous and most rapidly growing states within those regions: California, Florida and Texas.

3.5 Summary and Conclusions

The objectives of this study were to characterize and classify IBTs, linking IBTs to land uses occurring in the vicinity, and to examine development drivers for a subset of IBTs in the U.S through samples in different climate regions of the U.S. The samples included investigation of IBT construction dates and the original reasons for development, providing insight into the current status of IBTs.

Characterizing and classifying the IBTs revealed that most IBTs are constructed in proximity to agricultural lands, in particular in the South and Southeast climate regions. In the West climate region the close proximity of population and agriculture was reflected by over 70% of IBTs being within 100km of both a city and irrigated agricultural land. For other climate regions, the majority of IBTs were found to be agricultural or rural, reflecting the sparser population of these regions, with only the Northeast climate region having a significant number of IBTs occurring near cities.

Four major drivers of IBTs were identified in the U.S.: agriculture, municipal and industrial, drainage or flood management, and commercial shipping or navigation. The most common drivers were drainage or flood management and agriculture, although almost

45% of those for agriculture were developed also to provide water for municipal or industrial supply.

Historically, the earliest IBTs in the U.S. were for commercial shipping or navigation. Agricultural drivers of IBTs were prominent from 1880 to 1940. IBTs for drainage or flood management purposes were developed in significant numbers in the 1920s, though the 1960s saw the most IBTs constructed for this purpose. Municipal and industrial needs became important as a driver of IBT construction in the early 1900s and continued to be a consistent driver until the 1960s, when IBT development to supply both agricultural and municipal and industrial supply became more common. While the earliest IBTs in the U.S. were built in only two climate regions (Southeast and Central), as time progressed IBTs were constructed across the country. Only a small number of IBTs have been constructed after 1980.

While this study examined the drivers for the construction of IBTs in the U.S., it did not systematically examine effects of IBT size or flow volumes. Further analysis regarding the quantities of water transported, and if they are used or merely diverted could provide context regarding the drivers associated with major basin diversions. In turn, this could be used to analyze the regions of the U.S. most likely to require IBTs in the future, given the factors that have driven major IBT construction in the past.

3.6 Acknowledgements

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Chapter 4 : Water Risk in the United States

This chapter, written by Kerim E. Dickson and co-authored by Dr. David A. Dzombak will be submitted for publication

4.1 Abstract

Examination of water risk is important for identification of areas of potential insecurity, and to prioritize allocations of resources to reduce projected risk. This work builds on and advances a previous water risk analysis for the U.S. developed by Roy et al. (2012), which utilized risk factors primarily focused on available water as given by the difference between local precipitation and water demand and evapotranspiration at the county level. As that approach did not account for flow of water between counties it led to the identification of some counties located on major rivers as being at high risk. This limitation was addressed in the present study of water risk in the U.S. The analysis utilized data from the 2015 USGS Water Use Report and projected water use in 2050, assuming that only municipal and domestic water demand and thermoelectric power water withdrawal demand will change over time. Flow volumes were calculated using the Water Supply Sustainability Index (WaSSI) tool developed by the USDA Forest Service (Sun, 2008). The WaSSI model enabled the analysis to account for changes in the climate and related hydrology, including surface inflow in each county, and also changes in water demand. A modified water risk index was formulated and calculated for all counties in the contiguous U.S. The risk index includes comparison of water withdrawals to local flow, drought susceptibility in the present and future, projected growth in water withdrawal, and proportion of groundwater use relative total water use. Additionally, the index utilizes a scaled-value system for each factor, providing further context to the individual risks examined. Results indicate that accounting for natural importation of water in counties in addition to precipitation reduced the risk profile of many counties in the U.S. significantly, with a maximum of 36 counties classified as high or very high risk for the scenarios

examined, compared to over 400 identified in the highest risk category in the previous analysis by Roy et al. (2012).

4.2 Introduction

Water has been synonymous with civilization for thousands of years. As human populations have grown, spanning the globe, our water demands have increased not only for our own domestic consumption, but also for growing crops, industrial and commercial uses, and for generating electricity (Harvey et al., 2017).

In 1900 the total U.S. population was approximately 76 million, but by the turn of the millennium this number had increased to over 281 million, a greater than three-fold increase (U.S. Census Bureau, 2018a). With the increase in population came an increase in water demand and between 1950 and 1980 water use grew in a fashion approximately correlated with population growth of the United States (USGS 2017). However, since 2005 the most prodigious water withdrawers in the U.S. have reduced their demand slightly, in the case of irrigation (USGS, 2018a), or significantly, in the case of thermoelectric power generation (USGS 2018b).

Despite the recent reduction in water demand for some sectors of water users in the U.S., significant quantities of water are still in demand every day, with implications for the sustainability of water sources in the United States. With climate change effects already being recognized in drought conditions in the southwest U.S. (Cook, 2018) and extreme rain events across the U.S. occurring with increasing frequency (EPA, 2016), the risks of local governments and utilities being unable to continue uninterrupted and sufficient water supplies to their users are increasing in some areas and decreasing in others.

There have been examinations of water risk globally (Lloyd's, 2010; Gassert et al., 2015), with some focusing specifically on the United States such as that by Roy et al. (2012) and by Sun (2008) of the U.S. Department of Agriculture (USDA) Forest Service. Other studies have examined the water risk to specific users, such as examination of U.S. cities that showed over 15% of U.S. population can be considered at risk for water scarcity (Padowski and Jawitz, 2012)

The work by Roy et al. (2012) examined demand and supply factors across the United States, with the amount of risk for each county determined by several factors, including intensity of groundwater use, proportion of use compared to available precipitation, growth in demand, and the deficit between summer demand and available precipitation. Of the five risk factors, three partially depend on local precipitation which resulted in some counties with cities or other large-scale users on major U.S. rivers being classified as high or extreme risk, despite large local flows supplementing the available precipitation. Examples include Allegheny County in Pennsylvania into which two major rivers flow and converge to form the Ohio River; and also several counties that border the Mississippi River.

The present work builds on the previous efforts to quantify the risks to water supply and utilizes their strengths to advance water risk analysis with consideration of some additional factors. Examining multiple factors that may contribute to the overall risk in a watershed or county while also accounting for natural importation of water enables analysis that accounts for the combined effects of demand from upstream watersheds, seasonality, and local demand to enable improved resource planning for the future.

Following the work of Roy et al. (2012), greenhouse gas emissions scenarios including high (A2), medium (A1b) and low (B1) scenarios established by the UN Intergovernmental Panel on Climate Change (IPCC, 2000) were utilized in conjunction with 2050 projections of population-related water demand and thermoelectric power water demand to produce future scenarios for evaluation of water supply risk. The USDA Water Supply Stress Index (WaSSI) model (Sun, 2008) was used to project the monthly and annual flows for each watershed in the contiguous U.S. for each of the scenarios and results were converted to the county level to provide a basis for comparison with water withdrawals determined by the USGS and with the analysis of Roy et al. (2012).

The existence of an interbasin transfer (IBT) in a particular watershed can impact downstream supply values. Utilizing an inventory of IBTs in the U.S. (Dickson and Dzombak, 2017), consideration of IBTs can provide insights into both the subtraction of supply from some regions and the addition of supply to others. Such analysis can allow planners to examine both areas of elevated water supply risk in the U.S., and areas of low or negligible supply risk to see if water transfers from the low risk locations to higher risk locations are a feasible option. Consideration of IBTs was outside the scope of the work by Roy et al. (2012) and is not currently part of the WaSSI model. While quantitative consideration of IBTs was not possible in the present study which utilized the WaSSI model, some analysis of the potential effects of IBTs was performed based on the results obtained.

The objectives of this work were to examine the water risks in the United States by county considering both current and future conditions and accounting for natural water importation through streams and rivers. Additionally, the locations of existing IBTs identified at the HUC6 level were compared with regions shown to be at risk of water stress. This work utilized the WaSSI model, U.S. Geological Survey (USGS) Water Use reports (Maupin et al., 2014, Dieter et al., 2018) and geographical information system (GIS) analysis to produce maps showing the areas of greatest water risk in the U.S. considering the various scenarios for future changes in population, thermoelectric power water demand, and in surface water supply as affected by climate change.

4.3 Methodology

4.3.1 Water Supply Stress Index

The WaSSI model was originally released in 2008 (Sun, 2008), and subsequently modified and developed into a web tool in 2011. Version 2.0 of the tool was released in 2012 and updated several aspects of the model. Version 2.1 is the most recent version of the model and was released in 2013 (U.S. Forest Service, 2018). While the web tool provides an interface for use through the internet, the desktop version was utilized for this analysis. The desktop version was provided by the U.S. Forest Service by special arrangement.

The WaSSI model is a unique monthly water balance model including all watersheds in the contiguous U.S. that utilizes a variety of inputs to produce a suite of outputs, including estimated flow. The variables included within the model include land cover, climate, population, temperature, precipitation, and water withdrawal demands by sector. Furthermore, the model empirically derives evapotranspiration, infiltration, soil storage, snow accumulation and melt, surface runoff and base flows based on the input variables (U.S. Forest Service, 2018). The model outputs provide data at the watershed level across the U.S. The default inputs to the model are derived from a range of sources (U.S. Forest Service, 2018). All of the inputs are re-scaled to the HUC4 level or 0.5 degree grid. Specific inputs to the model include STATSGO-based soil properties, 2006 NLCD land and impervious cover, MODIS leaf area index by land cover, USGS water use estimates, population projections for 2010-2060, 1961-2010 PRISM historical monthly precipitation and temperature, and 1961-2099 climate projections derived from several general circulation climate models (U.S. Forest Service, 2018). The climate models are part of the CMIP3 and have been downscaled and bias corrected within WaSSI.

The WaSSI model consists of three modules, of which two are utilized in this work. A water balance module computes the ecosystem water use, evapotranspiration and water yield for each watershed, with yield being calculated as the runoff from hydrologic processes without flow contribution from upstream watersheds. A water supply and demand module then routes and accumulates the yield through the river network according to the topological relationships between adjacent watersheds, subtracting consumptive human uses.

The WaSSI model produces a water risk value for the watersheds examined. The risk value produced by WaSSI is based solely upon the modeled water demand and supply for each watershed given the specified model parameters and a set of water demand and climate conditions. Therefore, the WaSSI model doesn't produce a risk value indicative of the total risk from multiple factors influencing water resource supply as in the Roy et al. (2012) approach.

Both the web-based tool and the desktop version of WaSSI offer a group of variables that can be edited to run the model in a variety of modes. While the web-based tool did not offer customization of inputs, the desktop version allowed for new input files to be utilized. The default WaSSI model utilizes the 2005 USGS Water Report (Kenny et al., 2009) data, converted to the watershed level from the county level, as an input for the water demand. The present work substituted the 2010 Water Report data (Maupin et al., 2014) which were supplied in the appropriate watershed level input format by the U.S. Forest Service. Thus, the latest watershed level data compatible with the WaSSI input requirements were used to ensure consistency within the WaSSI tool. Per capita usage by watershed in WaSSI is calculated based on the input data files for population and water demand. As the default population data in WaSSI are for 2010, use of the 2010 watershed data instead of the default 2005 watershed data ensured that public and domestic supply water demand calculations within WaSSI utilized time-consistent data.

The WaSSI model variables available for editing include the year or span of years for examination, the climate model to utilize, both the forest land cover change and the type of land to which it is changed (such as crops or urban), precipitation change and temperature change fractions beyond the base scenario, the population scenario and change fraction, the change in groundwater supply, and the various water demand sectors.

4.3.2 USGS Water Use Reports

The USGS produces a water use report every five years that provides data on water withdrawals across the country at the county level. The USGS water withdrawal data have been processed by the U.S. Forest Service for WaSSI to provide water use data at the watershed level. While the latest county-level water withdrawal data available are from 2015 (Dieter et al., 2018), the Forest Service has not converted the data to the watershed level for WaSSI compatibility. In order that the present analysis utilized the 2015 county level data, the percentage change between 2010 and 2015 in national water use by sector was calculated for use to set the variables in the WaSSI model so that the equivalent water withdrawals from 2015 would be accounted for in each demand sector to produce the WaSSI results. The 2015 Water Use Report (Dieter et al., 2018) data were also utilized as the base scenario for projecting water withdrawals in 2050.

Following the assumptions made by Roy et al. (2012) to project water demand in 2050, the 2015 withdrawals for irrigation, livestock, industry, aquaculture and mining were held constant, while the growth in withdrawals for public supply (in relation to population growth) and for thermoelectric power generation were calculated for a range of scenarios based on population growth and energy use projections.

4.3.3 Population Estimation

For 2015 the U.S. Census Bureau county population estimates were utilized in the analysis (U.S. Census Bureau, 2018b). The year 2015 population was chosen for the starting population estimates in each county to ensure consistency with the latest county level water data available for 2015.

Three population estimates were determined for 2050 to be used for the high, medium and low population values. The high value was calculated utilizing the data from the Census Bureau's 2017 county population estimate data (U.S. Census Bureau, 2018b). The 2017 data were utilized to ensure the latest estimated population value for each year, including 2015, were applied in the analysis. The data included population estimates by county for each year between 2010 and 2017. From these values an average annual growth rate was calculated and applied linearly to extrapolate population for each county. For the contiguous U.S. this resulted in a total population estimate for 2050 of almost 432 million, broken down at the county level.

As part of WaSSI a population estimate is included as an input file on an annual basis. The total population for the contiguous U.S. for 2050 in WaSSI was calculated as the summation of the population within each watershed, yielding an estimate of just over 416 million. To convert the WaSSI population projection to the county level, the proportion of population within each county determined in the high population value estimate was utilized to allocate population for this estimate, which is referred to as the medium population value.

The U.S. Census Bureau national projections for 2050 predict much lower growth, with a total population estimated to be approximately 388 million (U.S. Census Bureau, 2018c). As this value is only projected at the national scale, the proportional method used in determining the medium value in allocating population to each county was again utilized to provide the county populations for this low population value.

4.3.4 Thermoelectric Power Water Demand

For 2015, the existing thermoelectric power plant water withdrawals detailed in the 2015 USGS Water Use Report (Dieter et al., 2018) were utilized. To determine projections for 2050, the Energy Information Administration (EIA) Annual Energy Outlook (EIA, 2018) was utilized to obtain the projected change in electricity generation between 2015 and 2050. The percentage increase in generation was then utilized to calculate the increase in water demand for 2050. This approach assumes that while new facilities may be built to replace retiring power generation capacity or to expand, the new facilities will be located near existing facilities due to the local power transmission infrastructure. As a result, only counties currently withdrawing water for thermoelectric power were assumed to be affected by increases or decreases in thermoelectric power water withdrawals.

The high scenario assumes that the existing water demand per kilowatt hour of generated electricity will remain constant between 2015 and 2050, resulting in a demand equivalent to the percentage increase projected by the EIA for thermoelectric power generation. For the medium and low scenarios, a reduction in water demand of 25% and 50% respectively from 2015 levels were assumed, reflecting a trend towards more use of recirculating cooling systems and dry cooling systems (Feeley et al., 2007) which withdraw reduced or negligible quantities of water, and the observed reduction in water withdrawals for thermoelectric power generation since 2005 (USGS, 2018b).

4.3.5 Climate Model Ensembles

For 2050 projections of precipitation and temperature changes, climate models were selected to be comparable to the methodology used by Roy et al. (2012). Three models were available through the WaSSI software that had all three IPCC greenhouse gas emissions scenarios utilized by Roy et al.: A2, A1b and B1. The climate models utilized in WaSSI for the present analysis were the HADCM3 model developed in the U.K. by the Hadley Centre, the CM2 model developed by the National Oceanic and Atmospheric Administration (NOAA), and the CGCM3 developed by the Canadian Centre for Climate Modelling and Analysis. The WaSSI model was run for each climate model and emissions scenario, keeping the other variables constant within each emissions scenario.

The outputs from WaSSI were then collated by the emissions scenario considered to form three sets of output data for each emissions scenario. The individual sets of output data were then averaged to provide a single ensemble value for each watershed in WaSSI that reflected the results from each climate model for a single emissions scenario.

These three models were included as part of the Coupled Model Intercomparison Project (CMIP) Phase 3. Recently CMIP Phase 5 updated models were released, but these are currently unavailable in WaSSI. However, while the magnitude of precipitation increases and decreases are larger in the higher emissions scenarios, the pattern of changes is similar between the CMIP3 and CMIP5 models. As a result the scenarios utilized are conservative in their estimate in water supply reduction for the southwest while potentially underestimating additional water supply from the north of the U.S. However, the range of model simulated precipitation changes is larger than the multi-model mean change, so individual models have a much greater uncertainty than the difference between CMIP3 and CMIP 5 ensembles (NOAA, 2015).

4.3.6 WaSSI Variable Settings

To adjust water supply estimates in WaSSI to 2015 (2010 water use data were the default values in the model), the PRISM Historic Climate model option in WaSSI was utilized, and the population scenario was set to utilize the 2010 Water Report data input file incorporated in WaSSI to calculate the outputs. To provide a representation of the surface water supply in 2015, each demand sector was given a change factor to reflect the change in demand nationally between the 2010 and 2015 water use report.

4.3.7 Water Risk Scenarios

Three scenarios were created to examine potential 2050 water supply risks in the U.S. based on consideration of greenhouse gas emissions scenarios coupled with projections for population related water demand and thermoelectric power water demand as summarized in Table 4-1. The high scenario included the high population estimate as a basis for estimating public supply and domestic use in 2050, and the high thermoelectric power demand projection determined from the EIA projection of electricity generation through thermoelectric means. These values were converted to provide a percentage increase or decrease nationally to serve as input variables for WaSSI and the model was run for each of the climate models with the A2 emissions scenario. The medium scenario was constructed with the default WaSSI input file for population, and a 25% reduction in thermoelectric power water withdrawals from 2015 levels on a national basis. These settings were used for each of the climate models with the A1b emissions scenario to produce results from the WaSSI model. The low scenario utilized the census bureau national projections to calculate the change factor to be applied to the population variable and included a reduction of 50% of thermoelectric power water withdrawals from 2015 levels on a national basis. This was then run with each climate model for the B1 emissions scenario.

Table 4-1 provides a summary of the values that were utilized for each of the scenarios implemented in this work. For each scenario three climate models were utilized with a specific emissions scenario while keeping all other variables constant to produce an ensemble estimate of water supply for 2050.

Table 4-1 Variables for the Low, Medium and High Scenarios Considered in the WaSSI Modeling for Evaluating Water Demand vs. Supply in 2050

Variables	Scenario		
	Low	**Medium**	**High**
Green House Gas Emissions (considered with ensemble of CGCM3, CM2, andHADCM3 models)	B1	A1b	A2
Thermoelectric Power Withdrawal in 2050 (Change from 2015 value)	-50%	-25%	+7.91%
Population in 2050 (millions)	388.34	416.36	431.92

4.3.8 GIS Data Acquisition

The WaSSI data inputs and outputs are given as values by Hydrologic Unit Code 8 (HUC8) scale watersheds. The watershed boundary file for GIS was downloaded through the U.S. Forest Service and provided the locations of the 2099 watersheds identified by the USGS at the HUC8 scale for the contiguous U.S.

To show the state boundaries for this analysis a shapefile was downloaded from the U.S. Census Bureau at the 1:500,000 resolution level (U.S. Census Bureau, 2015). The U.S. county boundaries were also obtained from the Census Bureau at the same resolution (Census Bureau, 2017). The USGS Small-scale Dataset of Cities and Towns of the United States was utilized for the location of cities in the U.S. (USGS, 2014).

4.3.9 WaSSI Data Conversion

To be able to compare the output generated by WaSSI with results by Roy et al. (2012), the watershed flow data were converted to the county level. This was achieved using GIS techniques in ArcGIS version 10.5.1 (ESRI, 2017). The output files from WaSSI are text files with comma separated values; these were opened with Excel to enable editing of the tables and so they could be imported into GIS.

To convert the watershed surface water supply values provided by the WaSSI model to the county level a weighted approach was utilized within ArcGIS. The WaSSI values in the Excel table were joined to the watershed boundaries and the intersect tool was utilized to segment the watersheds and counties into small sections. A new field was then created to calculate the area of the intersected sections using the calculate geometry function in ArcGIS. This was used to calculate the percentage of the area of the original watershed within each intersected segment. This percentage was then multiplied by the flow value to provide a weighted flow for each segment. Finally, the intersected segments were re-joined at the county level using the spatial join function, which allowed the summation of the weighted flows in each segment to the county level.

4.3.10 Summer Demand Value Calculation

To calculate the fraction of water use in summer at the county level WaSSI-based calculations at the HUC2 level were utilized. The fraction of water use for each month in each HUC2 were provided by the U.S. Forest Service for the domestic, irrigation and thermoelectric water demand sectors. All other sectors were assumed to have uniform distribution of demand annually. To find the total demand for the summer months, the fraction of use for June, July and August were summed within each HUC2 region. These values were then assigned at the county level using GIS analysis.

The area for each county was calculated using the "Calculate Geometry" tool in ArcGIS. Following this the HUC2 layer and the county layer were intersected, and the areas of the segmented sections were calculated. The intersected area was then divided by the area of the related county to provide a weighted fraction of demand during summer for those counties that overlapped two or more HUC2 regions. The segmented areas were then rejoined to form counties, with the weighted fractions within each segment summed to provide a weighted estimate of the fraction of demand occurring during the summer months. These county demand fraction values were then extracted to an Excel file to calculate the summer demand in millions of gallons per day (MGD), utilizing the 2015 USGS Water Use Report data.

4.3.11 Risk Factors

To emulate the water risk analysis approach used by Roy et al. (2012), five risk factors were defined. However, whereas Roy et al. utilized a binary risk value system the present analysis used risk scaling to provide more context to each risk factor. A risk value of between 0 and 5 was assigned to each risk factor, with higher values representing larger potential risk to the water supply of the county. Therefore the maximum risk value attainable by a county would be 25 points.

The risk factors were defined as follows:

1. The extent of use of the county water supply. This was calculated as the annual water demand for a county in 2015 divided by the total available water supply. WaSSI defines the total available supply as the sum of the surface water supply and groundwater withdrawals. The larger the proportion of use, the more risk there is for that county both locally and in downstream counties, both in terms of meeting demand and providing sufficient water for environmental and water quality needs.
2. The extent of use of the county surface water supply during summer months (June, July and August) in 2015. Due to typically decreased precipitation in summer, combined with increases in specific sector water demands such as irrigation, the surface water supply may become strained and unable to meet demands locally, environmentally and potentially downstream. Counties using more than 100% of the available surface water supply would need to be supplied through alternative means such as storage, groundwater or basin transfers.
3. Projected change in demand from 2015 to 2050. For counties undergoing rapid growth, increases in water demand over a short period of time may challenge the ability of the existing infrastructure to supply water.

4. The extent of use of the county surface water supply during summer months (June, July and August) in 2050. Like the second risk factor, this provides a view of risks due to increases in water demand in conjunction with decrease in supply. For some counties the risk value for this factor may be less than in 2015 due to projected reductions in demand and increases in the projected supply.
5. The extent of groundwater consumption in 2015. Counties meeting a significant portion of their total water demand as groundwater may be at risk of overdrawing the available supply leading to dry wells and subsidence. While some counties may be able to draw all of their demand from groundwater safely, this risk factor is an indicator that the sustainability of the groundwater use in the county should be reviewed to ensure continuous supply and may constitute a risk through depletion or saltwater intrusion for coastal areas.

Table 4-2 shows the bins corresponding to each of the risk values for the factors defined.

Table 4-2 Risk Factors and Corresponding Risk Value Scale for the Water Risk Index

Risk Number	Risk Factor	Risk Value Scale					
		0	**1**	**2**	**3**	**4**	**5**
1	Annual proportion of use of local water supply, 2015	0-5%	5-10%	10-15%	15-20%	20-25%	25%+
2	Summer proportion of use of local water supply, 2015	<60%	60-70%	70-80%	80-90%	90-100%	100%+
3	Projected increase in demand, 2015-2050	0-5%	5-10%	10-15%	15-20%	20-25%	25%+
4	Summer proportion of use of local water supply, 2050	<60%	60-70%	70-80%	80-90%	90-100%	100%+
5	Proportion of groundwater withdrawal to total withdrawal, 2015	0-10%	10-15%	15-20%	20-25%	25-30%	30%+

The sum of the values from each of the five risk factors provided a total risk, or Water Risk Index (WRI), for each county in the contiguous U.S. WRI values from zero to 4 were considered to constitute a negligible risk, from 5 to 9 were low risk, 10 to 14 were moderate risk, 15 to 19 were considered a high risk and values of 20 or more were considered as very high risk. Therefore, to obtain a very high risk classification a county would need to have a high level of risk in at least four of the defined factors. This is an ordinal scale of risk, where comparison of values do not provide insights into a comparative level of risk. This means that a county with a total risk value of 20 is not twice as risky as a county with a risk summation of 10.

4.4 Results and Discussion

While high, medium and low water demand vs. supply scenarios were examined for water risk in the U.S., only the medium scenario results are discussed here, although the number of counties in each risk classification are provided for all three scenarios. The high and low scenario results, and the risk values for each risk factor in all the scenarios are provided as supplementary information in Appendices B and C. The medium scenario provides a look at the mid-range IPCC emissions scenario along with a mid-range estimation for population growth in the U.S. and a reduction in thermoelectric power water demand reflective of recent trends in water withdrawals. For the medium scenario, the emissions scenario utilized is the A1b, the contiguous U.S. national population estimate for 2050 is 416.33 million, and the thermoelectric power water demand for 2050 is 25% less than the 2015 levels.

4.4.1 Projected Annual Surface Water Supply Change

The 2015-2050 projected surface water supply change for the medium scenario, utilizing the A1b emissions scenario in conjunction with the WaSSI population growth estimate and a reduction in thermoelectric water demand, is shown in Figure 4-1.

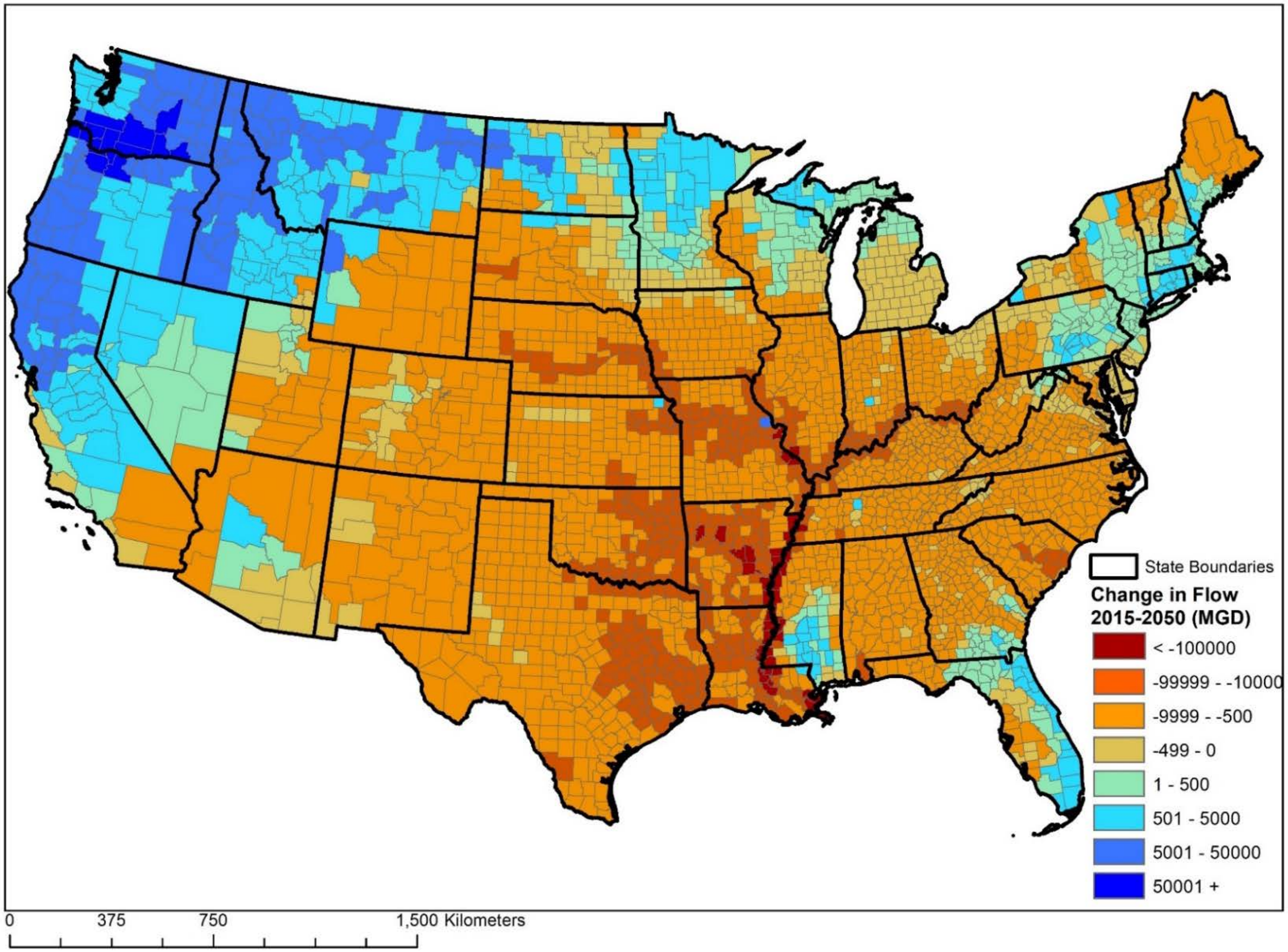

Figure 4-1 Projected Change in Surface Water Flow in Millions of Gallons per Day by County for the Medium Scenario between 2015 and 2050

Figure 4-1 shows counties projected to contain higher and lower flows on an annual basis in 2050 compared to 2015. Cumulative impacts are shown in this map, as lower precipitation upstream, combined with higher temperatures and evapotranspiration, can result in estimated severe reductions in flow, despite local increases in precipitation. This is seen in some counties showing an increase in supply while the surrounding areas show a decrease in supply. This can be because of the county being mostly within a headwater watershed or, rarely, an isolated watershed. It is also seen in the projected annual flow reduction for the lower Mississippi River, through counties in Arkansas, Tennessee, Louisiana and Mississippi to the coast, which is due to the decrease in flow from the upstream tributaries.

While most of California shows an increase in annual supply of water in 2050 compared to 2015, the seasonal supply varies, with many of the counties receiving minimal or no surface water supply during the summer months. The overall projected increase in supply shown for much of California is corroborated by the work done in Roy et al. (2012), which showed that most of California is projected to have an increase in precipitation by a majority of the climate models used to forecast future conditions. The precipitation projections for California in 2050 included in the 2014 National Climate Assessment (Walsh et al., 2014) also show increases.

4.4.2 Projected Change in Population

Water demand is linked to population change, particularly in proximity to population centers. Figure 4-2 shows the change in population between 2015 and 2050 for the medium scenario. The map indicates that many areas of the U.S. will experience a reduction in population, particularly in rural counties, with population shifting to be in proximity of the largest population centers

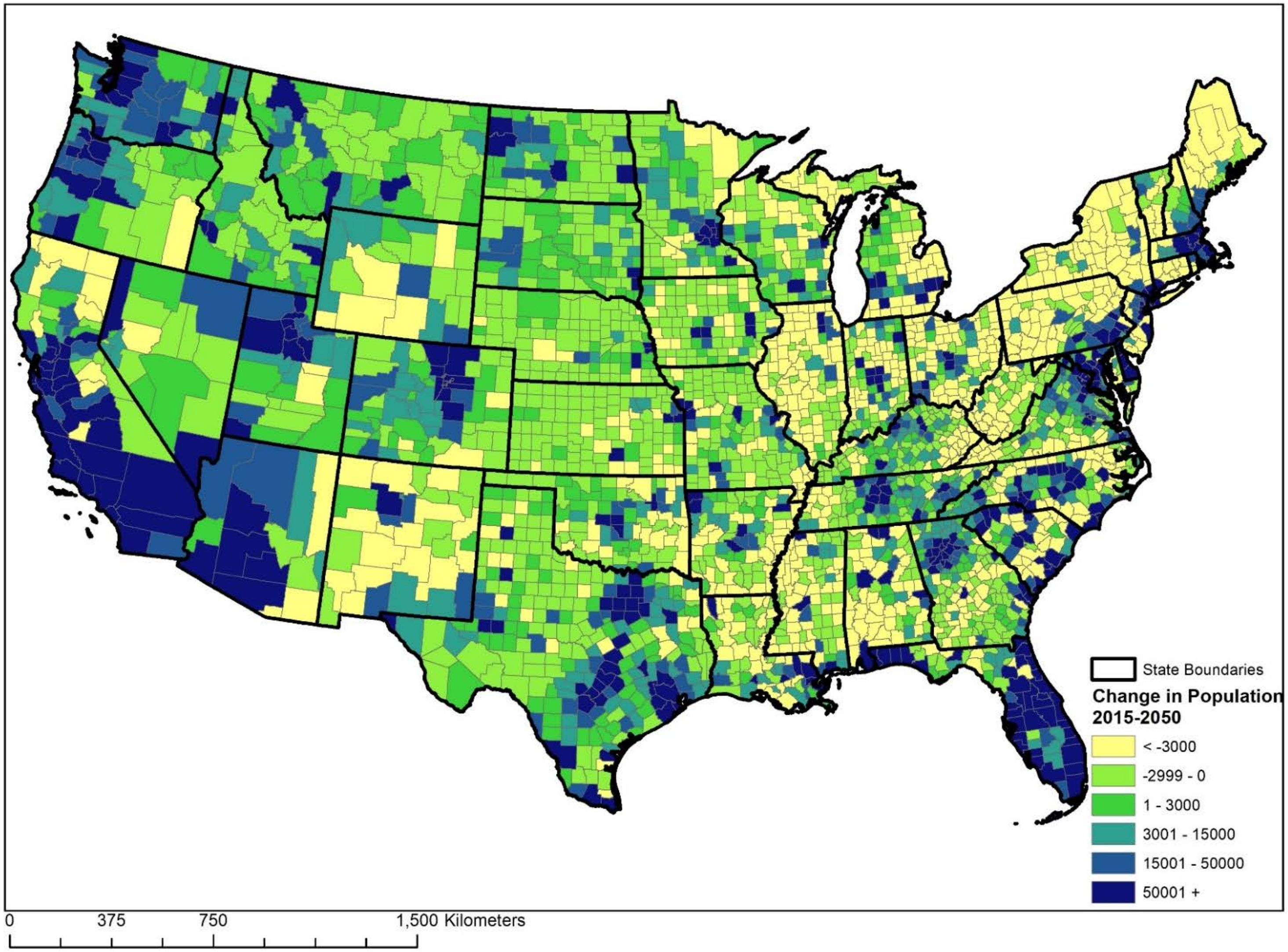

Figure 4-2 Projected Change in Population by County for the Medium Scenario between 2015 and 2050

Some rural areas are projected to have high population growth, however, reflecting extrapolation of current growth patterns. The use of the average growth rate of counties between 2010 and 2017 means that potentially temporary local effects, such as an increased employment demand for specific industries like oil and gas exploration, are extended out to 2050 and may result in the over-projection of population within some counties.

4.4.3 Projected Change in Thermoelectric Water Demand

As future thermoelectric water demand in the present analysis was limited to counties with current thermoelectric generation capacity, any reduction in water withdrawals due to technological changes in new generators and retrofitting of existing facilities will impact both those counties and the downstream counties.

Most of the water withdrawals for thermoelectric power production in the U.S. are located east of the Mississippi River. This reflects higher water supply availability in the east resulting in once-through cooling systems being utilized more frequently, which have a larger water demand than other thermoelectric power systems.

The projected amount of reduction in thermoelectric power water demand under the medium scenario for counties with withdrawal in this sector ranges from 2,500 gallons per day to over 712 million gallons per day. The five states which are impacted the most directly by thermoelectric water demand reduction in the medium scenario are Texas, Illinois, Michigan, Alabama and North Carolina. A 25% reduction of water withdrawals for thermoelectric power in Texas, which withdraws the most water for power generation, would decrease annual demand for water by over 2,400 million gallons per day.

4.4.4 U.S. Water Supply Risk Index

The water supply risk index results by county for the medium scenario are shown in Figure 4-3. The medium scenario includes the A1b emissions scenario, a medium population growth projection and a 25% reduction in water demand (medium scenario) for thermoelectric power water demand. The counties in the highest risk band are located within only three states - California, Nevada and New Mexico - with the majority located in California. All of the counties at very high risk are projected to have a withdrawal demand greater than available supply during summer. While Figure 4-1 showed that most of California is anticipated to receive additional supply on an annual basis in 2050, summer supply is projected as decreasing. Additionally, most of the counties have high risks in their proportion of groundwater use and their current summer surface supply use. Projected increase in demand between 2015 and 2050 had the least contribution to risk for these counties, with only Santa Clara County and San Diego County projected as having a greater than 25% increase in their demand for that span. High risk counties are located across the U.S. including California, Utah, Montana, Kansas, Texas, South Carolina and North Carolina. A range of factors drive the risk across the country with a combination of population growth and lower projected supply, particularly in summer, contributing to the highest risk summations. Counties with high risk also withdraw a large proportion of their demand as groundwater, across the country.

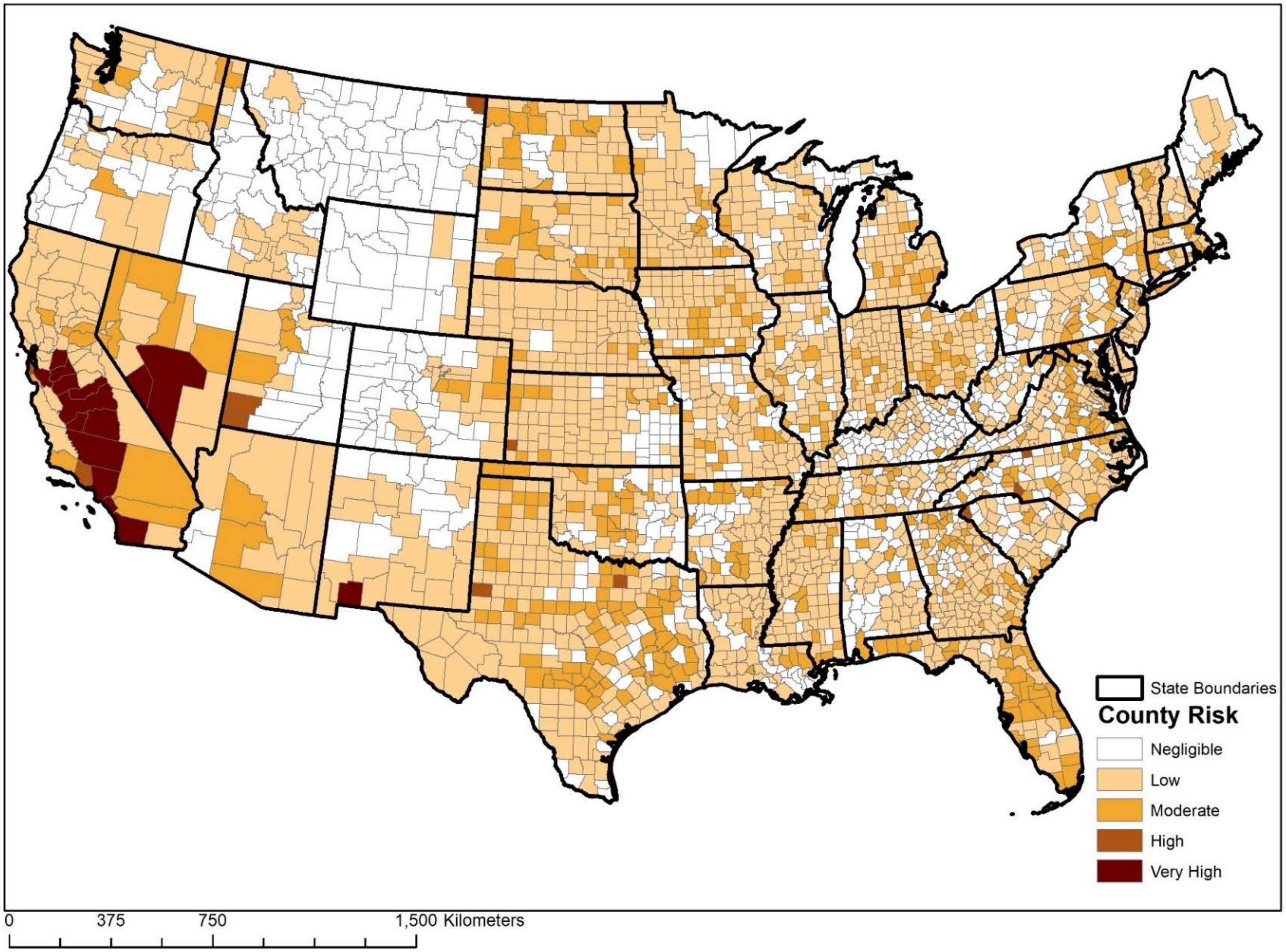

Figure 4-3 Water Risk Index by County under the Medium Scenario

Figure 4-3 has some clear differences with the prior results of the risk analysis conducted by Roy et al (2012). High-risk locations identified by Roy et al., such as Allegheny County in Pennsylvania and many counties bordering the Mississippi River, have reduced risk profiles in the present analysis, with many showing low or negligible risk. This reflects the very large water supply available through natural importation within or very close to these counties. In many of these counties, the single largest source of risk is groundwater withdrawals that exceed 30% of the total withdrawals. The addition of naturally imported water significantly influences the results, reducing the number of counties identified as high risk by 90% in comparison to the Roy et al work.

A large number of counties across the U.S. are considered as having a moderate risk to their water supply. In particular counties containing or near population centers are often classified as having moderate water risk. The breakdown of the number of counties at risk under each risk scenario is provided in Table 4-3.

Table 4-3 Breakdown of the Number of Counties per Risk Classification for the Low, Medium and High Scenarios

		Number of Counties		
Risk Value	**Risk Classification**	**Low Scenario**	**Medium Scenario**	**High Scenario**
0-4	Negligible	975	938	902
5-9	Low	1893	1885	1879
10-14	Moderate	212	257	290
15-19	High	15	11	25
20-25	Very High	12	16	11

While the medium scenario has the highest number of very high risk counties, the high scenario has more than double the number of counties considered at high risk and has the highest number considered a moderate risk. The reduction of counties in the very high risk band for the high scenario are due to climate changes, with the models utilized indicating that some counties will experience more rainfall in the higher emissions scenarios, resulting in an overall reduction in extreme risk.

Counties projected as having similar levels of risk are also not necessarily experiencing the same risks. As the risk value is a summation of the individual risk factors, counties with the same total risk score could, for example, experience very high levels of risk for some factors, but very low risk in others, or have moderate risk in all of the defined risk factors. This risk index therefore provides an indication of regions that may need to conduct localized risk analysis to ensure the identified risks are mitigated.

4.4.5 U.S. Water Risk and Interbasin Transfers

Figure 4-4 shows the locations of IBTs in the US determined by Dickson and Dzombak (2017), cross referenced with the medium risk scenario laid out in Figure 4-3.

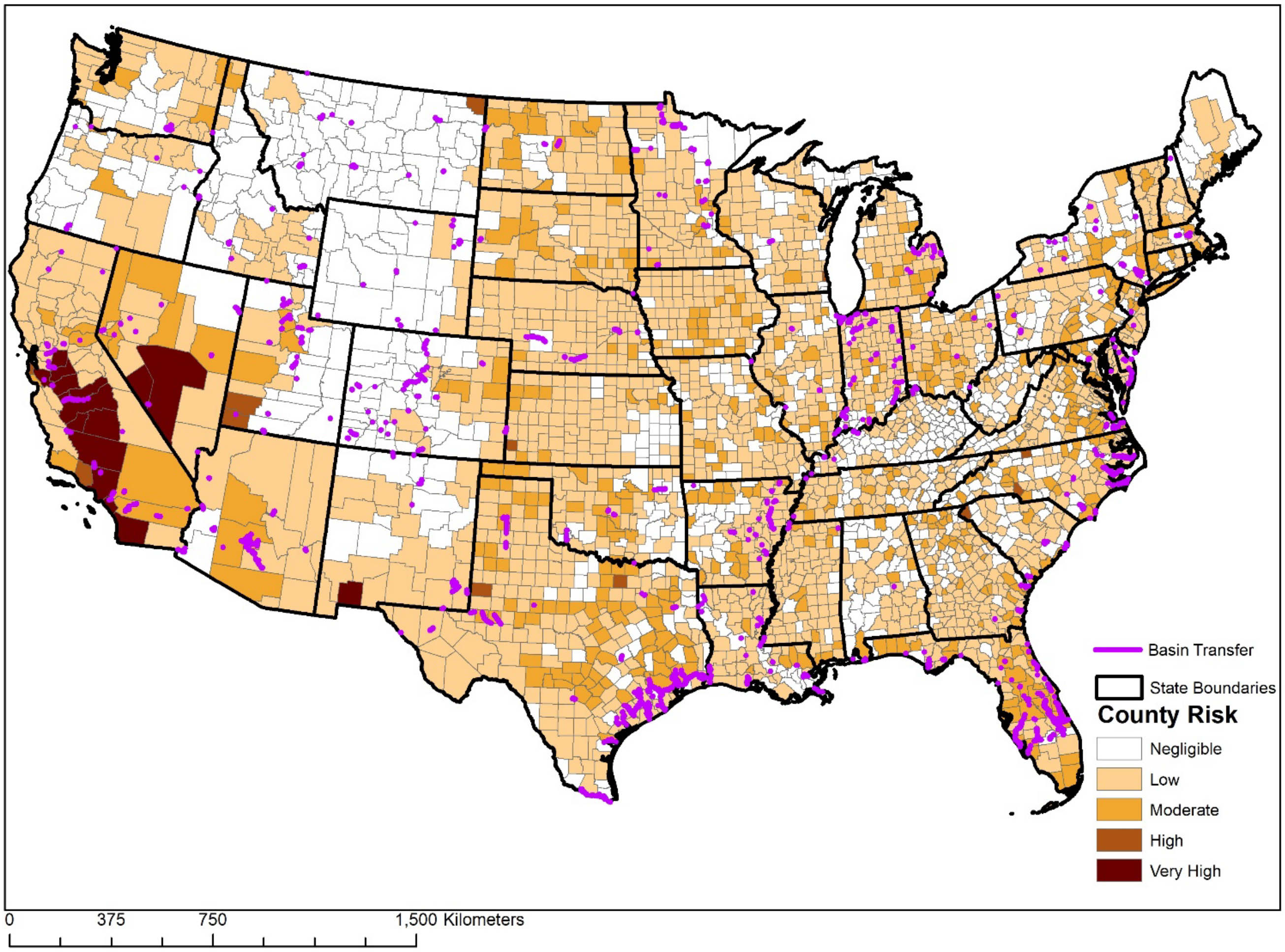

Figure 4-4 Water Risk Index by County under the Medium Scenario and Interbasin Transfers in the U.S.

Figure 4-4 shows that many IBTs occur in proximity to counties with moderate or higher risk. In Colorado most of the identified IBTs are located in counties with negligible risk, however, these IBTs are transferring water from the west side of the continental divide to the east side, towards regions with some water supply risk identified. The IBTs moving water to New York City are also located near counties with a mixture of water risks, although the withdrawals are occurring in counties with negligible risk. In California and Arizona many IBTs access the Colorado River, moving the water away from the lower risk counties to Phoenix and Los Angeles. However, California also moves large volumes of water from the north of the state to the south, even though nearby counties to that transfer are also shown as having moderate to very high risk to the water supply.

4.5 Summary and Conclusions

The overall objective of this work was to quantify the water supply risks in the United States by county considering both current (2015) and future (2050) conditions and accounting for natural water importation through streams and rivers.

Three risk scenarios (high, medium, low) of water demand vs. supply were developed to examine the water risk in the U.S. Each scenario was based on projected growth patterns for population and associated water demand, for thermoelectric power water demand, and a greenhouse emissions scenario determined by the IPCC. For the medium scenario, a medium rate of population growth was used, a 25% reduction in thermoelectric power water withdrawals, and a mid-range projection for emissions.

A revised water risk index building upon that of Roy et al (2012) was developed using the monthly water balance model WaSSI of the U.S. Forest Service. A water supply risk map was produced for the U.S. at the county level. Several counties that had been identified as high risk by the Roy et al. approach have low or negligible risk under the revised analysis due to natural importation of water through streams and rivers. Examples include Allegheny County in Pennsylvania, where two major rivers converge to form the Ohio River, and counties bordering the Mississippi River in Arkansas, Mississippi, Missouri and Tennessee.

Through analysis of current water supply conditions and three water risk scenarios for 2050 a maximum of 36 counties were identified as having high or very high risk. In contrast Roy et al. identified in excess of 400 counties as having extreme risk. A majority of counties in the present analysis were shown to have minimal risk, with almost 90% of them classified as low or negligible risk for all scenarios.

While the WaSSI model framework employed in the present analysis did not permit explicit consideration of the connection between IBTs and water supply risk, the results can aid in the selection of specific IBTs for further examination into the impacts of transfers on water supply risk for particular counties and watersheds, especially those IBTs moving water to or from areas of moderate or high risk. Additionally this risk assessment shows counties that have low or negligible risk to their water supplies and may be able to be considered as potential water donors via future IBTs to aid counties with elevated risk profiles.

Future work could be conducted to examine the correlation between the existence of IBTs and water supply risk, especially in areas where there are concerns about the sustainability of the existing supply. The groundwater supply risk factor used in the present analysis, based on current groundwater withdrawal, has limitations; withdrawals of even large quantities of water may not constitute a risk within some aquifers. A refinement of this analysis could include a weighted risk for risk factor 5, dependent on the use and recharge of the groundwater aquifer which may span many counties, as well as the risks of contamination of the groundwater supply through saltwater intrusion or other toxic substances.

4.6 Acknowledgements

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Chapter 5 : Summary, Conclusions, and Recommendations for Future Work

5.1 Summary and Conclusions

This research had three individual objectives to meet the overall goal of examining water resources in the U.S.

1. Quantify the number of IBTs that exist at a defined hydrologic unit code (HUC) level in the U.S. and examine the distribution of IBTs and potential causes associated with any observed clustering of IBTs.
2. Characterize and classify IBTs, and examine the development drivers for a subset of IBTs in the U.S through sampling in different climate regions of the U.S.
3. Examine the water risks in the U.S. by county, considering both current and future conditions and accounting for natural water importation through streams and rivers, and consider the potential role of IBTs in mitigating these risks.

Chapter 2 presents a new inventory of IBTs in the U.S. conducted with use of the National Hydrography Dataset (USGS, 2016) and with geographic information system (GIS) analysis. The GIS analysis performed in Chapter 2 identified 2,161 IBTs at the USGS HUC6 watershed level. This value was greatly in excess of the number of IBTs identified in 1985-1986 by the USGS (Petsch, 1985; Mooty and Jeffcoat, 1986), utilizing a survey methodology, at the HUC4 level. IBTs were found to be located in most U.S. states with 8 out of 50 containing none. The majority of IBTs were found to be located in Florida, Texas, North Carolina, Indiana and California. In Florida and North Carolina the vast majority of IBTs were discovered to be small canals and ditches whereas California had a significant proportion of the identified IBTs defined as large canals or aqueducts, or pipelines. The analyses do not provide information regarding flow volumes within each IBT as such data are not currently available in any compiled form.

Factors that have driven the development of IBTs in the U.S. are examined in Chapter 3. Analysis of a subset of 109 of the 2,161 IBTs showed that most IBTs have been constructed near irrigated agricultural land, particularly in the South and Southeast climate regions defined by NOAA. In the West climate region the proximity of agriculture and population was reflected by the majority of IBTs being located within a 100km radius of both irrigated agricultural land and a population center of more than 200,000 people. Evaluation of the subset of 109 of the IBTs identified in Chapter 2 showed that there have been four major drivers for IBT construction in the U.S.; agriculture, municipal and industrial water supply, drainage or flood management, and commercial shipping or navigation. The IBTs sampled were mostly constructed between 1880 and 1980 with the earliest IBT construction tending to be for shipping or navigation purposes. The main driver for IBT construction from 1880 to 1940 was agriculture, but since 1990 the IBTs have at least partially been driven by municipal and industrial water supply demand. While the earliest U.S. IBTs were predominantly constructed in the Southeast and Central climate regions, as time progressed IBTs were built across the country. Very few IBTs have been constructed since 1980.

Chapter 4 presents a revised water risk index developed based upon previous work by Roy et al. (2012) using the monthly water balance model WaSSI developed by the U.S.

Forest Service. Three scenarios for water supply and demand in 2050 were examined as part of this analysis, and a maximum of 36 counties were identified as being at high risk or more, in contrast with over 400 identified by the prior Roy et al. analysis. The reduction of risk identified in this analysis is due to inclusion of natural importation within the risk factors, whereas the Roy et al. (2012) analysis utilized local precipitation. This resulted in significant changes in the risk map produced. Previously many counties in close proximity to major US rivers such as the Mississippi had been defined as high or extreme risk and this work identified those counties as mostly at low risk. While the WaSSI model framework employed in this analysis did not allow explicit consideration of the connection between IBTs and water supply risks, these results can be utilized to select IBTs for examination of their impacts. In particular a focus on those transferring water to or from counties and watersheds with moderate to high risks is feasible. Additionally the analysis indicates counties that have low or negligible water supply risks and therefore could be considered as potential water donors via IBTs to aid those counties that were identified as having elevated risk profiles.

5.2 Research Contributions and Implications

This research has provided several original contributions to the field of environmental engineering and its scientific base. The contributions include:

1. Development of a new methodology utilizing the USGS National Hydrography Dataset and Watershed Boundary Dataset with Geographic Information System (GIS) techniques to identify the locations of IBTs at any basin level. Application of

this methodology produced the first inventory of IBTs conducted in the U.S. for over 30 years.

2. Determination of the main drivers of IBT construction and the temporal distribution of their implementation. The distribution of drivers by climate region were also determined as part of this examination.
3. Development of a revised water supply risk index that accounted for natural flows between watersheds to show the total risk for each county in the contiguous U.S. for several growth scenarios.

The research has provided information regarding where, how, and since when water has been moved for a variety of human purposes. The results can be applied to determining areas where pressure from several factors may influence the construction of new transfers, in particular population and economic growth most recently. Additionally the research has shown how water supplies may fare in the U.S. over the next 35 years considering population growth, trends of population movement, and projected growth in water demand from thermoelectric power generation. Utilized in conjunction with each other, the components of the research provide a new avenue to enhance projections of water supply and aid in ensuring supply risks are addressed before any shortfall becomes critical in nature.

5.3 Recommendations for Future Work

This body of work advances the knowledge relating to IBTs in the U.S. and the potential water risks posed through current and future water demand and supply, and there are many avenues of investigation to build upon these studies. Advancements could include the addition of flow characteristics for each identified IBT, seasonality of IBT use, and analysis of IBT occurrence at higher resolutions of basins, such as HUC12. The addition of flow data in particular to each IBT would also allow enhancement of the water risk analysis. At present, however, no compilations of IBT volumetric flow data exist, either at the state or federal level. Knowledge of flows in IBTs would enable an improved water balance model to judge the decreased risks associated with the recipient basin and the areas downstream, as well as the potential higher risks for the donor basin and the downstream implications of reduced flow.

The inventory of IBTs included as part of this work did not include data regarding the volumes of water transferred. This was due to a lack of available data concerning most of the transfers. This data would be essential in examining the impact of each IBT and producing a hierarchy of importance, that could include factors such as the percentage of flow diverted from the source point, and seasonal effects, such as reduced flows in summer coinciding with a potentially higher demand for water resources. Furthermore, quantifying the volumes transferred by each identified IBT would provide more data to aid in sampling of IBTs, to isolate those of greatest impact on water resources, and reveal information regarding the potentially different drivers behind IBTs that transfer small quantities, potentially intermittent or ephemeral in nature, and perennial IBTs that transfer large volumes of water.

Knowledge of flows in IBTs would enable enhancement of the WaSSI water balance model (Sun, 2008) utilized in Chapter 4, and of the new water risk index. Accounting for the potentially large transfers of water across basins would provide a clearer picture of the areas of greatest water risk in the U.S. by examining the sustainability of the donor basin and the downstream impacts it could have on both the environment and populations. Of particular importance for such work would be to focus on the potential for existing IBTs to be drawing from sources that will be unsustainable and the solutions that could be explored to resolve these situations, including conservation and unconventional water sources such as desalination and wastewater reuse.

The types of analyses conducted in Chapter 4 could also be improved with closer examination of the risks posed by excessive utilization of groundwater. A general scale of risk for the nation was developed for this risk factor based on the percentage of groundwater use compared to the total demand. However, this characterization could be significantly improved. In some areas the threshold percentage for groundwater withdrawals to constitute a risk would need to be reduced, as non-renewable fossil basins and the potential for contamination through salt water intrusion would impact the sustainability of continued extraction. Further, in some regions there are large groundwater basins that are recharged in excess of extraction, meaning that the threshold percentage for groundwater withdrawals to constitute a risk could safely be raised.

Another opportunity for further work could be to expand the analysis to examine a greater number of scenarios, including projections of water demand in sectors such as irrigation, and in connection to that also project changes in groundwater demand over time. These scenarios could include a reduced irrigation demand, due to projected improvements in water conservation and irrigation techniques to reduce loss of applied water, or the effect of increased groundwater use due to uncertainties surrounding surface water supply.

Additionally scenarios that include rising demand in a sector, such as public and domestic supply, but decreases in another, such as thermoelectric power water demand, could be examined to account for variability in future demands as part of the risk analysis and provide a more comprehensive picture of potential risks to counties given specific circumstances.

A further examination that could be conducted based on the work in Chapter 4 could be the aggregation of local groups of counties for the water risk analysis methodology. This would provide insights into regional risk that may include, for example, the suburbs of cities built on rivers. A potential aggregation that could provide valuable insights into risks concerning cities would be to combine counties that are part of a metropolitan region as defined by the Census Bureau. This may result in increased or decreased risk values dependent on the supply and demand for both cities and their suburbs.

While the work in Chapter 4 provides a general indication of risk, focused risk assessment at state and local levels is also needed. Examination of the specific sources of the local risk identified by the analysis conducted would provide valuable insight into potential solutions and mitigating factors that may not be apparent from a national scale analysis.

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APPENDIX A Supporting Information for Chapter 3: Case Studies Selected from Each Climate Region and their Information Sources

This appendix provides the supporting tables for the IBTs examined as part of Chapter 3. The tables include the unique reach code associated with the IBT to identify it within the National Hydrography Dataset. Sources are provided for the relevant construction dates and the initial drivers.

Table A-1 – Case Studies Conducted in the U.S. Northwest Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Northwest (Oregon/Idaho border)	Irrigated Agriculture	Owyhee Canal	Agriculture[1]	1928-1939[1]	17050115000540	0.923	Canal
Northwest (Oregon)	Multiclass	Unnamed	Drainage/Flood Management[2]	1927[3]	17080003038587	0.499	Pipeline
Northwest (Oregon)	Rural	Deadwood Tunnel	Agriculture[4]	1956-1958[4]	18010206004490	1.074	Pipeline

Table A-2 – Case Studies Conducted in the U.S. West North Central Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
West North Central (Nebraska)	Irrigated Agriculture	Tri County Supply Canal	Agriculture[5]	1936-1940[5]	10200101018356	15.323	Artificial Path
West North Central (Nebraska)	Irrigated Agriculture	Adams County Canal	Agriculture[6]	1935-1938[6]	10270206002607	9.072	Canal
West North Central (Nebraska)	City	Unnamed	Drainage/Flood Management[7]	1928[7]	10200202001264	3.729	Canal
West North Central (North Dakota)	Rural	McClusky Canal	Agriculture[8]	1968-present[9]	10200202001264	21.427	Artificial Path
West North Central (Montana)	Rural	Greenfields Main Canal	Agriculture[10]	1913-1920[10]	10030104009680	0.714	Artificial Path

Table A-3 – Case Studies Conducted in the U.S. East North Central Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
East North Central (Wisconsin)	Irrigated Agriculture	Hunters Peak Ditch	Agriculture[11]	1880s[11]	07040007011260	1.48	Canal
East North Central (Minnesota)	Multiclass	County Ditch 31	Drainage/Flood Management[12]	1898[12]	07010206013010	0.567	Canal
East North Central (Minnesota)	Rural	Ditch Number Thirty	Drainage/Flood Management[13]	1900s[13]	09020302000251	4.775	Canal
East North Central (Michigan)	Rural	Hewitt Drain	Drainage/Flood Management[14]	1894[14]	04090001000371	1.674	Canal

Table A-4 – Case Studies Conducted in the U.S. Northeast Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Northeast (Delaware)	Irrigated Agriculture	Lewes and Rehoboth Canal	Commercial Shipping / Navigation[15]	1913-1916[15]	02040207002692	1.564	Artificial Path
Northeast (Pennsylvania)	Rural	Erie Extension Canal	Commercial Shipping / Navigation[16]	1831-1844[16]	05010004007274	1.998	Canal
Northeast (New York)	City	Catskill Aqueduct	Municipal and Industrial[17]	1907-1916[17]	02020008001001	37.398	Pipeline
Northeast (New York)	City	Delaware Aqueduct	Municipal and Industrial[18]	1939-1945[18]	02020008009074	28.43	Pipeline

Table A-5 – Case Studies Conducted in the U.S. West Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
West (California)	Irrigated Agriculture	All American Canal	Agriculture[19]	1934-1942[19]	15030107000618	2.497	Artificial Path
West (California)	Irrigated Agriculture	Governor Edmund G Brown Coastal Branch California Aqueduct	Municipal/Industrial supply and Irrigation[20]	1994-199720[20]	18030012030902	20.78	Pipeline
West (California)	City	San Diego Aqueduct	Municipal and Industrial[21]	1945-1947[21]	18070302002240	11.97	Pipeline
West (Nevada)	Rural	Johnson Springs Transmission System	Municipal and Industrial[22]	Early 1940s[22]	16020308007085	25.581	Pipeline
West (California)	Multiclass	Governor Edmund G Brown West Branch California Aqueduct	Municipal/Industrial supply and Irrigation[23]	1963-1973[23]	18090206010890	4.474	Artificial Path
West (California)	Multiclass	Governor Edmund G Brown East Branch California Aqueduct	Municipal/Industrial supply and Irrigation[23]	1963-1973[23]	18070203006404	5.844	Pipeline
West (California)	Multiclass	Governor Edmund G Brown California Aqueduct	Municipal/Industrial supply and Irrigation[23]	1963-1968[23]	18030003002009 and 18040014004684	6.166 and 0.147	Pipeline
West (California)	Multiclass	Hetch Hetchy Aqueduct	Municipal and Industrial[24]	1914-1934[24]	18040003013145	25.558	Pipeline
West (California)	Multiclass	Herndon Canal	Agriculture[25]	1887-1894[25]	18040001105656	2.363	Canal

Table A-6 – Case Studies Conducted in the U.S. Southwest Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code(s)	Length (km)	Transfer Type
Southwest (Colorado)	Irrigated Agriculture	Laramie Poudre Tunnel	Agriculture[26]	1909-1911[26]	10190007025765	2.876	Pipeline
Southwest (New Mexico)	Irrigated Agriculture	Azotea Tunnel	Municipal/Industrial supply and Irrigation[27]	1964-1970[27]	13020102002698	15.549	Pipeline
Southwest (Utah)	Irrigated Agriculture	Duchesne Tunnel	Municipal/Industrial supply and Irrigation[28]	1948-1954[28]	14060003015374	9.613	Pipeline
Southwest (Utah)	Irrigated Agriculture	Utah Metal Company Tunnel	Municipal and Industrial[29]	1909-1913[29]	16020304001365	3.539	Pipeline
Southwest (Arizona)	City	Grand Canal	Agriculture[30]	1878[30]	15060106005058	21.462	Artificial Path
Southwest (Arizona)	City	Central Arizona Project	Municipal/Industrial supply and Irrigation[31]	1973-1993[31]	15060106005234 15060106001140 15050100023655	5.344 1.49 2.44	Artificial Path
Southwest (Colorado)	Rural	Charles H Boustead Tunnel	Municipal/Industrial supply and Irrigation[32]	1965-1971[32]	14010004016733	8.617	Pipeline
Southwest (New Mexico)	Rural	La Sierra Ditch	Municipal/Industrial supply and Irrigation[33]	Early 1700's[33]	13020101010443	8.806	Canal
Southwest (Arizona)	Rural	Central Arizona Project	Municipal/Industrial supply and Irrigation[31]	1973-1993[31]	15030104012944 15030204002303 15030105001266	11.839 3.655 10.588	Pipeline Artificial Path

Table A-7 – Case Studies Conducted in the U.S. South Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
South (Arkansas)	Irrigated Agriculture	Arkansas Post Canal	Commercial Shipping / Navigation[34]	1963-1971[34]	08020303009934	0.554	Artificial Path
South (Louisiana)	Irrigated Agriculture	Victoria Barge Canal	Commercial Shipping / Navigation[35]	1951-1965[35]	12100204007489	3.39	Artificial Path
South (Louisiana)	Irrigated Agriculture	Starks North Canal	Hunting/Trapping[36]	1900-1917[36]	08080206018760	0.046	Artificial Path
South (Louisiana)	Irrigated Agriculture	Starks Central Canal	Hunting/Trapping[36]	1900-1917[36]	08080206018824	1.37	Artificial Path
South (Louisiana)	Irrigated Agriculture	Burton Sutton Canal	Hunting/Trapping[36]	1900-1917[36]	12040201012947	1.56	Artificial Path
South (Texas)	Irrigated Agriculture	McAllen Main Canal	Agriculture[37]	1902[37]	13090002019210	0.526	Canal
South (Louisiana)	Irrigated Agriculture	Sixmile Canal	Commercial Shipping / Navigation[38]	1918[38]	08080202051079	1.518	Artificial Path
South (Texas)	Irrigated Agriculture	Santa Maria Main Canal	Agriculture[37]	1904-1905[37]	12110208011436	0.842	Artificial Path
South (Texas)	Irrigated Agriculture	Mission Main Canal	Agriculture[37]	1907[37]	12110208006798	5.999	Artificial Path
South (Texas)	Irrigated Agriculture	Leher Canal	Agriculture[39]	1901[40]	12090302005326	1.427	Artificial Path
South (Texas)	Irrigated Agriculture	La Gloria Main Canal	Agriculture[37]	1900-1910[37]	13090002019355	3.092	Canal
South (Louisiana)	Irrigated Agriculture	Bull Hole Canal	Drainage/Flood Management[41]	1955-1960[41]	08080202043213	1.179	Artificial Path
South (Texas)	Irrigated Agriculture	Adams Gardens Main Canal	Agriculture[42]	1930s[42]	12110208011625	5.269	Canal
South (Texas)	Irrigated Agriculture	Markham Canal	Agriculture[43]	1897[43]	12090302004889	1.641	Artificial Path
South (Texas)	Irrigated Agriculture and Multiclass	Canadian River Project	Municipal and Industrial[44]	1963-1966[44]	11120103001849 and 12050005004359	60.731 17.737	Pipeline
South (Louisiana)	City	Port Allen Canal	Commercial Shipping / Navigation[45]	1955-1959[45]	08070300004758	1.949	Artificial Path

Table A-7 – Case Studies Conducted in the U.S. South Climate Region (cont.)

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
South (Texas)	City	HL and P Canal	Municipal and Industrial[46]	1970-1972[46]	12040203000227	3.471	Artificial Path
South (Texas)	City	Lynchburg Canal	Municipal and Industrial[47]	1970-1973[47]	12040203002467	4.153	Artificial Path
South (Louisiana)	City	Cazezu Canal	Commercial Shipping / Navigation[38]	1925[38]	08090203057419	0.833	Artificial Path
South (Oklahoma)	City	Bluff Creek Canal	Municipal and Industrial[48]	1941-1944[48]	11100301006574	6.136	Canal
South (Oklahoma)	City	Spavinaw Water Project	Municipal and Industrial[49]	1922-1924[49]	11070105000659	44.943	Pipeline
South (Mississippi)	Rural	Tenn-Tom Waterway	Commercial Shipping / Navigation[50]	1972-1984[50]	06030005015825	1.106	Artificial Path
South (Texas)	Rural	Lower Neches Valley Authority Canal	Agriculture[51]	1895[51]	12020007004164	2.955	Artificial Path
South (Texas)	Rural	Unnamed	Municipal and Industrial[52]	2017[52]	13070004002922	16.865	Pipeline
South (Texas)	Multiclass	System Canal (Canal B – GCWA)	Agriculture[53]	1940s[53]	12070104016349	4.382	Artificial Path
South (Texas)	Multiclass	Velasco Drainage Ditch	Drainage/Flood Management[54]	1970s[54]	12070104016351	0.324	Artificial Path
South (Texas)	Multiclass	Unnamed	Municipal/Industrial supply and Irrigation[55]	1930s[55]	12040205003117	5.987	Artificial Path
South (Louisiana)	Multiclass	Outflow Channel	Drainage/Flood Management[56]	1955-1962[56]	08040301011074	3.646	Artificial Path

Table A-8 – Case Studies Conducted in the U.S. Central Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Central (Ohio)	City	Ohio and Erie Canal	Commercial Shipping / Navigation[57]	1825-1832[57]	04110002006285	2.5	Artificial Path
Central (Ohio)	Rural	Miami and Erie Canal	Commercial Shipping / Navigation[58]	1825-1845[58]	04100004002129	1.784	Artificial Path
Central (Indiana)	Multiclass	Indiana Harbor Canal	Commercial Shipping / Navigation[59]	1901-1907[59] [60]	07120003003395	0.020	Artificial Path
Central (Tennessee)	Multiclass	Loosahatchie River Drainage Canal	Drainage/Flood Management[61]	1951-1960[61]	08010100006689	0.773	Artificial Path
Central (Kentucky)	Irrigated Agriculture	Barkley Canal	Commercial Shipping / Navigation[62]	1957-1966[63]	06040005007338	0.728	Artificial Path
Central (Indiana)	Irrigated Agriculture	Danner Ditch	Drainage/Flood Management[64]	1902[64]	05120106001861	0.174827	Canal
Central (Illinois)	Irrigated Agriculture	Hennepin Canal	Commercial Shipping / Navigation[65]	1892-1907[65]	07130001000460	4.973	Artificial Path
Central (Kentucky)	Irrigated Agriculture	Haynes Woods Ditch	Drainage/Flood Management[66]	1880s[66]	05110005000439	2.367	Canal

Table A-9 – Case Studies Conducted in the U.S. Southeast Climate Region

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Southeast (South Carolina)	Rural	Diversion Canal	Commercial Shipping / Navigation[67]	1939-1941[67]	03050201000803	5.931	Artificial Path
Southeast (Georgia)	Rural	Brunswick-Altahama Canal	Commercial Shipping / Navigation[68]	1836-1839[68]	03070203000859	6.281	Canal
Southeast (South Carolina)	Rural	Santee Canal	Commercial Shipping / Navigation[69]	1793-1800[69]	03050112009236	2.696	Canal
Southeast (North Carolina)	Rural	Pungo River Alligator River Canal	Commercial Shipping / Navigation[70]	1922-1935[70]	03020104011803	3.500	Artificial Path
Southeast (North Carolina)	Rural	Dunbar Canal	Commercial Shipping / Navigation[71]	1823[71]	03010205054457	0.906	Canal
Southeast (Alabama)	Rural	Portage Creek	Commercial Shipping / Navigation[72]	1930-1934[72]	03160205002710	8.472	Artificial Path
Southeast (South Carolina)	Rural	Mosquito Creek Canal	Commercial Shipping / Navigation[73]	1883-1885[73]	03040207008965	1.233	Artificial Path
Southeast (Georgia)	Rural	Dundee Canal	Drainage/Flood Management[74]	1893[74]	03060109000310	1.412	Artificial Path
Southeast (North Carolina)	Rural	B Canal	Drainage/Flood Management[75]	1917[75]	03020104013181	1.748	Canal
Southeast (North Carolina)	Rural	Harlowe Canal	Commercial Shipping / Navigation[76]	1795-1828[76]	03020204007619	2.531	Artificial Path
Southeast (Florida)	Multiclass	Disston Canal	Drainage/Flood Management[77]	1881[77]	03090101011377	1.861	Canal
Southeast (Florida)	Multiclass	E-15 Landfill Canal	Drainage/Flood Management[78]	1960s[78]	03090101042750	1.864	Canal
Southeast (Florida)	Multiclass	Unnamed	Drainage/Flood Management[79]	1967-1974[79]	03100201001403	2.241	Canal

Table A-9 – Case Studies Conducted in the U.S. Southeast Climate Region (cont.)

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Southeast (Virginia)	City	Hudnell Ditch	Drainage/Flood Management[80]	1950s[81]	03010205050831	6.133	Canal
Southeast (Virginia)	City	Portsmouth Ditch	Drainage/Flood Management[80]	1890s[81]	02080208007633	2.995	Canal
Southeast (Virginia)	City	Jericho Ditch	Drainage/Flood Management[80]	1810s[81]	03010205050824	1.861	Canal
Southeast (Virginia)	City	North Ditch	Drainage/Flood Management[80]	1950s[81]	02080208002031	1.919	Canal
Southeast (Alabama)	City	Bouldin Canal	Municipal and Industrial[82]	1963-1967[82]	03150107011612	1.805	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Indian Prairie Canal (C-40)	Drainage/Flood Management[83]	1922[83]	03090201002596	2.898	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Melbourne Tillman Canal (C1)	Drainage/Flood Management[84]	1920s[84]	03080101051382	2.852	Canal
Southeast (Florida)	Irrigated Agriculture	Fellsmere Main	Drainage/Flood Management[84]	1920s[84]	03080101052153	4.15	Artificial Path
Southeast (Florida)	Irrigated Agriculture	C-54	Drainage/Flood Management[84]	1969[84]	03080101052151	1.445	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Sottile	Drainage/Flood Management[84]	1920s[84]	03080203008163	2.092	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Harney Pond Canal (C41)	Drainage/Flood Management[85]	1960s[85]	03090201000490	3.380	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Butterford Waterway	Drainage/Flood Management[86]	1960s[86]	03100201000330	0.438	Artificial Path
Southeast (Florida)	Irrigated Agriculture	March Waterway	Drainage/Flood Management[86]	1960s[86]	03100102010843	1.052	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Sioux Waterway	Drainage/Flood Management[86]	1960s[86]	03100201003309	1.049	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Unnamed	Drainage/Flood Management[87]	1980s[87]	03120003002355	7.624	Canal

Table A-9 – Case Studies Conducted in the U.S. Southeast Climate Region (cont.)

Region (State)	IBT Class	Name	Initial Driver	Construction Dates	Reach Code	Length (km)	Transfer Type
Southeast (Florida)	Irrigated Agriculture	Belcher Canal (C-25)	Drainage/Flood Management[88]	1962-1964[88]	03080203017965 03080203019301 03080203032126	2.484 1.068 0.807	Artificial Path
Southeast (Florida)	Irrigated Agriculture	C-25 extension	Drainage/Flood Management[88]	1962-1964[88]	03080101052144	2.892	Artificial Path
Southeast (Florida)	Irrigated Agriculture	Rim Ditch	Drainage/Flood Management[88]	1962-1963[88]	03090206001870	2.498	Artificial Path

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APPENDIX B Supporting Information for Chapter 4: WaSSI Desktop Version Software File Settings

This appendix provides the variables utilized for each run of the WaSSI model software through the desktop version. The variables are input in the applicable text file that determines the inputs to the model.

Table B-1 List of Input Variables for the WaSSI Desktop Model General Input File, 2015

Variable Name	Variable Input
Region	US
Climate Scenario	US_01
Start Year for Average Annual Output	2015
End Year for Average Annual Output	2015
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	9000
Population Change Fraction	0.00
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.186480148
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-2 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Low Scenario, CGCM Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_08
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	-0.067308897
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.593240074
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-3 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Low Scenario, CM2 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_11
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	-0.067308897
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.593240074
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-4 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Low Scenario, HADCM3 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_14
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	-0.067308897
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.593240074
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-5 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Medium Scenario, CGCM Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_06
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.00
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.389860111
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-6 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Medium Scenario, CM2 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_09
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.00
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.389860111
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-7 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Medium Scenario, HADCM3 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_12
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.00
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.389860111
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-8 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 Medium Scenario, HADCM3 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_07
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.0373641947914058
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.122146781751571
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-9 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 High Scenario, CM2 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_10
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.0373641947914058
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.122146781751571
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

Table B-10 List of Input Variables for the WaSSI Desktop Model General Input File, 2050 High Scenario, HADCM3 Climate Model

Variable Name	Variable Input
Region	US
Climate Scenario	US_13
Start Year for Average Annual Output	2050
End Year for Average Annual Output	2050
Forest Land Cover Change Fraction	0.00
Forest Land Cover Converted to Other Use	1
Forest LAI Change Fraction	0.00
Precipitation Change Fraction	0.00
Temperature Change	0.00
Base Population Scenario	8000
Population Change Fraction	0.0373641947914058
Groundwater Supply Change Fraction	0.00
Domestic Sector Water Demand Change Fraction	-0.094986675
Industrial Sector Water Demand Change Fraction	-0.063884259
Irrigation Sector Water Demand Change Fraction	0.023413635
Livestock Sector Water Demand Change Fraction	0.000175766
Mining Sector Water Demand Change Fraction	-0.170244853
Thermopower Sector Water Demand Change Fraction	-0.122146781751571
Public Supply Sector Water Demand Change Fraction	-0.070850145
Aquaculture Sector Water Demand Change Fraction	-0.184088957

APPENDIX C Supporting Information for Chapter 4: Supply Change, Population and Risk Maps for the Low, Medium and High Scenarios

This appendix provides the projected change in water supply by county, projected population change by county and the water risk maps for the low, medium and high scenarios.

For each scenario, the first map is the projected change in annual surface water supply by county between 2015 and 2050. The second map is the projected change in population by county between 2015 and 2050. The third map provided is the overall water risk index determined for each county.

Low Scenario Maps

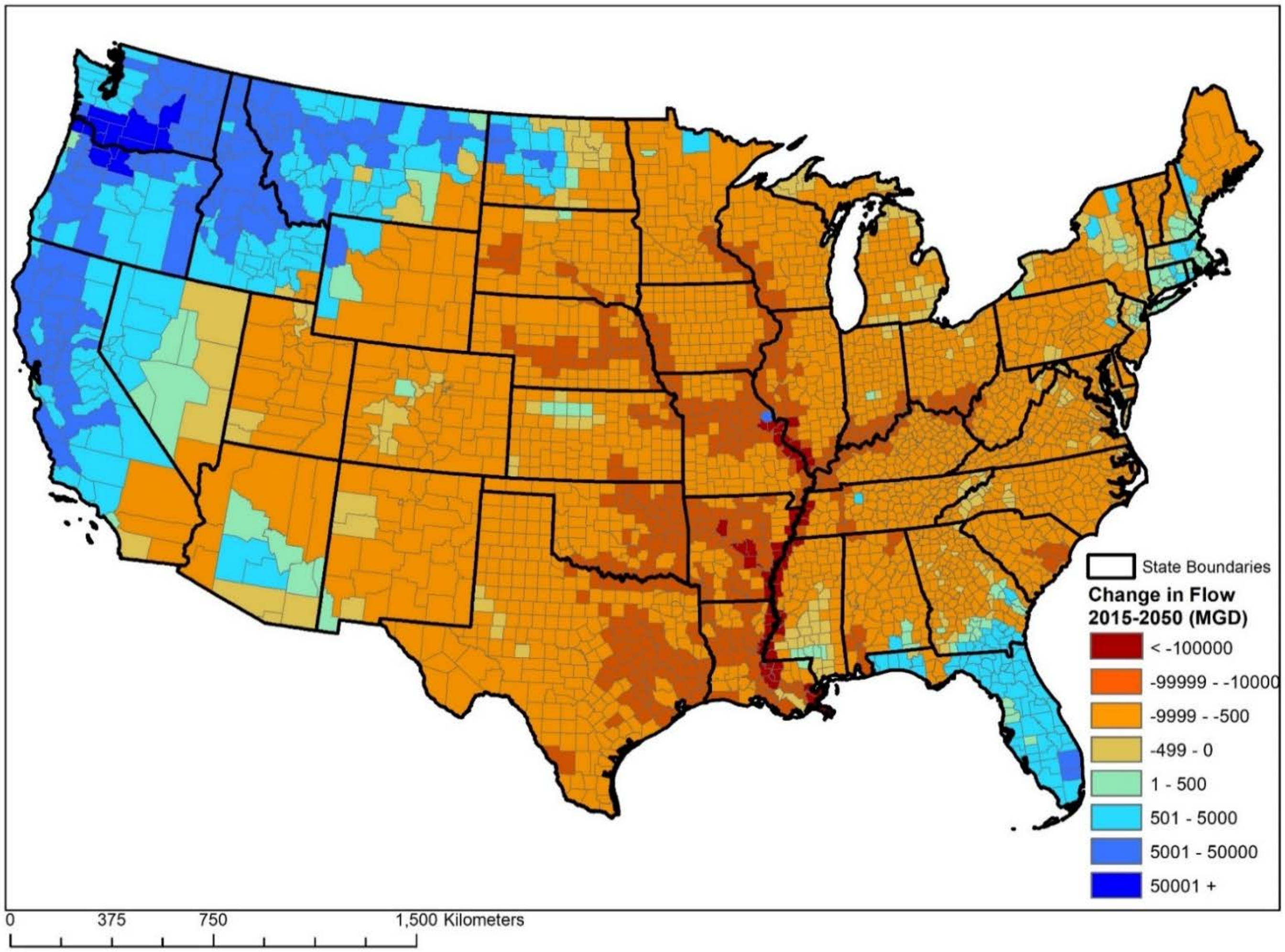

Figure C-1 Projected Change in Surface Water Flow in Millions of Gallons per Day by County for the Low Scenario between 2015 and 2050

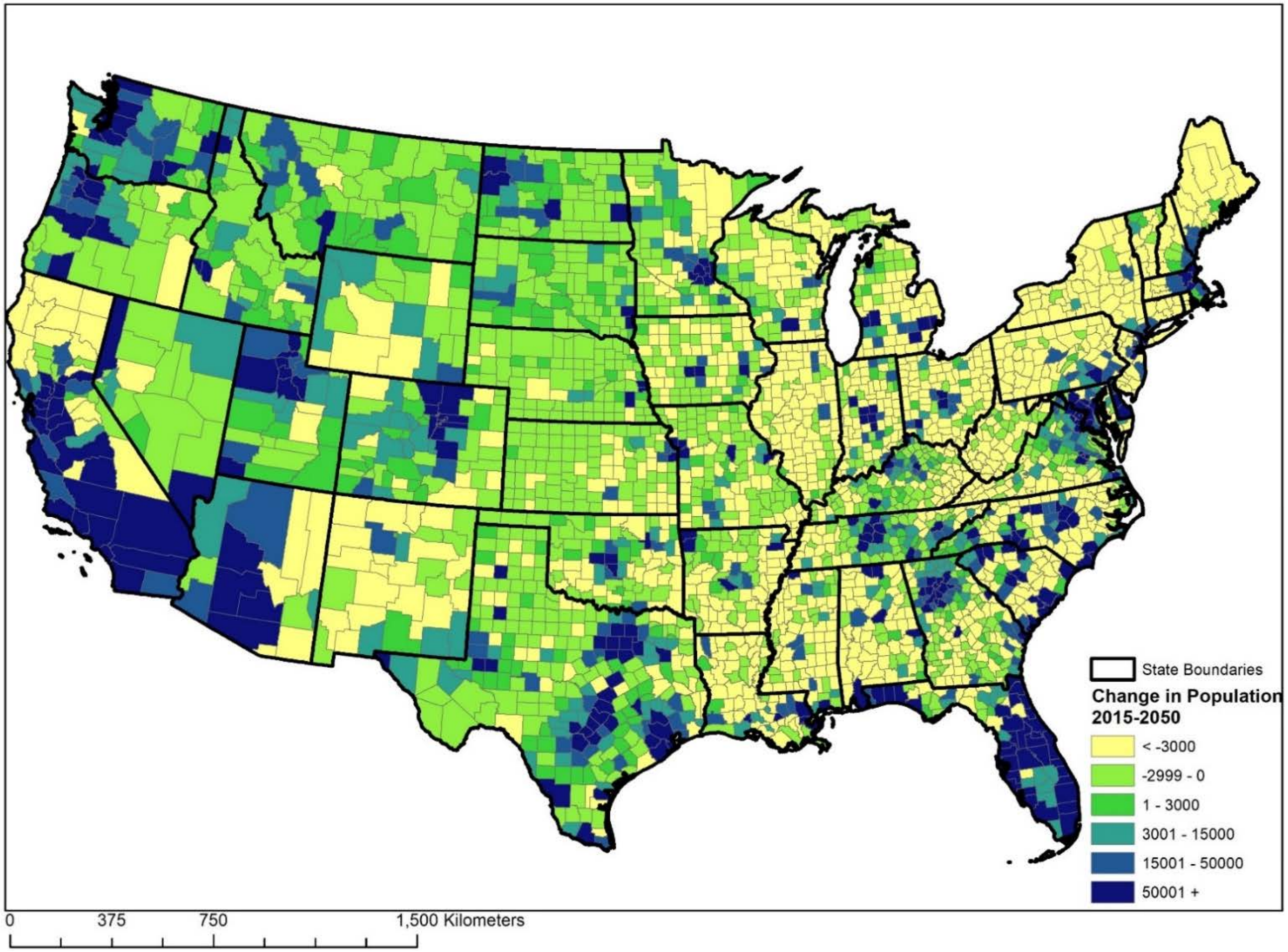

Figure C-2 Projected Change in Population by County for the Low Scenario between 2015 and 2050

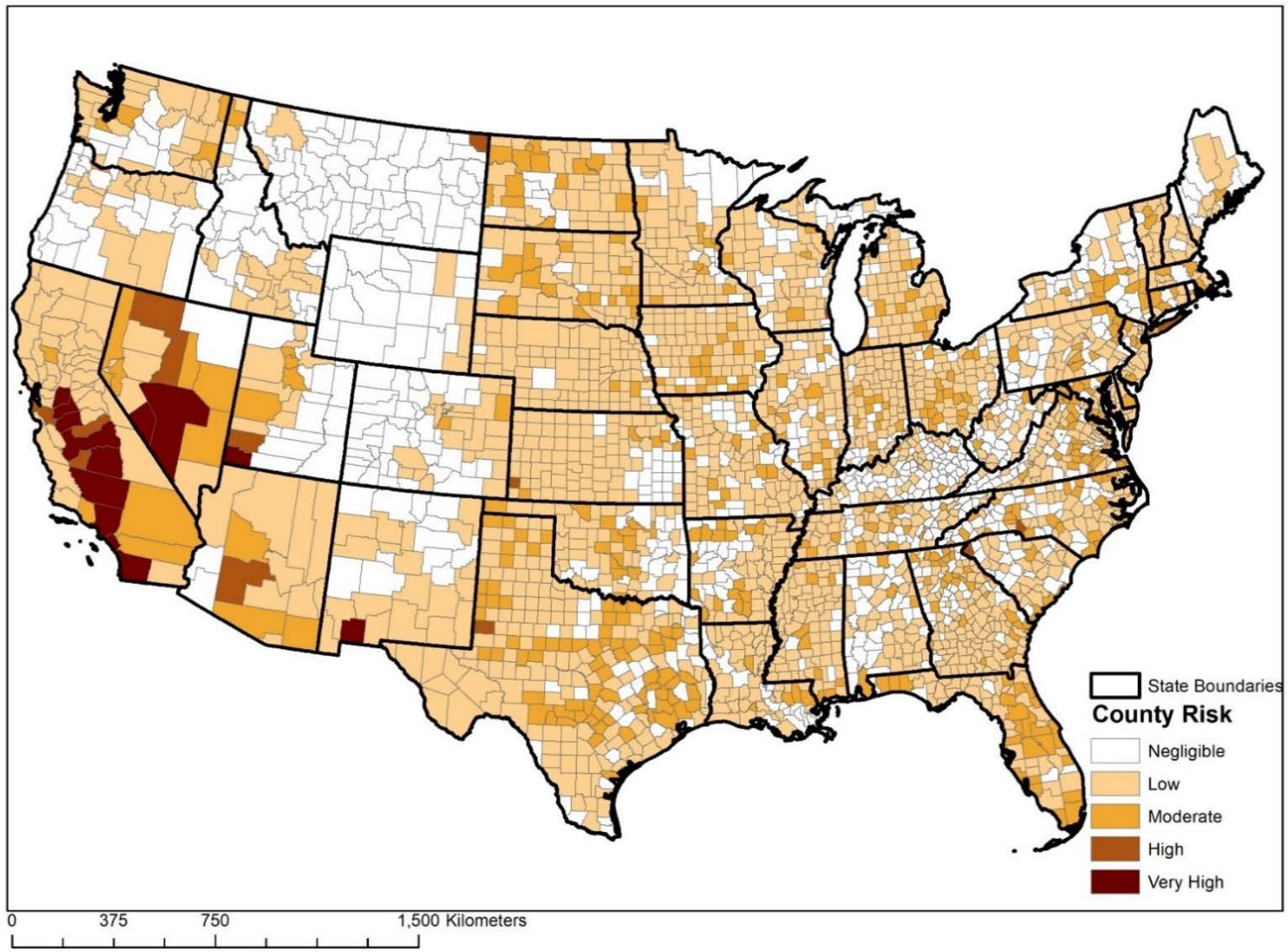

Figure C-3 Water Risk Index by County under the Low Scenario

Medium Scenario Maps

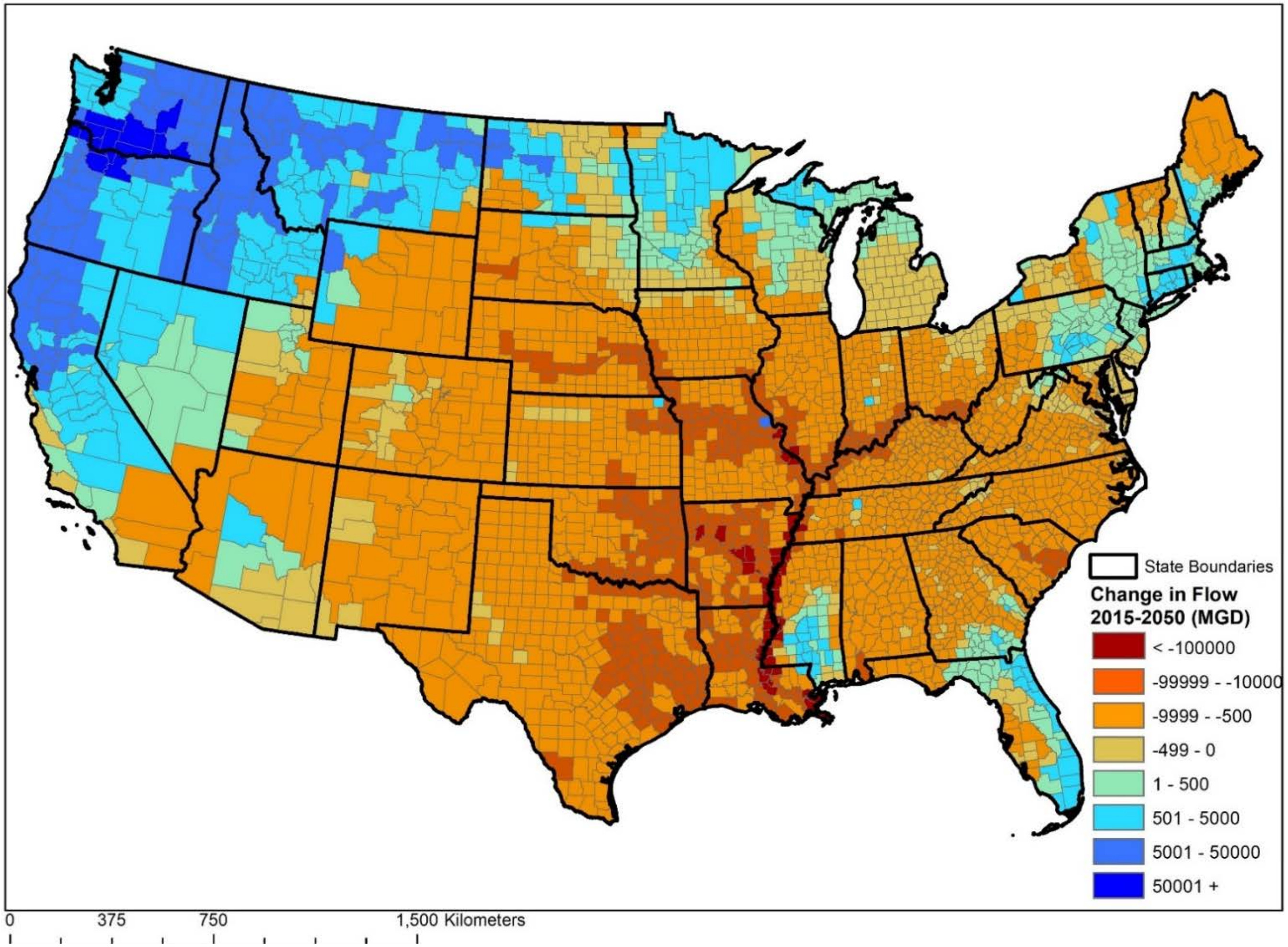

Figure C-4 Projected Change in Surface Water Flow in Millions of Gallons per Day by County for the Medium Scenario between 2015 and 2050

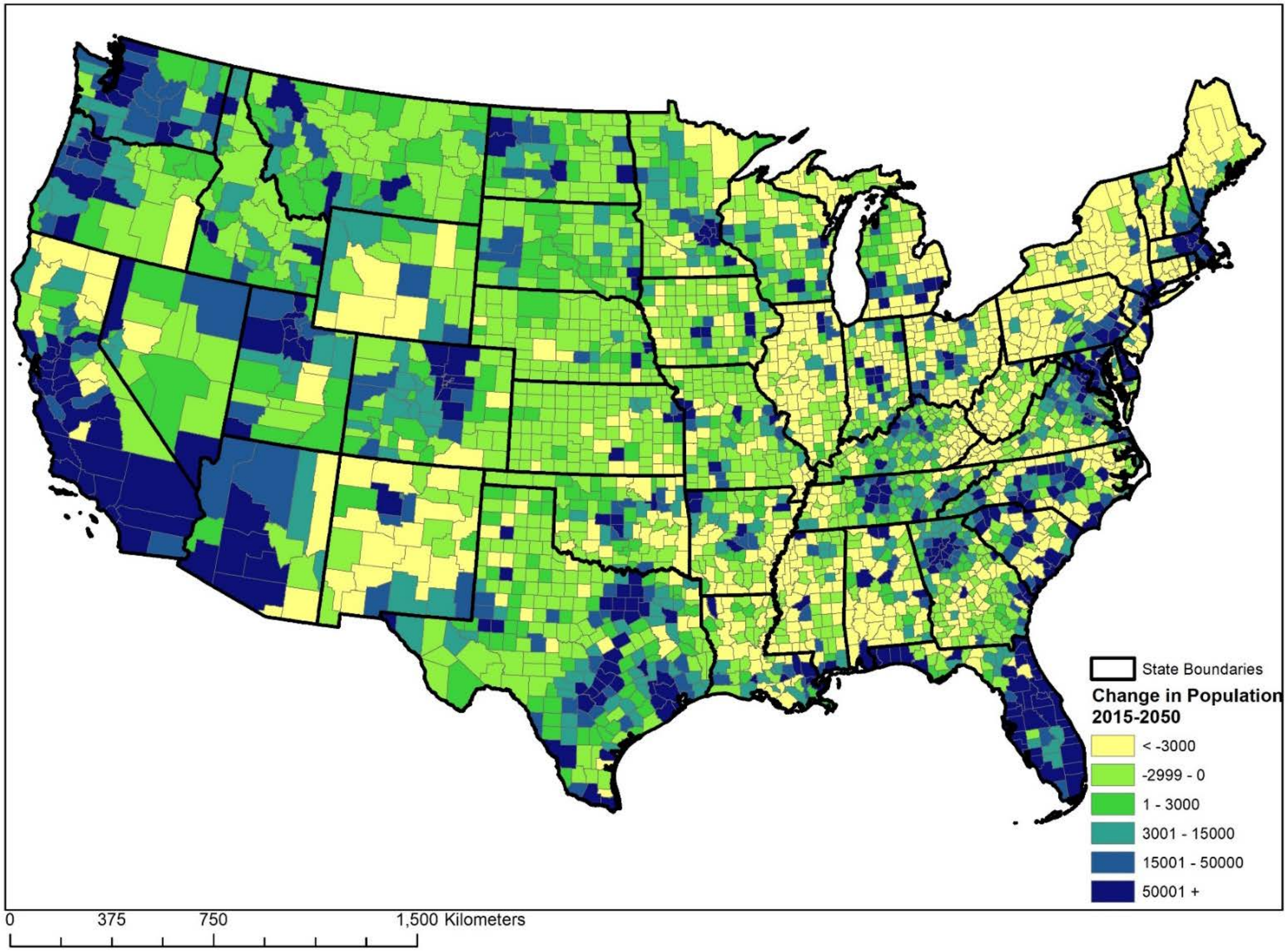

Figure C-5 Projected Change in Population by County for the Medium Scenario between 2015 and 2050

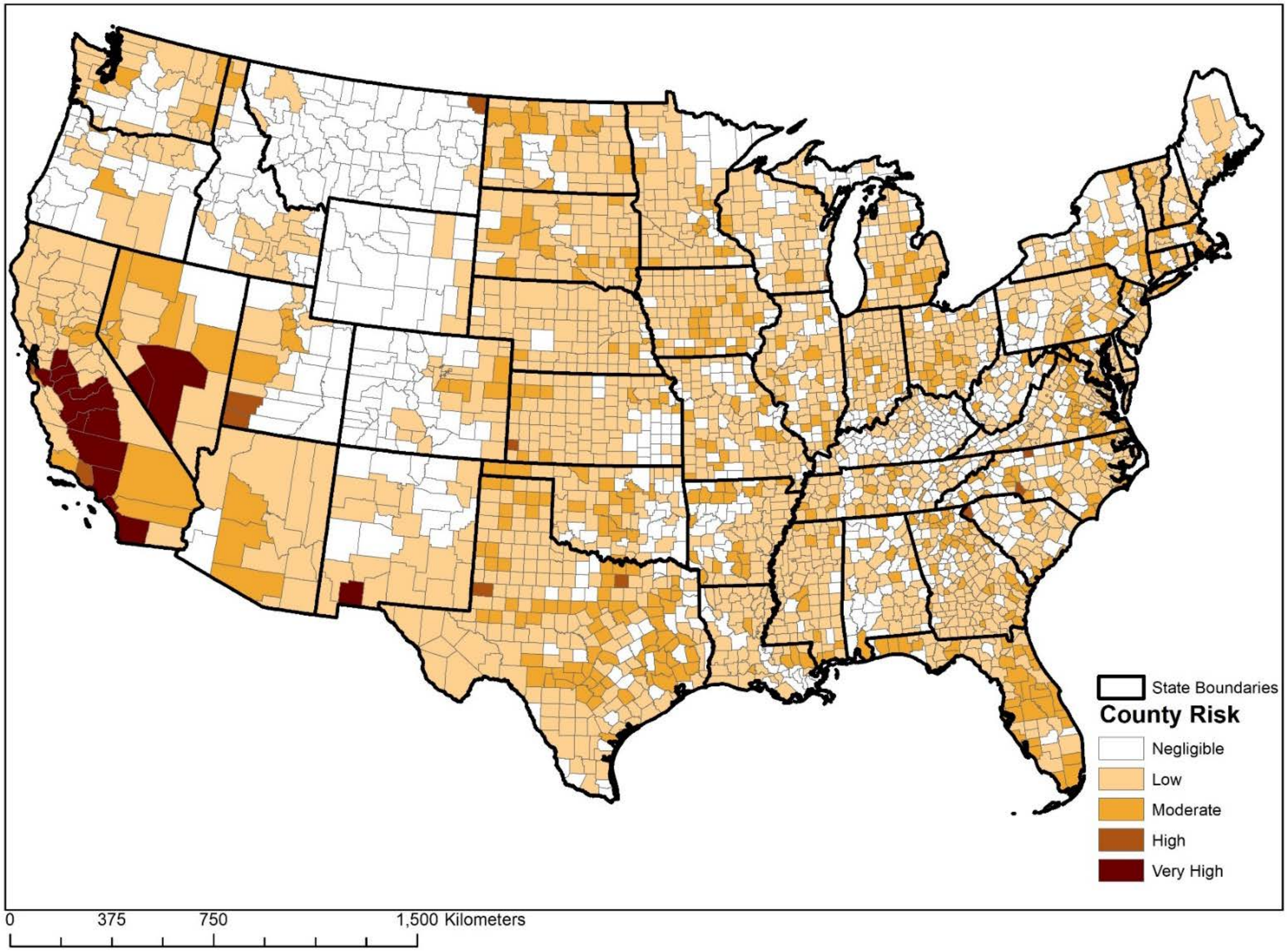

Figure C-6 Water Risk Index by County under the Medium Scenario

High Scenario Maps

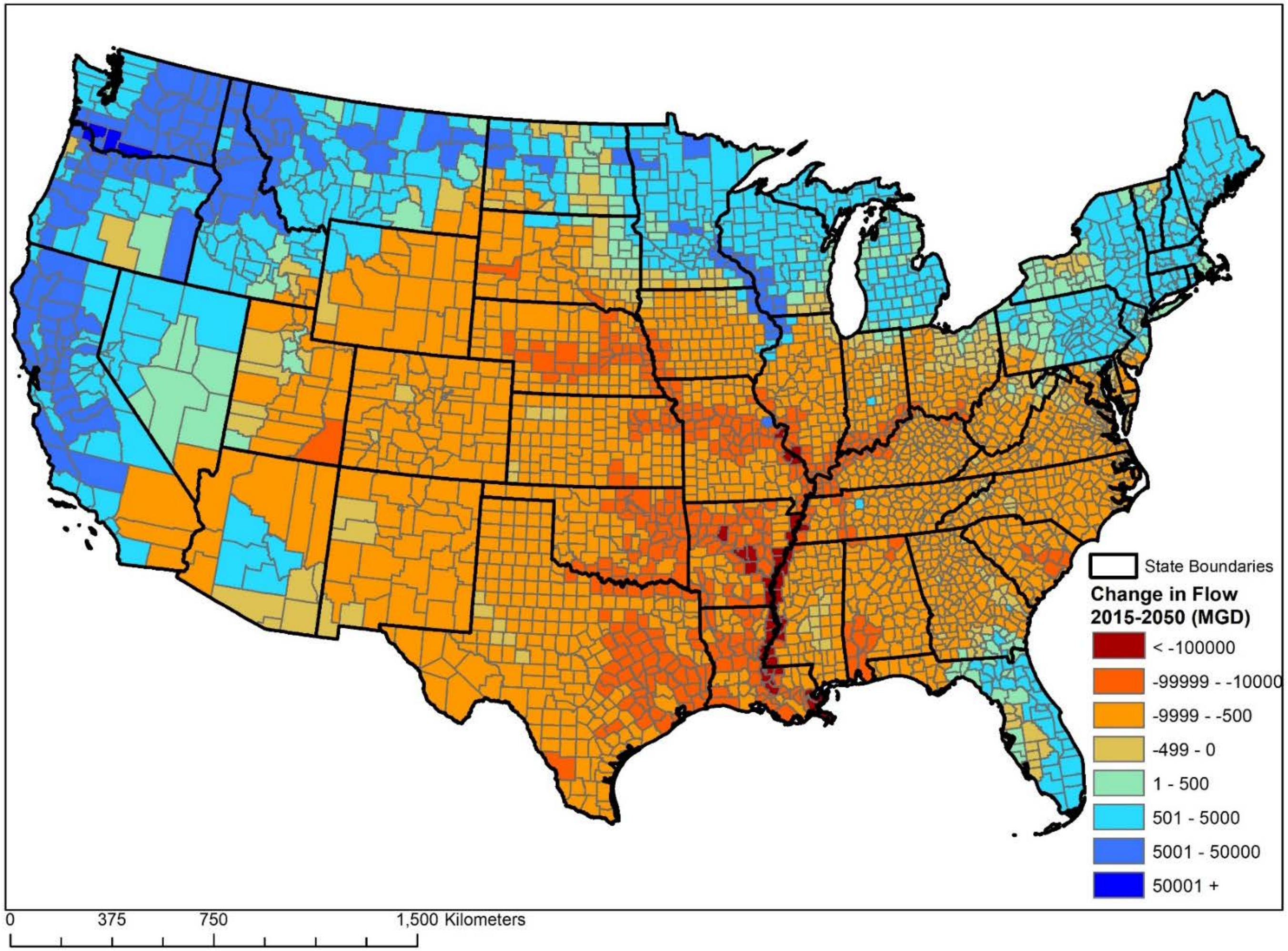

Figure C-7 Projected Change in Surface Water Flow in Millions of Gallons per Day by County for the High Scenario between 2015 and 2050

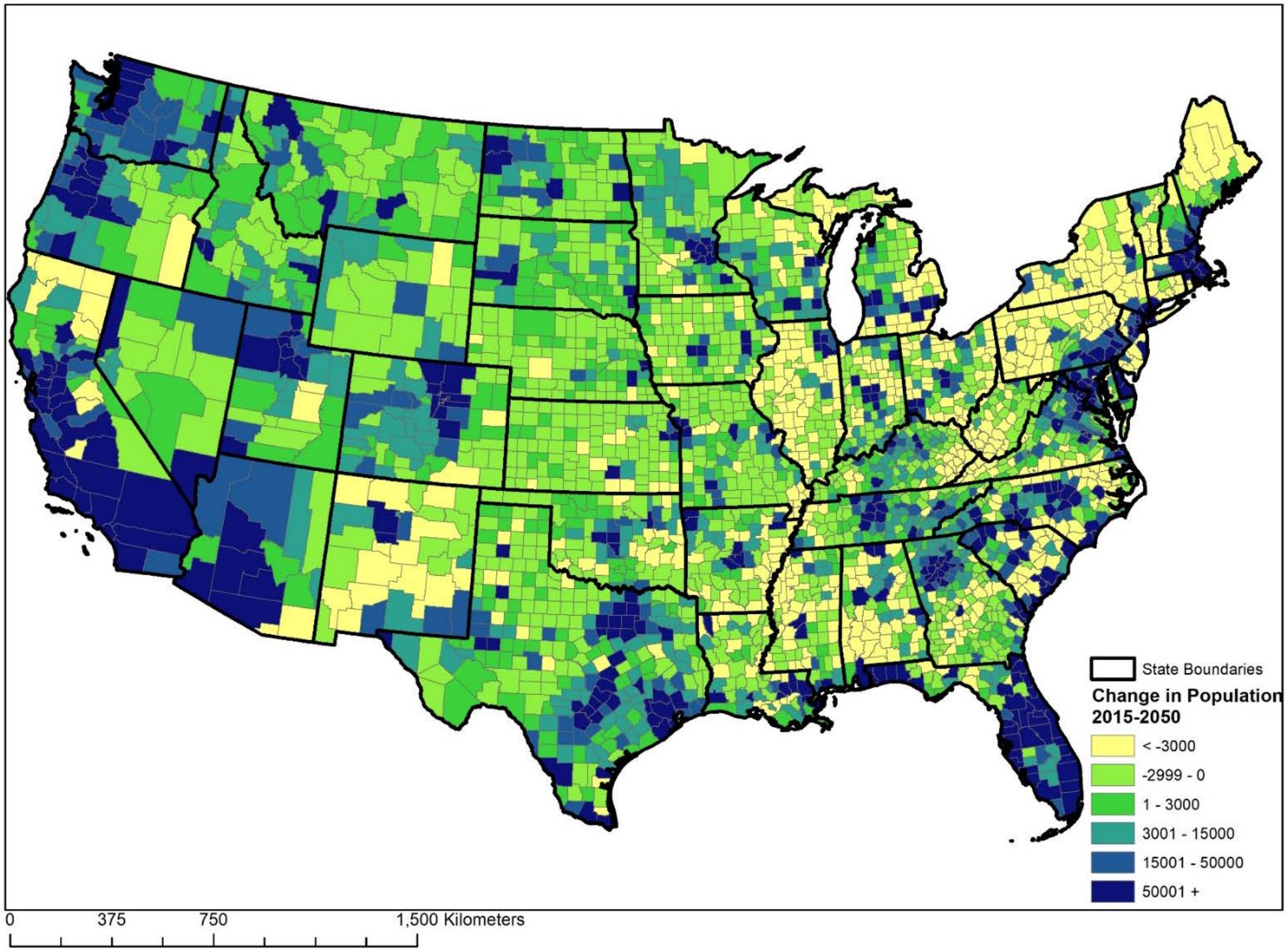

Figure C-8 Projected Change in Population by County for the Medium Scenario between 2015 and 2050

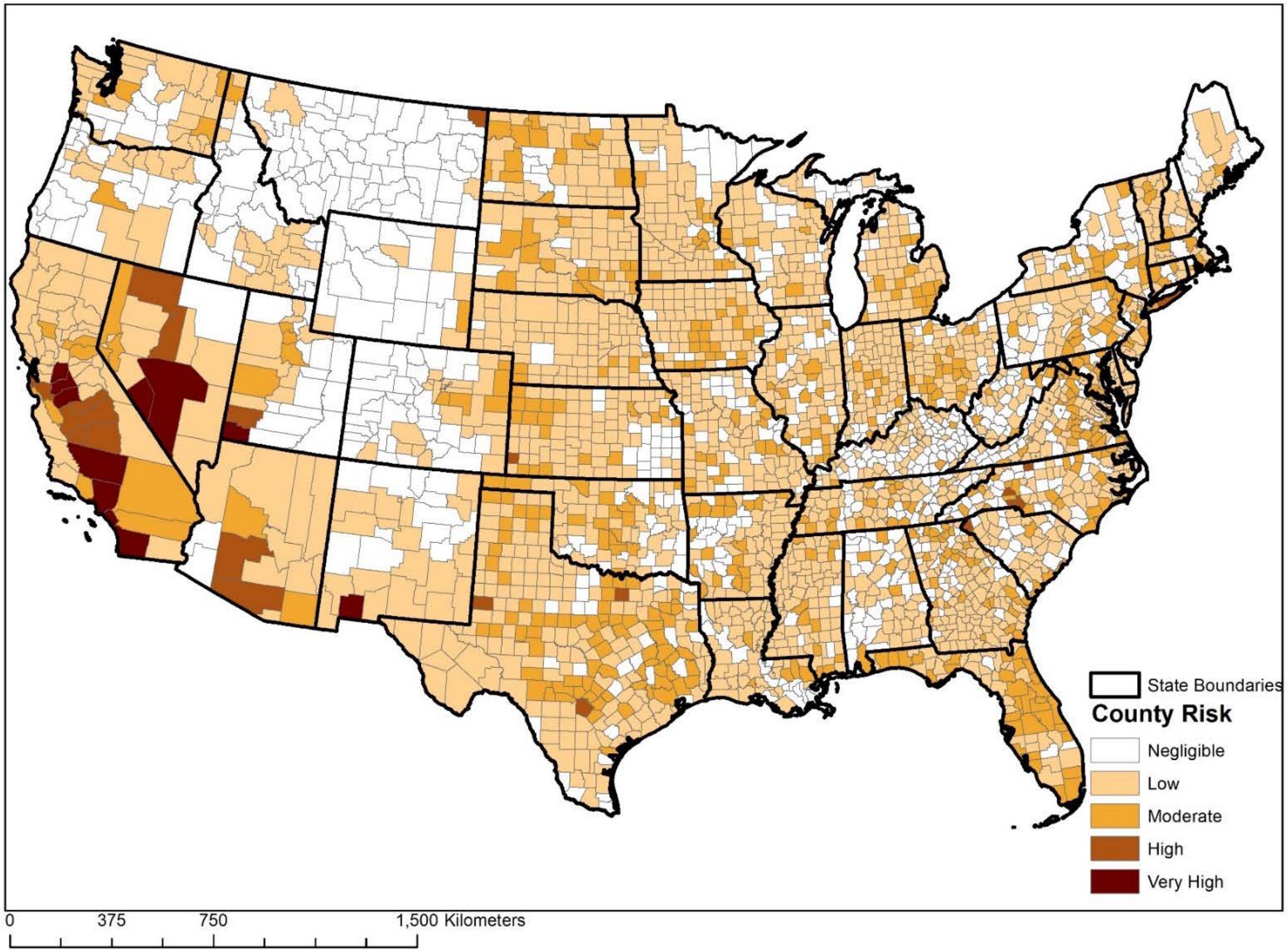

Figure C-9 Water Risk Index by County under the High Scenario

APPENDIX D Water Risk Index Values by County

This appendix provides the full table containing the risk values for each risk factor in all counties in the contiguous US for the low, medium and high scenarios. The tables are provided in Microsoft Excel Format. The file can be downloaded from:

https://figshare.com/s/ab7a3d9d787152df111a