ANALYSIS OF URBAN WATER USE AND URBAN CONSUMPTIVE WATER USE IN NEBRASKA - CASE STUDY IN THE CITY OF LINCOLN, GRAND ISLAND AND SIDNEY

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ANALYSIS OF URBAN WATER USE AND URBAN CONSUMPTIVE WATER USE
IN NEBRASKA - CASE STUDY IN THE CITY OF LINCOLN, GRAND ISLAND
AND SIDNEY

by

Yao Li

A THESIS

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Lincoln, Nebraska

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ANALYSIS OF URBAN WATER USE AND URBAN CONSUMPTIVE WATER USE
IN NEBRASKA - CASE STUDY IN THE CITY OF LINCOLN, GRAND ISLAND
AND SIDNEY
Yao Li, M.C.R.P
University of Nebraska, 2013

Adviser: Zhenghong Tang

The trends of increasing water demand and drought occurrences in Nebraska’s urban areas pose a new crucial issue to water resource management. Former studies in Nebraska mainly focused on rural water demand caused by intensive agricultural irrigation, while largely ignoring the growing municipal water use. Therefore, this thesis aims to investigate total water use and consumptive water use in three major urban land use categories of residential, CIO (commercial, industrial and others), and open space. Three case cities are City of Lincoln, Grand Island and Sidney. First, a reliable and feasible methodology of estimating consumptive water use is developed based on the analysis of end water use activities. Then, possible influential factors (e.g. population, total landscape area) are statistically examined to evaluate their effects on the amount of total and consumptive water use. Afterwards, quantity classification and spatial autocorrelation analyses are used to visually assess and quantify the spatial patterns of total and consumptive water use at the census block level, 2010.

In the three case cities, residential consumptive water use varies from 31% to 57% of total water use, and positive relationships with precipitation and aridity are identified. CIO consumptive water use percentage ranges from 19% to 27%. Open space consumptive water use is nearly equal to the open space total water use. Census block
level linear models are identified between influential factors and amount of water use, which has been rarely applied by previous research. First, the best predictors of residential total water use area population and total landscape area in three case cities. A positive correlation between residential consumptive water use and total landscape area is identified in the Sidney while similar relationship is not found in the other two cities. Second, there is no linear regression relationship identified between CIO total water use/consumptive water use and available independent variables in this study. Third, both open space total water use and consumptive water use can be positively related to total landscape area. Spatially, high water use blocks are commonly clustered in suburban areas with larger lots and lower population densities. Low water use blocks are commonly located near downtown living areas with less yard area and higher population densities. Overall, the methodology and statistical outcome can improve the understanding of urban water supplies and uses in dissimilar urban areas across Nebraska, providing foundation for further urban water studies and integrated water management.
Acknowledgement

This work would not have been possible without my adviser Dr. Zhenghong Tang and the Nebraska Department of Natural Resources (NDNR). During my study at University of Nebraska Lincoln, I have always been supported and encouraged by Dr. Tang in my study and life. I really appreciate his great advice and continuous patience. Thanks also go to NDNR for funding this project and trusting my research capability. I can never forget the wonderful experience working with my supervisors and colleagues: Jennifer Schellpeper, Douglas Hallum, Amy Wright, Mahesh Pun, Brandi Flyr, James Gilbert, Ruopu Li etc. Thank you all for being so nice and for the numerous constructional advices.

I would also like to thank my other two committee members: Dr. Yunwoo Nam and Dr. Ayse Kilic. I learned most of the GIS knowledge from Dr. Nam’s classes and they provide a solid foundation for my research. Dr. Kilic ’s expertise in evapotranspiration helped me improve my methodology significantly. Many thanks to Mr. Arnold J. Radloff (City of Lincoln Department of Public Work and Utilities), Mr. Kurt W. Spiehs (Grand Island Utilities Department), Mr. Bill Taylor (Sidney Water Department) and other staff from their departments. It would be impossible to conduct this research without the fundamental data provided from them. Additionally, I am grateful to the help offered by the GIS and planning departments of the three cities. Their well-maintained GIS and land use database is indispensable to this project. Thanks for the grammar and writing advices from my friends: Kevin McMillan, Jeff Polkowski, Junyi Yang, and Xinyu Fu.

Finally, Thanks to my parents, Hongmei Yao and Qunli Li, and my fiancée, Can Liu. Your endless love has been accompanying me every moment and everywhere.
# Abstract

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Chapter 1 Introduction

1.1 Total water use and consumptive water use

Urban (municipal) total water use and urban (municipal) consumptive water use are two concepts that reflect the water supplies and uses within the urban environment. Urban total water use and consumptive water use are functions of climate, economics, and culture (Shaffer et al., 2008).

In this study, total water use is defined as the gross water use amount (off stream) pumped from city water supply systems within a specific time period: months and calendar year (National Research Council, 2002; Wilson, 2000). Urban consumptive water use is the water use amount that is removed from the urban water supply system without returning to the urban water environment; which is caused by evaporation, plant transpiration and product consumption (USGS, 2008; Canada and US EPA, 1995; Shaffer et al., 2008). Water losses because of leakages in the process of transportation and uses are excluded.

1.2 Research importance

Nebraska’s population was 1,826,341 at the 2010 census, 6.7 percent increase from 2000. The growth rate of population is 13.7% in metropolitan areas (Deichert, 2011). Urban expansion and population growth triggered the urban water demand growing in Nebraska (USGS circulars, 1980 to 2005). Guarantee of water supply and water quality is needed to ensure the economy development and the quality of residential life.

The optimum supply of water is one of the top concerns to citizens and firms, which leads to the fragile nature of urban water supplies and uses (Day, 2003). 73% percent of Nebraskans live in urban areas. Their specific water use activities of residents
determine how much water would be consumed or wasted (Mike, 2012). The activities such as lawn watering would significantly affect the quantity of residential water supply during the summer months (Balling and Gober, 2007). Urban water use is closely related with residents’ daily life and other human activities (e.g. manufacturing, entertainment, etc.). An investigation of the total and consumptive amount of water within urban boundary is crucial to the water resource management.

Finally, this study can help decision makers have a more complete understanding of urban water usage in Nebraska, which is a piece of the overall water use in the state. Water uses and supplies are to be balanced as an objective of integrated water management (Nebraska Groundwater Management and Protection Act, 2007; LB962, 2004). Well-balanced urban water supplies and uses are essential to ensure the well-being of economic viability, social and environmental health, safety, and welfare in cities; especially when taking the growing urban water demand and population into consideration. This study quantifies how much water is needed and lost in cities and investigates the statistical relationship between the amount of water use and its determinants at current, and potentially future conditions (Falkenmark, 2005; Fanning, 2007). The study also provides information about municipal water use which could be an asset in future decision making and planning in Nebraska.

1.3 Research questions and objectives

In the United States, few analyses have been conducted to calculate the total water use and consumptive water use at the census block scale. In Nebraska, considerable research is focused on water use of agricultural irrigation and crop evapotranspiration. A lesser known area is urban water use and its determinant factors (e.g. population, total
landscape area). Though major water resources are utilized by agricultural irrigation in Nebraska, additional research of urban water use is essential because over seventy percent of the Nebraska residents live in cities. Therefore, this study aims to provide a pioneer exploration in understanding the urban total water use and consumptive water use in three Nebraska case cities at a refined level of detail (census block unit).

The specific research objectives are as follow:

1. Develop a method of estimating urban consumptive water use at the census block level in Nebraska.

2. Investigate statistical relationships between influential factors (e.g. population, building footprints, total landscape area etc.) and urban water use/ urban consumptive water use.

3. Analyze spatial patterns of urban total water use and consumptive water use comprehensively in the City of Lincoln, Grand Island, and Sidney.

1.4 Thesis structure

This thesis investigates the urban total water use and consumptive water use through five chapters as follows:

Chapter one provides the introduction of research topics. The definition and background of total water use and consumptive water use are demonstrated to understand the importance of urban water use issue. Additionally, the reason why this research was conducted and objectives are highlighted.

Chapter two reviews diverse literature and the state government concern regarding urban water use. Papers from previous scholars provided the definitions, research strategies, and methods for urban water use. A systematic review is provided to
illustrate the previous scholars’ research methods and results, which is based on three major categories: residential, CIO (commercial, industrial and others) and open space. In addition, this chapter highlights the other state agencies’ concern on urban water use. The website review can provide the mainstream awareness of the urban water use importance at state agencies.

Chapter three demonstrates the research methodology. The research objects are total water use and consumptive water use within urban area. They are analyzed in three categories: residential, CIO (commercial, industrial and others) and open space. The first step is to calculate the amount of total water use and consumptive water use. Then, the statistical relationship between water use amount and its influential factors (e.g. population) is examined by linear regression models. Finally, spatial clustering analysis is illustrated by Global Moran’s I and Getis-Ord Gi*.

Chapter four describes the result of statistical and spatial analysis from previous chapters. Linear regression models results are presented in this chapter. Significant linear relationships are found between amount of water use and its influential factors (e.g. population and total landscape area) within the categories of residential and open space. Additionally, the spatial distribution and cluster condition of high or low water consumers of total water use and consumptive water use in each category is demonstrated by maps and Moran’s I and Getis-Ord Gi*.

Chapter five highlights the major findings of this study and their implication or potential utilization for the water resources planning and management. This study proposed a pioneer exploration in urban water study in Nebraska which can help planners
and decision makers have a better understanding on urban water supplies and uses. Lastly, the limitations and future study directions are identified.
Chapter 2 Literature review

2.1 Urban total water use

2.1.1 Total urban water supply

An understanding of multi-scalar relationships between human activity and natural systems is needed to integrate and forecast urban water demand (Hill and Polsky, 2007; House-Peters, 2010). To ensure the municipal water supply, various statistical models and methods have been employed to estimate how well current water supply systems meet demand during peak time and future city expansion. Back in 1972, Hoppel and Viseeman established a linear model to predict the peak urban water use and recommended the development of two more water supply wells to meet high water demand in the near future for the City of Lincoln, Nebraska (Hoppel, 1973). A time series model has been applied to forecast hourly water consumption (Zhou et al., 2002). An Ordinary Least Square (OLS) regression model was employed using monthly water use as the dependent variable and climate variables as independent input (Morgan, 1976). However, these studies were mainly based on historical water use records rather than current condition analysis. Identifying the synchronous determinants of present water consumption is needed to indicate further conservation potential and decision-making (Cassuto and Ryan, 1979; Morales, 2009). Therefore, this study investigates the determinant factors within each of the major water use categories: residential, CIO (commercial, industrial and others), and open space.
2.1.2 Residential total water use

Residential water consumption can be affected by various factors such as: climate, economy, demographic conditions, spatial structures, culture, techniques, policy, and as such the relationship between climate variation and residential water consumption has been investigated widely (Balling and Gober, 2007; Balling et al., 2008; Bougadis et al., 2005; Foster and Beattie, 1979; Franczyk and Chang, 2009; Wentz and Gober, 2007). For example, higher temperature, lower precipitation, and drought can cause the amount of water use to rise (Balling and Gober, 2007; Campbell, 2004). However, residential water use is not always sensitive to climate conditions. Balling et al. (2008) found that water consumption with higher neighborhood density had little to no sensitivity to the climate, at census tract level. Recently, drought condition has been disturbing the urban water supply across the U.S. Evaluating water consumption under drought conditions is necessary to assist water resources planners and managers in developing effective countermeasure for extreme climate situations (House-Peters, 2010).

Residential lawn watering also attracts attention from scholars, because residential outdoor irrigation could account for up to fifty percent of total water use (Hilaire, 2008; Mayer, 1999). A sample survey was accomplished in Las Cruces, New Mexico, which concluded that 40 to 65 percent of metered water is used for maintaining plants in landscape (Chavez, 1973). Scholars also found that garden size and species planted were determinants of water use (Domene and Saurí, 2006; Wentz and Gober, 2007). However, there are barriers to understanding the lawn effects on the total water use, because of the rare fine resolution raster image and the high cost of producing the accurate total lawn area (Milesi et al., 2009; Milesi et al., 2005).
Residential water use amount also correlates with urban development patterns and socioeconomic factors. Accompanying growing lot size and building size, the average water use in a block group is increasing while the building age and building density show the opposite relationship (Chang, 2010). In Chang’s study review, eighteen factors were identified to explain the relationship between structure patterns and economic indicators with residential water use (Chang, 2010). Income, education level and housing values also have been found to positively related with household water consumption (Domene and Saurí, 2006; Franczyk and Chang, 2009; House-Peters, 2010). Additionally, factors such as land use (Day, 2003; Durga Rao, 2005), human behavior (Wentz and Gober, 2007), prices and policies (Foster and Beattie, 1979; Olmstead et al., 2007) have been analyzed to forecast the peak demand in order to ensure adequate residential water supply and formulate planning strategy of residential water resources.

2.1.3 Commercial and industrial total water use

For commercial and industrial water consumers, the water consumption varies significantly with regard to the purpose of water use (Dziegielewski, 2000). Thus, statistical models based on historical water usage are reliable resources to forecast and analyze present or future water usage, such as IWR-MAIN (Institute of Water Resources Municipal and Industrial Needs model) and WEAP (Water Evaluation and Planning model) (Opitz et al., 1998; Sawyer, 2004; SEI, 2009; SWFWMD, 2006). However, researchers keep making progress in understanding various water use activities and the driving forces behind them. End use of the water is a clear way to analyze the determinant factors of water consumption (EPA, 2007; Maddaus, 2004). The inputs for the model based on end uses are number of employees, price of water and sewer services,
and presence of conservation programs and industrial groups (Morales, 2009). Also, a relationship exists between total number of customers, total number of employees, total water output (Dziegielewski, 2000; Mercer and Morgan, 1974), acreage, gross area, and sales area (Kim and McCuen, 1979; Mercer and Morgan, 1974).

2.1.4 Open space total water use

Urban vegetation land cover is actually everywhere: residential lawns, commercial and industrial landscapes, and public open spaces (Costello, 2000). Scholars sometimes analyze the importance of lawn or landscape water use within residential water use studies, and those research questions are sparked from the awareness of large amount of water use that contributed to urban landscape irrigation (Ferguson, 1987; Pittenger et al., 2001). Positive relationships have been found between total landscape area and total water use (Sovocool et al., 2006; Wentz and Gober, 2007). Additionally, the research on turf grass evapotranspiration and landscape water management is becoming more and more extensive (Harivandi, 2009; Romero, 2009). Hilaire et al. (2008) proposed that the landscape water use should be one of the most important urban water conservation components. Most elements that affect landscape water requirement have been addressed, such as plant species, landscape design, irrigation strategies, human activities, the reuse of water resources, economic and noneconomic incentives, and policy and ordinances (Bennett and Doss, 1960; Hilaire, 2008; Zazueta, 2000).

2.2 Urban consumptive water use

Generally, consumptive water use is defined as the water that is evaporated, transpired, consumed by humans or livestock, or otherwise removed from an immediate water environment (Shaffer et al., 2008). In agricultural areas, the consumptive water use
is approximately equal to evapotranspiration since the water use is mostly used for the plant transpiration, growth and inevitable evaporation (http://www.idwr.idaho.gov/GeographicInfo/METRIC/et.htm). In urban environments, the water use activities are more complicated than those in agricultural areas, so evapotranspiration and consumptive water use are not interchangeable. Therefore, calculation of consumptive water use amount considers more elements and conditions than that in agriculture.

There are two main algorithms to estimate consumptive water use: the measurement-based method and the coefficient-based method (Shaffer et al., 2008). As table 2.1 displays, the coefficient-based method could directly estimate the volume of consumptive water use in the Great Lake Basin and climate similar area. However, the state of Nebraska is located 500 miles west of the Great Lake Basin and has not been included. To monitor the input flow and output flow at all facilities and buildings is more accurate, but this method requires a much higher technique complexity on infrastructure design and is much more costly (Shaffer et al., 2007). Researchers in Colorado have estimated return flow from lawn irrigation based on lawn evapotranspiration calculations (Oad et al., 1997). Overall, there is still lack of concepts and research on urban consumptive water use (Falkenmark, 2005). This study estimates the urban consumptive water use through the end uses of water, which is rarely used by other scholars. End use of water refer to all of the specific destinations where water is used such as faucets, lawn irrigation, machines, product production, toilets, etc (Dziegielewski, 2000; Mayer, 1999). Therefore, this study estimates consumptive water use through analyzing end use of water and measurement-based methodology.
Table 2.1 Comparison of methods of estimating consumptive water use

<table>
<thead>
<tr>
<th>Methods to estimate consumptive water use</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, withdrawal- return flow</td>
<td>Measurement-based</td>
<td>Leaks and conveyance losses; Difficult to measure</td>
</tr>
<tr>
<td>2, withdrawal° coefficient</td>
<td>Widely adopted in the Great Lake Basin</td>
<td>Mostly empirical</td>
</tr>
</tbody>
</table>

References: (Shaffer et al., 2008; Shaffer et al., 2007)

2.2.1 Urban water use investigations by government agencies.

Natural resources management agencies in state government paid different attention to urban water uses (Table 2.2). The State of California is now the most advanced explorer on urban water research methods. The Urban Water Management Planning (UWMP) Act in California provides support for long-term resource planning and adequate water supplies for metropolitan areas. They also developed the methodologies to calculate the urban water consumption, which includes the common-accepted methods such as per capita water use estimation, and land use oriented algorithms (California Department of Water Resources, 2009). The Colorado Water Conservation Board led the development of the Municipal Water Efficiency Guidance Document to establish an integrated water resources planning process for sustainable urban water supply in Colorado. Arizona had a similar ongoing program. The natural resources management agencies in these three states valued the importance of municipal water resources significantly. With the awareness of how water is consumed and the need to conserve water, municipalities in the States of Arizona and California have already facilitated water-saving techniques, low-flow devices, and pricing structures as well as tried to achieve the goal of no increase of total water use amount even with growing population in a given time period (Campbell, 2004).
State governments in both Georgia and Oklahoma developed the urban water reuse plans that aimed to improve the municipal water use efficiency. Texas, Louisiana, and Utah paid attention on different aspects of urban water use such as the lawn watering and water conservation techniques. However, other state level agencies have not conducted much research or programs on municipal water uses that published on official websites.

Around the Great Lakes Basin, United States Geological Survey (USGS) developed consumptive water use coefficients for more than 20 states to estimate consumptive water use within similar climate scenario. Thus, this study did not review the water management resources in those states for extra information; most of them have had abundant urban water use and consumptive water use studies cooperated with or based on USGS research. For example, relying on a comprehensive dataset provided by National Pollutant Discharge Elimination System (NPDES), the State of New Hemisphere aims to use the equation method to measure consumptive water use through monitoring the inflow and outflow within each census block (Hayes, 2009).
### Table 2.2 Review of urban water use management in state agencies and USGS

<table>
<thead>
<tr>
<th>Regions or States</th>
<th>Attention level*</th>
<th>Highlight</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>High</td>
<td>Urban Water Management Planning (UWMP) Act</td>
<td><a href="http://www.water.ca.gov/urbanwatermanagement/">http://www.water.ca.gov/urbanwatermanagement/</a></td>
</tr>
<tr>
<td>Colorado</td>
<td>High</td>
<td>Municipal water efficiency plan</td>
<td><a href="http://dnr.state.co.us/Pages/DNRDefault.aspx">http://dnr.state.co.us/Pages/DNRDefault.aspx</a></td>
</tr>
<tr>
<td>Arizona</td>
<td>High</td>
<td>Municipal conservation program; Arizona municipal water uses association</td>
<td><a href="http://www.zawater.gov/ArizonaWR">http://www.zawater.gov/ArizonaWR</a>; <a href="http://www.amwua.org/">http://www.amwua.org/</a></td>
</tr>
<tr>
<td>Georgia</td>
<td>High</td>
<td>Urban water reuse; urban water use efficiency analysis</td>
<td><a href="http://www.gadnr.org/">http://www.gadnr.org/</a></td>
</tr>
<tr>
<td>Oklahoma</td>
<td>High</td>
<td>Urban water reuse; Oklahoma city and Tulsa water supply analysis</td>
<td><a href="http://www.owrb.ok.gov/">http://www.owrb.ok.gov/</a></td>
</tr>
<tr>
<td>Texas</td>
<td>Mid</td>
<td>Texas water matters municipal water conservation</td>
<td><a href="http://www.tpwd.state.tx.us/landwater/">http://www.tpwd.state.tx.us/landwater/</a></td>
</tr>
<tr>
<td>Utah</td>
<td>Mid</td>
<td>Lawn water use monitoring</td>
<td><a href="http://www.water.utah.gov/#">http://www.water.utah.gov/#</a></td>
</tr>
<tr>
<td>Louisiana</td>
<td>Mid</td>
<td>Urban storm water runoff and pollution</td>
<td><a href="http://dnr.louisiana.gov/">http://dnr.louisiana.gov/</a></td>
</tr>
<tr>
<td>Great lake Basin (24 States)</td>
<td>High</td>
<td>Consumptive water use coefficient; estimate water use report;</td>
<td>pubs.usgs.gov/fs/2008/3032/pdf/fs2008-3032.pdf;</td>
</tr>
<tr>
<td>Other States</td>
<td>No</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Attention level*: High stands for high attention with relative legislation or research report found through state agency website; Mid stands for mid attention with specific urban water related concern or conservation highlighted on state agency website; No stands for no relative information found through online review.

Cooperation between state agencies and research institutes exists as another way reflecting the government concern on urban water use. In Florida, researchers developed water use coefficient based on different urban land uses via statistical models (Morales, 2011). Specifically for the landscaped area within an urban boundary, many researchers in State of Utah conducted the ET calculation method utilizing Lysimeter and Bowen ratio facilities, which has commonly been used in agricultural and natural land. Additionally, information and data sharing networks also exists, such as in the state of
Oregon. Its website shares the link of the urban water research program conducted by Portland State University (Chang, 2010).

In summary, municipal water use has attracted attention from state agencies in highly urbanized states such as California. In states such as Nebraska, urban water use has not been researched in any detail. Variable climate accompanied by more frequent occurrences of drought conditions and more severe drought places municipal water infrastructure in a more vulnerable condition. Hence, this study fills the gap of urban water research in state of Nebraska and proposes a pioneer estimation method of urban consumptive water use. This study can help the state decision makers to have a better understanding of the water supplies and uses in the urban areas of the state.
Chapter 3 Methodology

3.1 Research framework

A three-phase methodology is employed to analyze urban total water use and consumptive water use (Figure 3.1). Case study cities are City of Lincoln, Grand Island and Sidney.

The first phase is to develop the use estimation method of urban consumptive water based on three major land use categories: residential, CIO (commercial, industrial and others), and open space. Amount of consumptive water use is the subtraction of amount of discharge water use from amount of total water use. Total water use is the bimonthly or monthly water meter sale data aggregated into research units (census blocks). Amount of discharge depends on the concept of end use of water that refers to all of the specific places where water is used in a given area (Mayer, 1999). For each water end user, ratio of discharge amount is determined by previous research or subjective understanding on specific water use activities. For example, faucets and bathroom water use in houses are considered to have 100 percent discharge, while 0 to 10 percent of outdoor water use is considered to be discharged. To aggregate the water meter data into research unit, the records are projected into geographic layers based on street network through the function of Geocoding (ArcGIS) and then classified into the three major categories determined by land use types.
Figure 3.1 Conceptual illustration of research process

The second phase is to conduct the statistical analysis within each major category through Microsoft Excel and Statistical Package for the Social Sciences (SPSS). As Figure 3.1 displays, the major land use types of residential, commercial, industrial, agricultural and open space are combined into three categories. The objective is to explore the linear regression relationship between the possible influential factors (e.g. population, building footprints, etc.) and total water usage or consumptive water usage at the census block level (Ordinary least square regression model). Dependent variables are amount of total water use and consumptive water use. Most of the independent variables are retrieved from the 2010 census, such as population, housing units et cetera (specific information is explained in the data sources section). Block group analysis is included in this project because it is the units with readily available data of potential influential factors. However, there is no significant relationship at the census block group level. Therefore, the block group data is eliminated from the result chapters.

With the total water use and consumptive water use data on each block, the last phase is to analyze their spatial pattern within case cities. First, the urban water use and consumptive water use could be mapped through ArcGIS to visually assess the spatial
pattern of high and low water use blocks. Global Moran’s I and Getis-Ord Gi* are adopted to quantify the scale of spatial dependence in water use (House-Peters, 2010). Global Moran’s I, an ArcGIS function, is a global measure of spatial autocorrelation with possible values from positive (dispersed) to negative (clustered) and 0 means a perfect random spatial pattern (O’Sullivan and Unwin, 2002). Getis-Ord Gi*, another ArcGIS function, is used to recognize the hot spots and cold spots through Z-score and P-value (O’Sullivan and Unwin, 2002).

3.2 Study area

The City of Lincoln, Grand Island, and Sidney are chosen as the case cities. There are four main reasons. First, these cities are generally located from east to west across Nebraska. They generally represent the climate variations across the state (Figure 3.2). For example, the precipitation is declining and ET0 (Penman Evapotranspiration, HPRCC, 2010) is increasing from east to west. Second, ground water is the principal water resource for these cities, which is one of the most important issues for integrated water management in Nebraska. Third, the population of case cities varies from 6,500 to 250,000 so that they could represent different city scales. Last but not least, their municipal departments are willing to provide the meter sale records. Smaller towns rarely (population is lower than 6,000) employ meter techniques for water service in Nebraska.
The City of Lincoln is the capital and the second most populous city in the State of Nebraska, and is located in eastern Nebraska with relatively high precipitation in the state. The Grand Island is the fourth populous city and the retail hub in central Nebraska (Grand Island, 2013). The Sidney is a small town in western Nebraska. It represents the relatively arid climate condition in the state. According to US census data, the City of Lincoln, Grand Island and Sidney are expanding with population growth rate at least 5.4% in the past two decades. Also, the City of Lincoln and Grand Island are among the top 5 fastest growing large cities in Nebraska (Deichert, 2011). These cities are potentially facing a challenge of increasing water demand caused by the growing population.

3.3 Data collection and sources

Information is collected in four major categories: water use, GIS layers, census data, and climate data (specific detail displays in Table 3.1).
Table 3.1 Data resources list

<table>
<thead>
<tr>
<th>Data Sources (City Departments)</th>
<th>City of Lincoln</th>
<th>Grand Island</th>
<th>Sidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS layers: parcel; current land use; zoning;</td>
<td>Planning Department</td>
<td>Regional Planning/Community Development Department</td>
<td>Planning/Zoning Department, GIS Department</td>
</tr>
<tr>
<td>Bimonthly metered water sales</td>
<td>Public Works/ Utilities Department</td>
<td>Utility Department</td>
<td>Water Department</td>
</tr>
<tr>
<td>GIS layers: parcel; land use 2003 (CAD); zoning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly metered water sales</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIS layers: parcel; zoning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly metered water sale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather data (Daily Precipitation; Daily ET_o)</td>
<td>High Plain Regional Climate Center (HPRCC) online data services Automated Weather Data Network (AWDN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIS layers: census block; block groups; city limits; street network</td>
<td>U.S. census Bureau; NDNR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial discharge</td>
<td>National Pollutant Discharge Elimination System (NPDES)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We obtained monthly or bimonthly water use records for each address around the year of 2010 through telephone and email communications with utility departments (Table 3.1). More than 81,000 meter records were received from the City of Lincoln. Meanwhile approximately 16,000 records were received from the Grand Island and 1,800 records from the Sidney. The sum of water use records in each block is one of the
dependent variables (total water usage) for statistical analysis and also used to calculate another dependent variable, consumptive water use.

For the GIS layers, different cities have various maintenance strategies on land uses and parcels information. The City of Lincoln has monthly update on their current land use while other cities use zoning map as their land use information. The best available GIS layers data is obtained in those case cities through telephone and email communication with GIS or planning departments in those case study cities. The categories in which the water records are summarized depend on their location. This means that if a record is located in the residential land use area, its water use amount is summarized into residential water use.

Parcels are the units of property owners and meter records. Thus, whether there are enough meter records in a block could be examined through the comparison between numbers of water meters and parcels within a block. The City of Lincoln provides the GIS layers of building footprints in 2010.

Total landscape area, one of the independent variables, is derived from Nebraska Farm Service Agency (FSA) 2010 Imagery (4-band color). If the NDVI (Normalized Difference Vegetation Index) index is larger than 0.15 in a raster cell (1m²), it is considered to be total landscape area (ArcGIS Help, 2013).

Influential factors (independent variables) including social demographic, economic and urban development patterns are collected based on block and block group mostly from 2010 census and American Community Survey. Social factors used for both block and block group level analysis are population, housing units, block area, population density, and housing density (Table 3.1). Block area (square meter) is calculated through
the ArcGIS geometry calculation function based on the projected coordinate system of NAD 1983 StatePlane Nebraska FIPS 2600 Feet. Population density and housing density are directly calculated from the above states information using the following equations:

Population density = population / block area (number of people/ acres)
Housing density = housing units / block area (unites/ acres)

Economic factors could only be obtained at block group level through US census American Community Survey (2006-2010), which is composed of average income and total housing values.

For urban development pattern factors, the shapefiles of building footprints are available on block and block group level from GIS or planning departments in the City of Lincoln only. Rooms and years built are downloaded from US census American Community Survey (2006-2010).

Climate data in the year of 2010 is downloaded from AWDN (Automated Weather Data Network) on HPRCC (High Plain Regional Climate Center), which could be directly used for ET calculation as the input in a software calculator named REF-ET (Allen, 2013).

Few industrial discharge records for consumptive water use calculation can be found from NPDES (National Pollutant Discharge Elimination System). Precipitation and industrial discharge water use is used in the outdoor and industrial consumptive water use calculation process.
3.4 Data analyses

3.4.1 Research unit

Blocks (census blocks) are statistical areas bounded by visible features, such as streets, roads, streams, and railroad tracks, and by nonvisible boundaries, such as selected property lines and city, township, school district, and county limits (2010 US census Summary File 1). The mean area is about 10 acres and population is around 45 in Nebraska cities.

Block groups (BGs) are statistical divisions of census tracts, are generally defined to contain between 600 and 3,000 people, and are used to present data and control block numbering (2010 US census Summary File 1). The mean block group area in Nebraska is approximately 2693 acres while it is down to 150 acres within city boundary. The average population is about 1158 in Nebraska.

Census block is the main analysis units in this study, which is defined by U.S. census for demographics related management (Figure 3.3). The reason why census blocks were selected is that block is the finest unit with population summary (independent variables). One of the objectives of this study is to investigate the statistical

Figure 3.3 Examples of census blocks and a block group
relationship between the influential factors (e.g. population) and total water use / consumptive water use. Block group is listed as an assisting unit to check if there could be any economic related factors significantly influencing the total water usage/ consumptive water usage at census block group level. Block group is smallest unit accompanied with economy and housing conditions data. Additionally, block group is the maximum unit that could be accepted for this study according to the urban structure in Nebraska. The census tract is a potential unit option for analysis. It is another statistical unit developed by the US census with a population of around 4,000 within the boundary (2010 US census Summary File 1). However, it is difficult to find a 70 to 90 percent single type water users in one census tract and there are few census tracts in a single city with less than 200,000 populations. For example, approximate 60 census tracts are in the City of Lincoln but this number is down to 10 in the Grand Island and 2 in the Sidney. It is impossible to test the linear regression relationship for such a small sample size. Another reason to use census block is that it is seamless across the state and well maintained by US census.

If there is more than one category within a block, it would be split into sub-blocks as analysis units. In the block group level analysis, there is hardly a single category within one block group so that the analysis would be conducted based on the land use percentage within a block group. In the later analysis, there is either similar relationship as block analysis or no significant relationship found at block group level. Thus, this study keeps block level analysis only in the result chapter.
3.4.2 GIS process

The first phase of this study is to calculate consumptive water use at census block level in three major categories: residential, open space, commercial, industrial and others (e.g. public office, institutions etc.). The meter records need to be classified into one of the categories. Specifically, if a meter record location is intersected with the residential land use, it is classified as residential category.

Figure 3.4 Procedure to build the water use GIS dataset

The overall GIS process is illustrated in Figure 3.4. First, each census block is assigned to one of the three categories. GIS layers of census blocks and land uses can be intersected to decide the categories of blocks. Whether it is single category within each block could be identified by their attribute. If there is more than one type of categories within a block, the split sub-blocks are the research unit in this study. The polygons (blocks and sub-blocks) under same category could be merged into one shapefile using merge tool. Thereafter, spatial join, is adopted to append point geographic layer of the water meter records on classified block polygons. The point layer is projected from table records into point feature with attribute of water use amount through Geocoding.
During the process, there are two options to transform the water meter records from spreadsheets to GIS shapefiles. One way is attribute join, which can link the water usage to the parcel dataset through an exact match of expression of addresses. Attribute join in ArcGIS is to append the water usage information to parcel data through the address attribute in both tables (ArcGIS Resources Help). However, attribute join requires a match of exact words, which usually lead to a lower percentage of address matches. For example, as a result of attribute join in the City of Lincoln, nearly fifteen percent meter records cannot be located.

Attribute join result could only match around 85% of total meter records. Thereafter, geocoding function is adopted in this study. Geocoding is the process of transforming the water usage with addresses to geographic features (shapefiles of points) based on street network (ArcGIS Resources Help). This study designs a three step geocoding process. The matched record number can be improved significantly through this process. For instance, in the City of Lincoln, the number of unmatched address using attribute join is 18,582 while that number is down to 4,692 at first step of geocoding (geocode through census street network). Purely relying on census network, the matched record number can

![Figure 3.5 City of Lincoln geocoding process](image)
reach to 95%. The consecutive two steps transform the rest 5% of total records (Figure 3.5). ArcGIS online network is adopted as the geographic reference system for the second geocoding process. If there are still unmatched records, the limited number of records can be found through detailed manual correction based on the Google map system. Very few records are left after this three step process and, if so, they would be treated as invalid data and removed from calculation. The received water meter records in each city and the geocoding result based on census and online network are listed in the Table 3.2. According to the communication with municipal utility departments, few invalid water records do exist in their billing system. Hence, the three-step geocoding is the most reliable and accurate way to transform the water meter records.

Table 3.2 Water meter records and geocoding result in three case cities

<table>
<thead>
<tr>
<th>Cities</th>
<th>Records received (approximately)</th>
<th>Geocoded result</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Lincoln</td>
<td>81,555</td>
<td>81,376</td>
</tr>
<tr>
<td>Grand Island</td>
<td>15,652</td>
<td>15,578</td>
</tr>
<tr>
<td>Sidney</td>
<td>2,150</td>
<td>2,150</td>
</tr>
</tbody>
</table>

3.4.3 Analytical criteria

In order to ensure the quality of analysis result, this study set several thresholds to eliminate the unqualified research units (census blocks). For residential blocks, the meter numbers need to meet more than ninety percent of the total housing units or parcels. Meter data is usually equal to number of parcels in a block of apartments while the meter records shall be the same as number of housing units in block of single family houses. Thus, if a residential block can meet either of the two criteria, it is kept for further analysis. For CIO (commercial, industrial and others) category, the meter records need to reflect more than ninety percent of total parcel numbers for further analysis. For open
space category, at least sixty percent of the total area should be healthy vegetation. Otherwise, it may be abandoned or have a lack of irrigation and management.

Table 3.3 Analysis criteria

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Either meter numbers / housing units &gt;= 90% or meter numbers / parcels &gt;= 90%</td>
</tr>
<tr>
<td>CIO</td>
<td>Meter numbers / parcels &gt;= 90%</td>
</tr>
<tr>
<td>Open Space</td>
<td>Vegetation area &gt;= 60% total block area</td>
</tr>
</tbody>
</table>

3.4.4 Consumptive water use calculation

In this study, the consumptive water use in Nebraska is estimated through the concept of “end uses of water” and a well-accepted equation method (Dziegielewski, 2000; Mayer, 1999; Shaffer et al., 2008). Each end use of water is evaluated to determine the amount used and the percentage of discharged water. As stated in the GIS process, three major categories (residential, CIO (commercial, industrial and others), open space) are assigned to each research unit (census block). For each major category, consumptive water use is calculated through the equation as follows:

Consumptive water use amount = total water use amount – discharge water amount

Total water use is the bimonthly or monthly water meter sale data aggregated at the block level. Discharge water amount is estimated from water end use, which refers to all of the specific places where water is used in a given area (Mayer, 1999).

3.4.4.1 Residential consumptive water use calculation

In residential area, two major terminals of water flow are buildings and landscape area. According to American Water Works Association Research Foundation (1999),
indoor water usage consists of bath, clothes washer, dish washer, faucet, shower, toilet, leaks and other domestic uses. Consumptive water use items are drinking, indoor watering etc., which is less than one percent of the total indoor water use. Therefore, in this study, indoor consumptive water use is ignored.

Outdoor water usage consists of irrigation, car washing, swimming pools and others. Consumptive water use occurs in irrigation and swimming pools, which refers to the evaporation of water bodies and evapotranspiration of plants. Outdoor water use activities (e.g. swimming pools, flower or garden irrigation) are irregular except for turfgrass irrigation. Consequently, this study assumes that the outdoor water use is the landscape (turfgrass) irrigation at growing (irrigation) season and outdoor consumptive water use is determined by the actual outdoor water use and the theoretically required amount of water for evapotranspiration of landscape (turfgrass).

In order to estimate the amount of actual outdoor water use, the analysis of water meter data from three cities are needed. The raw water usage data we received from municipal utility departments are spreadsheets of address and monthly or bimonthly water usage for each address. There is no separate record of indoor and outdoor water use. The method to estimate indoor and outdoor water use in this study is the same way that the City of Lincoln utility department charges the waste water bill. It collects the sewer system fee (discharge water) consistently during the whole year based on winter water usage (City of Lincoln, 2013). Therefore, this study assumes that indoor water use is consistent during the entire year and outdoor water use occurs only for landscape (turfgrass) irrigation from April 1st to October 31st. Indoor water use amount (IWU) could be calculated based on winter water usage (WWU). The complete indoor water
usage is from December 21st, 2009 to February 18th, 2010 in the City of Lincoln and from December 1st to February 1st in the Grand Island and Sidney. These depend on the different collection time periods of three case cities. Outdoor water use amount (OWU) is the subtraction of indoor water usage (IWU) from total water usage:

\[ \text{IWU (annual)} = 12 \text{ months (1 year)} \times \left( \frac{\text{WWU}}{\text{winter time period}} \right) ; \]

\[ \text{OWU (annual)} = \text{total water usage} - \text{IWU (annual)}. \]

Since the indoor consumptive water use is zero, the residential consumptive water use amount (RCWU) is equal to the outdoor consumptive water use amount. The relationship between outdoor water use (OWU) and outdoor irrigation demand (OID) determines the actual residential consumptive water use amount (RCWU). As Figure 3.6 displays, if outdoor water use amount is larger than outdoor irrigation demand, the irrigation demand part is used by plant (turfgrass) evapotranspiration and the rest part of outdoor water use goes back to urban environments. It means that OID is equal to the amount of RCWU. If outdoor water use is less than irrigation demand, this indicates that all of the outdoor water use (OWU) is consumed by plant (turfgrass) evapotranspiration, which equals to RCWU.

The outdoor irrigation demand (OID) is the subtraction of precipitation from evapotranspiration \((\text{ET}_c)\). To transfer the length to volume, the equation is as follows:

\[ \text{OID} = \text{Total landscape area} \times (\text{ET}_c - \text{precipitation}) \]
Evapotranspiration and precipitation are often expressed in dimension of depth and time, such as inches (in) per day, while the water usage record from utility departments is expressed in dimension of volume such as cubic feet or cubic meters. Hence, the irrigated area (total landscape area) in each block needs to be calculated. Due to the time and labor limitation, this research employs a general estimation on the irrigated area (total landscape area) based on NDVI. Precipitation is obtained directly from High Plain Regional Climate Center’s (HPRCC) Automated Weather Data Network (AWDN) (http://www.hprcc.unl.edu/awdn/). \( \text{ET}_c \) can be calculated based on the fundamental data from the same resources and a software called Ref-ET (Richard, 2013). All the units employed in this study are unified into meters, square meters, and cubic meters.

1. delineation of total landscape area:

NDVI (Normalized Difference Vegetation Index) can display which cell is the plant area (landscape) and which cell is non-plant area and it is a standardized index that utilizes contrast of features of red and near-infrared bands. The contrast is derived from the chlorophyll absorption in the red band and high reflection of plants in the NIR band (ArcGIS help, (Lillesand et al., 2004). Therefore, the total landscape area can be extracted from the raster image through GIS. The equation is:

\[
\text{NDVI} = \frac{(\text{Infrared} - \text{Red})}{(\text{Infrared} + \text{Red})}
\]

Instead of achieving NDVI of raster data through ENVI or ErDAS, the NDVI function can be calculated through raster calculator in ArcGIS. In this study, the Nebraska Farm Service Agency (FSA) 2010 Imagery is the basic data for total landscape
area delineation. It is 1 meter resolution raster imagery and consists of four bands: blue, green, red, and infrared.

According to the ESRI resources (2010), the NDVI values range from -1 to 1. Values of 0.1 and below indicate barren area such as rock, sand etc., and values of 0.2 and higher represent vegetation such as shrub, grass, trees etc. In this study, an average value of 0.15 is set as the threshold to define the total landscape area within the case study city boundary. If the pixel value is higher than 0.15, the 1 square meter cell is the landscape (vegetation) area. Thereafter, the cells with NDVI value higher than 0.15 can be reclassified into unique value and summarized into each research unit (census block) through zonal statistics function in ArcGIS.

2. Calculation of \( \text{ET}_c \) and precipitation:

Evapotranspiration (\( \text{ET}_c \)) is the water consumed by plants without returning back to the sewer system and it represents the water lost from the soil through the combination of evaporation and plant transpiration (Allen et al., 1998; Romero, 2009). Actual turfgrass evapotranspiration is difficult to measure. Thus, meteorological data and computation models are utilized to estimate reference evapotranspiration (\( \text{ET}_o \)). \( \text{ET}_c \) is calculated through multiplying reference evapotranspiration (\( \text{ET}_o \)) by coefficient (\( K_c \)). The effect of different climate condition is reflected by \( \text{ET}_o \) and crop characters determines the \( K_c \) (Allen et al., 1998; Brown and Kopec, 2000). The calculation formula is written as follows:

\[
\text{ET}_c = K_c \times \text{ET}_o
\]

\( K_c \) is the single crop coefficient incorporates both crop transpiration and soil evaporation. In Nebraska, The dominant species is Kentucky bluegrass across the state,
followed by tall fescue then buffalograss, which belong to cool season turfgrass. Under mean maximum plant heights for non-stressed and well-managed condition, the single crop coefficient of cool season turfgrass is 0.9 for use with the FAO Penman-Monteith ET₀ (Allen et al., 1998).

ET₀ is calculated through REF-ET, a reference evapotranspiration calculation software for FAO and ASCE standardized equations developed by University of Idaho and Dr. Richard G. Allen. The input data for ET₀ calculation are downloaded from HPRCC (High Plain Regional Climate Center) and AWDN (Automated weather data network), and include time, max air temperature (F), min air temperature (F), average relative humidity (%), average wind speed (mile/hour), solar radiation (w/m²), precipitation (inches), anemometer height (m), temperature height (m), weather station elevation, and latitude and longitude (degrees). Additionally, some of the parameters are set as default, including the default day or night wind ratio (2), the vegetation height (0.12m), and the green fetch on the class A pan (1000m). The specific equation selected is ASCE Penman-Monteith Standardized form and the grass referenced ET₀ is selected. As Table 3.4 displayed, the ET₀ and ETc represent the average grass referenced evapotranspiration in three case cities and the actual evapotranspiration that calculated from ET₀ multiplied by crop coefficient (0.9). Additionally, the evapotranspiration increases from the east to west (City of Lincoln to Sidney).

<table>
<thead>
<tr>
<th>City</th>
<th>ET₀ (mm/day)</th>
<th>ETc (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincoln</td>
<td>6.88</td>
<td>6.19</td>
</tr>
<tr>
<td>Grand Island</td>
<td>7.19</td>
<td>6.47</td>
</tr>
<tr>
<td>Sidney</td>
<td>7.97</td>
<td>7.17</td>
</tr>
</tbody>
</table>
The meter records provided by case cities are different from each other. For example in the City of Lincoln, the data is collected every two months while the Grand Island and Sidney have monthly cycle. In this study, the actual evapotranspiration is calculated during the irrigation season (April 1st to October 31st) only, because the non-irrigation season evapotranspiration consumes no water from municipal water supply system.

3.4.4.2 Commercial, industrial and others (CIO) consumptive water use calculation

In this category, commercial and industrial areas have similar end uses as residential. The water is used in both indoor and outdoor activities. Besides commercial and industrial users, the water use activities of public schools, public offices, undeveloped land and others are divergent (Dziegielewski, 2000). For example, some schools have football fields that can consume much more water than the other water users during summer. However, these water users occupy only a few percent in this large category. Therefore, all water users are considered to have indoor water use and outdoor water use as commercial and industrial users for the purpose of analysis. If there is no extra water billed during summer, these water users are considered to have indoor water uses only. The CIO consumptive water use is composed of indoor consumptive water use and outdoor consumptive water use.

Indoor water use activities are more diverse for CIO. A purified water manufacture may have 90 percent consumptive water usage while a restaurant may only have 5 to 10 percent consumptive usage. Consumptive water use amount is hard to estimate due to the variety of users and behaviors. Therefore, 0.1 of total indoor water use
amount is adopted for Nebraska indoor consumptive water use amount estimation (Shaffer et al., 2007). This percentage is the median value according to the summarization of ninety studies of consumptive water use around the Great Lake Basin (Fanning, 2007; Shaffer et al., 2008; Shaffer et al., 2007). Though the climate conditions between the Great Lake Basin and Nebraska are different, the indoor water use activity shall be similar. In conclusion, the amount of indoor consumptive water use is ten percent of total indoor water use amount. There are also several industries with indoor discharge water use amount that is recorded by NPDES (National Pollutant Discharge Elimination System). NPDES permit program is managed by US EPA (Environment Protect Agency) to monitor the water pollution from both quality and quantity aspects (EPA, 2013).

In category of CIO, Amount of outdoor total water use and outdoor consumptive water use is calculated in the same way as residential outdoor total water use and outdoor consumptive water use. Indoor water use amount (IWU) could be calculated based on winter water usage (WWU), period from December 21st, 2009 to February 18th, 2010 in the City of Lincoln and from December 1st to February 1st in the City of Grand Island and City of Sidney. Outdoor water use amount (OWU) is the subtraction of indoor water usage (IWU) from total water usage.

The relationship between outdoor water use (OWU) and outdoor irrigation demand (OID) determines the CIO outdoor consumptive water use amount (COCWU).
The determination process is the same as residential outdoor consumptive water use. As Figure 3.7 displays, if outdoor water use amount is larger than outdoor irrigation demand, the irrigation demand part is used by plant (turfgrass) evapotranspiration and the retaining part of outdoor water use goes back to the urban environment. It means that the amount of OID is equal to the amount of COCWU. If outdoor irrigation demand is larger than outdoor water use, this indicates that all of the outdoor water use is consumed by plant (turfgrass) evapotranspiration, which equals COCWU.

The CIO outdoor irrigation demand (OID) is calculated the same way as residential outdoor irrigation demand, through crop coefficient method.

Therefore, the CIO consumptive water use amount is the sum of indoor consumptive water use amount and outdoor consumptive water use amount. Indoor consumptive water use amount is calculated based on empirical coefficient or monitored record. Calculation process of outdoor consumptive water use amount and residential consumptive water use a similar, which determined by actual outdoor water use and theoretical evapotranspiration.

**3.4.4.3 Open space consumptive water use calculation**

In this category, the agricultural water use within urban boundary is included. However, the agricultural space is often missing the water meter data within urban boundary and it considered same as the landscape (turfgrass) area. Indoor water use and indoor consumptive water use is considered both zero, though occasionally management warehouses locate within the open space.

Open space irrigation water uses include irrigation for a variety of landscape plant species (e.g. turfgrass, flowers, trees etc.). However, all of the plant species occur
irregularly except for turfgrass. We assume that the outdoor water use is the turfgrass irrigation at growing (irrigation) season and outdoor consumptive water use is determined by the actual outdoor water use and the theoretically required amount of water for evapotranspiration of landscape (turfgrass).

Most of the meter records have small amounts of water consumption during winter time. Therefore, it is assumed that all year water usage is for outdoor irrigation. The outdoor water usage equals total water usage.

Since the indoor consumptive water use is zero, the open space consumptive water use amount (OpCWU) equals the outdoor consumptive water use amount. The relationship between outdoor water use (OWU) and outdoor irrigation demand (OID) determines the real open space consumptive water use amount (OpCWU). As Figure 3.8 displays, if outdoor water use amount is larger than outdoor irrigation demand, the irrigation demand part is used by plant (turfgrass) evapotranspiration and the rest part of outdoor water use goes back to the urban environment. The open space consumptive water use (OpCWU) is equal to the irrigation demand (OID). If outdoor irrigation demand is less than outdoor water use amount, this indicates that all of the outdoor water use is consumed by turfgrass evapotranspiration, which equals to OpCWU.

Figure 3.8 Open space consumptive water use determination process
The outdoor irrigation demand (OID) is estimated through the same procedure as residential outdoor irrigation demand and CIO outdoor irrigation demand.

### 3.4.5 Statistical analyses

Bivariate correlation is calculated through SPSS (Statistical Package for the Social Sciences, SPSS Inc., Chicago, Illinois) to investigate the relationship between independent (e.g. population, housing units) and dependent (water usage, consumptive water usage) variables. This function examines the degree of relationship of two quantitative variables through Pearson correlation coefficient (Mertler and Vannatta, 2002). The values of the Pearson correlation coefficient (r, varies from -1 to 1) and P-value can be used to determine the strength of the relationships; the higher absolute value of r with less than 0.05 P-value, the stronger relationship exists between two variables. Therefore, every possible independent and dependent variable can be examined by bivariate correlation and the result is used as reference for linear regression analysis. For example, if the Pearson correlation coefficient is 0.9 between population and residential total water usage, these two parameters are the variables for linear regression models.

A linear ordinary least square (OLS) regression model is used to estimate the correlation between influential factors (e.g. population, total landscape area) and water use amount (total water use and consumptive water use amount) within blocks through SPSS and Microsoft Excel. The model can provide a more accurate understanding of statistical relationship between variables. Successful understanding of these two datasets establishes an impetus foundation that enhances the knowledge of drivers of small scale water use and consumptive water use within urban boundary.
3.4.5.1 Residential water use

Residential consumptive water use is calculated through outdoor irrigation so that total landscape area is the only driving force in this study. Therefore, it is hypothesized that the larger the total landscape area contained within each block, the higher the consumptive water use in the analysis unit.

Total water use is much more complicated, which involves human activity, customs, water saving technologies etc. Based on literature review and data availability, this study makes a comprehensive investigation of each possible influential factor into this linear regression analysis (Table 3.5). The hypothesis is that population, housing units, landscape and block area are positively correlated to total water use amount. Housing density and population density might be negatively correlated to total water use amount in the analysis unit. In addition to the block level factors provided by census 2010 summary file 1, American Community Survey (2006-2010) provides more social economic indexes on block group level as listed in Table 3.4. The hypothesis is that with the increasing of these indexes, the total water use amount is higher.

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Independent: Block level</th>
<th>Independent: Block group level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumptive water use (2010, m³)</td>
<td>Total landscape area (m²)</td>
<td>Average income (dollars)</td>
</tr>
<tr>
<td>Water use (2010, m³)</td>
<td>Population</td>
<td>Rooms</td>
</tr>
<tr>
<td></td>
<td>Housing units</td>
<td>Values</td>
</tr>
<tr>
<td></td>
<td>Block area (m²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total landscape area (m²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Population density (person/acre)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Housing density (Units/acre)</td>
<td></td>
</tr>
</tbody>
</table>
### 3.4.5.2 Commercial, industrial and others (CIO) water use

CIO consumptive water use is calculated based on both indoor and outdoor consumptive water usage. Therefore, the hypothesis is that total landscape area, building area and block area are positively correlated to total water use amount and consumptive water use amount based on the literature and available data. There is no block group level analysis in CIO category.

Table 3.6 CIO influential factors

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Independent: Block level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumptive water use (2010, m³)</td>
<td>Block area (m²)</td>
</tr>
<tr>
<td></td>
<td>Building area (m²), City of Lincoln only</td>
</tr>
<tr>
<td></td>
<td>Total landscape area (m²)</td>
</tr>
<tr>
<td>Total water use (2010, m³)</td>
<td>Block area (m²)</td>
</tr>
<tr>
<td></td>
<td>Building area (m²), City of Lincoln only</td>
</tr>
<tr>
<td></td>
<td>Total landscape area (m²)</td>
</tr>
</tbody>
</table>

### 3.4.5.3 Open space water use

Open space consumptive water use is calculated based on outdoor consumptive water usage only. Open space outdoor water usage is equal to total water usage. Therefore, the hypothesis is that total landscape area and block area are positively correlated to open space total water use amount and consumptive water use amount based on the literature and available data. There is no block group level analysis in this category (Table 3.7).

Table 3.7 Open space influential factors

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Independent: Block level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumptive water use (2010, m³)</td>
<td>Block area (m²)</td>
</tr>
<tr>
<td></td>
<td>Total landscape area (m²)</td>
</tr>
<tr>
<td>Total water use (2010, m³)</td>
<td>Block area (m²)</td>
</tr>
<tr>
<td></td>
<td>Total landscape area (m²)</td>
</tr>
</tbody>
</table>
3.4.6 Spatial analyses

With the attached total water usage and consumptive water usage in each analysis unit (census block), the next step is to analyze spatial pattern of total water use and consumptive water use distribution within sample cities. Firstly, the spatial pattern of high and low water use blocks of total water use and consumptive water use can be visually assessed. Then Global Moran’s I and Getis-Ord Gi* are adopted to quantify and identify the scale of spatial dependence in water use and consumptive water use (House-Peters, 2010). Moran’s I, which can be calculated through ArcGSI, is a global measure of spatial autocorrelation with possible values ranging from -1 to 1 and 0 means a perfect random distributed (O'Sullivan and Unwin, 2002). Getis-Ord Gi* is used to recognize the hot spots and cold spots (O'Sullivan and Unwin, 2002).
Chapter 4 Results

4.1 Statistical results

4.1.1 Statistics

4.1.1.1 Total water use and consumptive water use of three categories

Residential water use is commonly considered as the most important consumer within urban boundaries (Endter - Wada et al., 2008). In this study, the various water users are divided into three major categories: residential, CIO (commercial, industrial and others), and open space. Residential water use consumes more water than the other two categories. Table 4.1 is a summary of the water use and consumptive water use data that can meet the analysis criteria, which means that this table does not reflect the actual water use condition in each case city. In the City of Lincoln and Grand Island, the residential water use percentages reaches 60 percent. This explains why the water conservation technology is commonly developed for residential customers and landscape irrigation devices. Only 42 percent of residential water use occurs in the Sidney. A 700 acres agricultural land within the Sidney consumes a large amount of the water used within the city. The percentages of open space total water usage from the City of Lincoln compared to the Sidney illustrate the population density of each city.

Considering the geographic location and climate condition of each city (from east to west: City of Lincoln, Grand Island, and Sidney), these three cities show increasing trends of consumptive percentages in residential areas. The consumptive water use percentage of the residential category changes from 31(east: City of Lincoln) to 57 (west: Sidney). The higher water demand leads to a higher consumptive percentage.
Additionally, the open space consumptive water use percentages are 100 percent in the three case cities. The irrigation management strategies in these three cities results in almost no waste of turfgrass irrigation.

### Table 4.1 Total water use and consumptive water use in three categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Total water use (m³)</th>
<th>Total Water use percentage</th>
<th>Consumptive water use (m³)</th>
<th>Consumptive water use/ Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>City of Lincoln</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>20,662,270</td>
<td>63%</td>
<td>6,441,145</td>
<td>31%</td>
</tr>
<tr>
<td>CIO</td>
<td>11,525,289</td>
<td>35%</td>
<td>3,088,110</td>
<td>27%</td>
</tr>
<tr>
<td>Open Space</td>
<td>681,993</td>
<td>2%</td>
<td>681,374</td>
<td>100%</td>
</tr>
<tr>
<td>Overall</td>
<td>32,869,552</td>
<td>100%</td>
<td>10,210,629</td>
<td>31%</td>
</tr>
<tr>
<td><strong>Grand Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>5,463,336</td>
<td>65%</td>
<td>1,925,622</td>
<td>35%</td>
</tr>
<tr>
<td>CIO</td>
<td>2,416,819</td>
<td>29%</td>
<td>466,196</td>
<td>19%</td>
</tr>
<tr>
<td>Open Space</td>
<td>539,966</td>
<td>6%</td>
<td>539,754</td>
<td>100%</td>
</tr>
<tr>
<td>Overall</td>
<td>8,420,121</td>
<td>100%</td>
<td>2,931,572</td>
<td>35%</td>
</tr>
<tr>
<td><strong>Sidney</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>424,764</td>
<td>42%</td>
<td>241,892</td>
<td>57%</td>
</tr>
<tr>
<td>CIO</td>
<td>203,886</td>
<td>20%</td>
<td>53,343</td>
<td>26%</td>
</tr>
<tr>
<td>Open Space</td>
<td>377,481</td>
<td>38%</td>
<td>377,425</td>
<td>100%</td>
</tr>
<tr>
<td>Overall</td>
<td>1,006,131</td>
<td>100%</td>
<td>672,660</td>
<td>67%</td>
</tr>
</tbody>
</table>

Note: this table does not reflect the actual water use condition in each city and it is summarized from the data that could meet the analysis criteria.

#### 4.1.1.2 Per capita total water use and consumptive water use

Since residential housing is the dominant water consumer in each city, this study made an extra analysis of the driving forces and specific activities of residential water use. Residents’ daily water need (e.g. shower, faucets, drinking etc.) and landscape irrigation are the two major components of water use activities. From table 4.2, the per capita total water usage and consumptive water usage are increasing from the City of Lincoln to Sidney. However, the per capita total landscape area is decreasing. The analysis in this study illustrates that the consumptive water use is determined by landscape water need and climate condition. The opposite trend of per capita consumptive water usage and per capita total landscape area proves the climate variation between these cities. From east to
west of Nebraska, the precipitation is decreasing and the humidity tends to be lower in the west. Therefore, the water demand for evapotranspiration has a larger effect than the area of irrigation. These facts lead to the conclusion that the general climate condition and population are the most important determinant factors for residential water use.

According to USGS investigation survey (Kenny, 2012), a 21 sample cities survey shows that the residential per capita water use ranges from 15,695 to 64,605 gallons per person per year in the United States. The result is similar in this study.

<table>
<thead>
<tr>
<th>Cities</th>
<th>Per capita Total Water Usage (gallons/person per year)</th>
<th>Per capita Consumptive water usage (gallons/person per year)</th>
<th>Per capita landscape area (m²/person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Lincoln</td>
<td>33,814</td>
<td>11,095</td>
<td>426</td>
</tr>
<tr>
<td>Grand Island</td>
<td>47,023</td>
<td>14,794</td>
<td>367</td>
</tr>
<tr>
<td>Sidney</td>
<td>60,760</td>
<td>32,229</td>
<td>360</td>
</tr>
</tbody>
</table>

Note: these data are summarized from analyzed data in this study, the analyzed population in the City of Lincoln is 172,047 (Census population, 2010: 258,381), 32,142 in the Grand Island (Census population, 2010: 48,520), and 1,861 in the Sidney (Census population, 2010: 6,758).

4.1.2 Linear regression models

4.1.2.1 Residential water use

As the methods section stated, bivariate correlation examines the degree of relationship between potential determinant factors and dependent variable of total water usage. Residential consumptive water usage correlates with total landscape area only. If the Pearson correlation coefficient is higher than 0.5, there is usually a significant relationship between the two variables (http://statistics-help-for-students.com/). The Pearson correlation coefficients of total population, total housing units, block acres,
vegetation area (total landscape area, $m^2$), building footprints (City of Lincoln only) and total water usage are higher than 0.5 and the P-value is less than 0.01. The coefficient of housing unit density and population density are lower than 0.1. Therefore, the strongest predictors of residential total water use are total population, total housing units, block acres and vegetation area (Appendix 1).

Thereafter, linear ordinary least square (OLS) regression model is used to investigate the accurate mathematical relationship between total population, total housing units, block acres and vegetation area with residential total water usage. However, the collinearity diagnostics function shows that the multicollinearity exists between total population, total housing units and block acres. Ultimately, the observed values for 2010 annual residential total water usage are regressed against the total population and vegetation area to determine the best-fit relationship. The empirical relationships are as follows (variables are statistically significant at the 0.01 level):

City of Lincoln:

Residential total water usage (cubic meters of annual use per census block)

\[ = -24 + 106 \times \text{Population} (\text{individuals per census block}) + 0.049 \times \text{Vegetation area} (\text{square meters per census block}) \]

\[ R^2 = 0.83, \, P < 0.01, \, N=2720 \, (\text{census blocks}) \]

Grand Island:

Residential total water usage

\[ = -219 + 150 \times \text{Population} + 0.081 \times \text{Vegetation area} \]

\[ R^2 = 0.83, \, P < 0.01, \, N=1253 \, (\text{census blocks}) \]

Sidney:
Residential total water usage

\[ = -1309 + 172 \times \text{Population} + 0.46 \times \text{Vegetation area} \]

\[ R^2 = 0.83, \ P < 0.01, \ N=102 \text{ (census blocks)} \]

Combination of three cities:

Residential total water usage

\[ = 271 + 106 \times \text{Population} + 0.057 \times \text{Vegetation area} \]

\[ R^2 = 0.81, \ P < 0.01, \ N=4075 \text{ (census blocks)} \]

These linear regression models illustrate that per capita water use amount and vegetation area water use are increasing from east to west (City of Lincoln to Sidney). It is explained by the climate variation and population density difference among them. From the future application perspective, the population data is accurate and reliable, and is conducted every ten years by US census. Vegetation area is developed based on remote sensing image using the NDVI index. The independent variables are accurate and achievable without heavy labor input requirement. First three models could be potentially used to predict case cities’ future total water demand and applied to surrounding climate similar regions for water resources management. The last combined model could be potentially used to estimate other cities residential water usage in Nebraska.

The Pearson correlation coefficients of residential consumptive water usage and total landscape area are lower than 0.7 in the City of Lincoln and Grand Island though they are significantly correlated. Ultimately, there is no significant linear relationship found between residential consumptive water usage and total landscape area in these two case cities. However, the Pearson correlation coefficient is 0.85 and the P-value is less
than 0.01 in Sidney. Therefore, the regression model is identified in the Sidney. The empirical relationship is as follow:

Residential consumptive water usage (cubic meters of annual use per census block)

\[
\text{Residential consumptive water usage} = -259.632 + 0.522 \times \text{Vegetation area (square meters per census block)}
\]

\[R^2 = 0.72, \ P < 0.01, \ N=102 \text{ (census blocks)}\]

The reasons why the relationship is not consistent among those case cities could be the accuracy of NDVI index and the threshold, variation of irrigation management and landscape species. Since the NDVI threshold in this study can tell the difference between the vegetation area and others, the tree canopy makes the delineation of turfgrass more difficult. Some of the barren ground and roofs might be considered as vegetation area since the tree canopy over their top. Also, trees can affect the evapotranspiration calculation due to the shade effect on turfgrass and the groundwater abstraction from their root. This study makes a general estimation of vegetation area due to limits on both time and labor. The various irrigation habitat and devices of different residents determine the efficiency of irrigation and some garden plants, vegetable flowers, and private pools can interfere with the relationship between consumptive water usage and total landscape area.

### 4.1.2.2 Commercial, industrial and others (CIO) water use

Both CIO total water use and consumptive water use failed to build relationship with the potential independent variables of block acres and total landscape area, (Appendix 2). Scholars have explored the commercial and industrial end uses of water based on sample studies and found statistical relationships between influential factors (e.g.
number of employees) and water use amount (Dziegielewski, 2000; EPA, 2009; Kim and McCuen, 1979; Mercer and Morgan, 1974; Morales, 2011; Morales, 2009). However, the existing studies are mainly sample studies and survey or historical water use. Confidentiality has always been a barrier for this category of studies. Though the data at the street level is available from the US census and the Department of Labor Statistics, the procedure to analyze those data is very time consuming and labor intensive. Therefore, based on the available data online, there is no statistical relationship found in this study.

The commercial and industrial water uses are relatively consistent through the time. The historical data and water use category based on land use can provide foundation for future analysis and studies.

4.1.2.3 Open space water use

According to the stated results, open space total water usage is equal to consumptive water usage. Independent variables are block area and total landscape area. The Pearson correlation coefficients show the relationship of both independent variables. However, the collinearity diagnostics function shows the multicollinearity between block area and total landscape area. Therefore, based on the consumptive water use calculation method designed in this study, the linear regression analysis is conducted between open space total water usage (consumptive water usage) and total landscape area. The following equations are (variables are statistically significant at the 0.01 level):  

City of Lincoln:

Open space total water usage/consumptive water usage (cubic meters of annual use per census block)
= -7880.220 + 0.207 * Vegetation area (square meters per census block)

\[ R^2 = 0.79, \ P < 0.01, \ N=49 \) (census blocks)

Grand Island:

Open space total water usage/consumptive water usage

= 1921.712 + 0.084 * Vegetation area

\[ R^2 = 0.61, \ P < 0.01, \ N=39 \) (census blocks)

Sidney:

Open space total water usage/consumptive water usage

= 1240.438 + 0.103 * Vegetation area

\[ R^2 = 0.57, \ P < 0.01, \ N=19 \) (census blocks)

Combination of three cities:

Open space total water usage/consumptive water usage

= -3623 + 0.141 * Vegetation area

\[ R^2 = 0.63, \ P < 0.01, \ N=107 \) (census blocks)

4.2 Spatial analysis results

4.2.1 City of Lincoln

Global Moran’s I is a commonly accepted index that indicate the spatial cluster and dispersion (Chang, 2010). A positive index value illustrates a clustering trend while a negative index value illustrates a dispersion (ArcGIS resource help). The z-score and p-value explains the statistical significance, which is similar to regression models. As Figure 4.1 displays, a z-score of 45.69 and a P-value less than 0.01 indicate that “there is less than 1% likelihood that this cluster pattern could be the result of random chance”. 
The z-score scale has its corresponding P-value scale to indicate the clustering or dispersing condition.

CIO consumptive water use, residential total water use and consumptive water use are clustered. (Table 4.3) In order to investigate where exactly the clusters occurs in each case city. Getis-Ord Gi* function is calculated through ArcGIS (Figure 4.3, 4.5, 4.7). The Z-score could indicate the hot spots and cold spots distributed within the sample cities. Hot spots (red) are clusters of high water usage blocks. Cold spots (blue) are clusters of low water usage blocks.

In the City of Lincoln, the suburban residential area near the city boundary uses more water than the surrounding downtown residential area (Figure 4.2). The blocks of higher total water use cluster in the southern suburban areas (Figure 4.3). The blocks of higher residential consumptive water use tend to be closer to the city boundary (Figure 4.4). This is illustrated by the increasing total landscape area from the core to the edge of the city. The blocks of lower consumptive water use cluster in the south of downtown and the northern suburban areas while the higher consumptive water use blocks cluster in the southern suburban areas (Figure 4.5).

CIO water use blocks are distributed randomly in the city. However, higher CIO consumptive water use blocks cluster in the north of city and south of 9th street (Figure 4.6, 4.7, 4.8).

Open space areas analyzed in this study are apparently less than the amount present in the city. This is because of the lack of meter data in these blocks (Figure 4.9, 4.10).
Figure 4.1 Interpretation of Global Moran’s I index

Table 4.3 Global Moran’s I index for the City of Lincoln

<table>
<thead>
<tr>
<th>City of Lincoln</th>
<th>Total Water Usage</th>
<th>Consumptive Water Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global Moran’s I</td>
<td>Z-score</td>
</tr>
<tr>
<td>Residentia l</td>
<td>0.133</td>
<td>45.68</td>
</tr>
<tr>
<td>CIO</td>
<td>-0.007</td>
<td>-</td>
</tr>
<tr>
<td>Open Space</td>
<td>0.011</td>
<td>0.454</td>
</tr>
</tbody>
</table>

Given the z-score of 45.69, there is a less than 1% likelihood that this clustered pattern could be the result of random chance.
Figure 4.2 City of Lincoln: residential total water use distribution, by census block
Figure 4.3 City of Lincoln: residential total water use clusters distribution, by census block

Std.Dev. stands for standard deviation
Figure 4.4 City of Lincoln: residential consumptive water use distribution, by census block
Figure 4.5 City of Lincoln: residential consumptive water use clusters distribution, by census block
Figure 4.6 City of Lincoln: CIO total water use distribution, by census block
Figure 4.7 City of Lincoln: CIO consumptive water use distribution, by census block
Figure 4.8 City of Lincoln: CIO consumptive water use clusters distribution, by census block
Figure 4.9 City of Lincoln: open space total water use distribution, by census block
Figure 4.10 City of Lincoln: open space consumptive water use distribution, by census block
4.2.2 Grand Island

Based on the interpretation of Figure 4.1, in the Grand Island, residential total water use and consumptive water use are, overall, clustered within the Grand Island (Table 4.4). In order to investigate where exactly the clusters occurs in the Grand Island, the Getis-Ord Gi* function is calculated through ArcGIS (Figure 4.12, 4.14).

Table 4.4 Global Moran’s I index for the Grand Island

<table>
<thead>
<tr>
<th>Grand Island</th>
<th>Total Water Usage</th>
<th>Consumptive Water Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global Moran’s I</td>
<td>Z-score</td>
</tr>
<tr>
<td>Category</td>
<td>Index</td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>0.139</td>
<td>3.112</td>
</tr>
<tr>
<td>CIO</td>
<td>0.014</td>
<td>0.318</td>
</tr>
<tr>
<td>Open Space</td>
<td>0.145</td>
<td>0.707</td>
</tr>
</tbody>
</table>

In the Grand Island, the western and southern suburban residential area near the city boundary use more water than the surrounding downtown residential area (Figure 4.11). The blocks of higher total water use within these areas as well (Figure 4.12). The blocks of higher residential consumptive water use tend to be closer to the city boundary (Figure 4.13). The general distribution and cluster condition of consumptive water use are similar to residential total water use (Figure 4.13, 4.14).

CIO and open space water use blocks are distributed randomly in the city (Figure 4.15, 4.16, 4.17, 4.18).
Figure 4.11 Grand Island: residential total water use distribution, by census block
Figure 4.12 Grand Island: residential total water use clusters distribution, by census block
Figure 4.13 Grand Island: residential consumptive water use distribution, by census block
Figure 4.14 Grand Island: residential consumptive water use clusters distribution, by census block
Figure 4.15 Grand Island: CIO total water use distribution, by census block
Figure 4.16 Grand Island: CIO consumptive water use distribution, by census block
Figure 4.17 Grand Island: open space total water use distribution, by census block
Figure 4.18 Grand Island: open space consumptive water use distribution, by census block
**4.2.3 Sidney**

Based on the interpretation of Figure 4.1, residential total water use and consumptive water use are clustered within the Sidney (Table 4.5). However, the clusters of residential blocks are not as obvious as that in the city of Lincoln and Grand Island. Therefore, there is no Getis-Ord Gi*’s calculation for the Sidney.

<table>
<thead>
<tr>
<th>Category</th>
<th>Total Water Usage</th>
<th>Consumptive Water Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global Moran’s I Index</td>
<td>Z-score</td>
</tr>
<tr>
<td>Residential</td>
<td>0.116</td>
<td>5.202</td>
</tr>
<tr>
<td>CIO</td>
<td>-0.111</td>
<td>-2.325</td>
</tr>
<tr>
<td>Open Space</td>
<td>0.269</td>
<td>1.678</td>
</tr>
</tbody>
</table>

In Sidney, the outbound residential areas use more water than the surrounding downtown residential areas (Figure 4.19). The blocks of higher residential consumptive water use tend to be closer to the outbound of the whole residential area (Figure 4.20). This is illustrated by the increasing total landscape area from the core to the edge within the city.

CIO total water use blocks are distributed spatially dispersed and open space water use blocks are distributed randomly in the city (Figure 4.21, 4.22, 4.23, 4.24). The huge block in the open space category is agricultural use within the city boundary.
Figure 4.19 Sidney: residential total water use distribution, by census block
Figure 4.20 Sidney: residential consumptive water use distribution, by census block
Figure 4.21 Sidney: CIO total water use distribution, by census block
Figure 4.22 Sidney: CIO consumptive water use distribution, by census block
Figure 4.23 Sidney: open space total water use distribution, by census block
Figure 4.24 Sidney: open space consumptive water use distribution, by census block
Chapter 5 Conclusions and Discussions

5.1 Key findings and discussions

5.1.1 Consumptive water use calculation

This study develops a novel methodology to estimate the amount of consumptive water use in three Nebraska cities. Based on end uses of water (Mayer, 1999), it has been applied to three major water use categories within urban boundaries: residential, CIO (commercial, industrial and others), and open space. The first urban consumptive water use calculation method in Nebraska is delivered and a new parameter for analyzing the urban water supplies and uses in the case cities is provided.

5.1.2 Statistical analyses

The statistical analyses of total water use and consumptive water use and their driving force are conducted through the linear regression models. Significant results are found in two categories of water use: residential and open space. Conversely, the linear connection between consumptive water use within categories of residential and CIO is poor in this study.

The residential total water usage is predominantly explained by population and total landscape area ($R^2 = 0.83$, P<0.01). With the help of regression models, population and total landscape area can be used to predict consumptive water usage. In addition, housing units, building footprints (City of Lincoln only) and block area correlate well with the total water usage. In this study domain, the effect of total landscape area on total water usage increased generally from east to west in Nebraska. Considering that the major herbaceous plant in the yard is cool season turfgrass, the climate condition could
be a dominant determinants for the amount of water needed for outdoor irrigation and total water use during summer.

The residential total water usage is predominantly explained by population and total landscape area, where the two correlated coefficients equal to 0.83. With the help of regression models, population and total landscape area can be used to predict consumptive water usage. In addition, housing units, building footprints (only in the city of Lincoln), and block area correlate well with the total water usage. In our study domain, the effect of total landscape area on total water usage increases generally from east to west in Nebraska. Considering that the major herbaceous plant in the yard is cool season turfgrass, the climate condition could be a dominant determinant for the outdoor irrigation and total water use during summer.

The total water use of open space, which equals to consumptive water use, can be linearly correlated to the total landscape area. The correlated coefficients ($R^2$) vary through three case cities. One of the possible reasons is the sample size of blocks differs: 19 for Sidney, 39 for Grand Island, and 49 for Lincoln.

Since the consumptive water use is calculated based on the total landscape area, it is unexpected when the weak connection among them is showed. Two potential reasons might interfere with the regression analyses results. First, the uncertainties in outdoor water usage have significant effects on consumptive water use determination. Individual irrigation habit, various water activities, and the consumption of consistent indoor water use throughout the year make it difficult to accurately calculate the actual amount of outdoor water usage. For instance, the water usage of showers and washing machines are likely to differ during summer and winter, which leads to a larger estimation of outdoor
water usage and consumptive water usage. Second, the delineation of total landscape area is from all vegetation cover including both trees and turfgrasses while the consumptive water use calculation is only based on turfgrass evapotranspiration. The insufficient evapotranspiration calculation for other plants (trees, scrubland etc.) could weaken the connection between total landscape area and the amount of consumptive water use.

5.1.3 Spatial analyses

The spatial analyses results indicate that the clustering of higher water consumer does exist in the residential area of these cities. The suburban residential area has a higher total and consumptive water use amount than central part of city. Two potential main reasons are proposed: first reason is that suburban areas possess more yard area with turfgrass than central urban areas, resulting in the increasing amount of both total water demand and consumptive use. The second reason is that central part of city is more likely to have a mature tree canopy than suburban communities, therefore reducing the water need from turfgrass evapotranspiration (Chang, 2010). CIO (commercial, industrial and others) and open space water use does not display a clear cluster or disperse pattern, which is mostly caused by their limited blocks’ number within the cities.

This study provides the first exploration of calculating urban consumptive water use and analyzing urban water use statistically and spatially. With the pace of growing urban population and physical urban boundary, these results will offer a better understanding of urban water use in Nebraska and potentially a fundamental study for future urban water resources management. The relationship among residential total water use, population and total landscape area is similar to the established in previous studies in other states. Besides, population has a lager effect on residential total water usage than
total landscape area while the increasing trend of total landscape area from core part of city to the suburban does accompany with higher total and consumptive water usage. Therefore, water resource and land use planners should consider the water conservation from two ways. First is to improve the indoor water use efficiency. Remodeled or redesigned water saving utilities could account for around 50-70 percent of total residential water use. The suburban water supply and need can be stressed in the future, especially during summer (Chang, 2010). New development with higher building density and less total landscape area should be recommended. Planting more native vegetation is another way to increase the resilience to the drought condition and reduce the outdoor water consumption.

5.2 Limitations and future studies

There are five limitations in this study. Firstly, ignoring the variation of water use activities, this thesis assumes that indoor water use is consistent during four seasons. Secondly, leakages during the water supply and discharge process are disregarded in the analysis process. Thirdly, irrigation season is assumed during April 1st to October 31st while actual irrigation period may vary, which depends on irrigation awareness and habits. Fourthly, there is a lack of separation of turfgrass and trees for land cover classification and evapotranspiration calculation in this study. Fifthly, the mixed use area in single block is not reclassified into the three major land use categories. They are considered as single use based on the dominant land use type according to each municipal zoning code or land use classification standard. Lastly, there is a lack of regression models for the category of commercial, industrial and others in this study.
Future research can be done to achieve a more elaborate calculation method of urban consumptive water use from outdoor water use perspective. For instance, a study with large samples can be performed including measuring the actual outdoor water use, monitoring the data of the leaks during the water use process, and recording the actual outdoor irrigation period. In addition to the sample study, a more detailed delineation of land cover and evapotranspiration calculation could be utilized in the future study, such as separation of trees and turfgrass. Previous literatures has found the regression relationships existing between CIO (commercial, industrial and others) water use with specific classification, number of employees and scale or tax information (e.g. The North American Industry Classification System). Similar relationship might exist in Nebraska as well.

Moreover, this study can be applied and extended to larger urban area in Nebraska as long as the data is available. The applicability and generalizability of the findings can be re-examined throughout the state or other US cities. Additionally, more sophisticated models may be developed and utilize the water record in multiple years. A comparison between relatively arid years and humid years is necessary and long-term climate data can be incorporated in water use study for integrated water management.
References


Brown, P., and Kopec, D., 2000, Converting reference evapotranspiration into turf water use, College of Agriculture and Life Sciences, University of Arizona (Tucson, AZ).


Dziegielewski, B., 2000, Commercial and institutional end uses of water., American Water Works Association


—, 2009, Water efficiency in the commercial and institutional sector: considerations for a watersense program.


Harivandi, A.B.J.H.J.H.M.S.D., 2009, Managing turfgrass during drought, ANR Publication 8395, University of California Division of Agricultural and Natural Resources.


Mike, L., 2012, Nebraska urban population totals by county Volume 2013, Nebraska Department of Economic Development.


Romero, C., Michael DD., 2009, Turfgrass and ornamental plant evapotranspiration and crop coefficient literature review.
SWFWMD, 2006, Regional water supply plan., in District, S.F.W.M., ed.
Zazueta, F.S., 2000, Reduced irrigation of St. Augustinegrass turfgrass in the Tampa Bay Area, University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS.
Appendix 1 Pearson Correlation Coefficients of Residential Water Use

1.1 Pearson Correlation Coefficients of the City of Lincoln

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total population</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Total housing units</td>
<td></td>
<td></td>
<td>.929(**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Block area (acres)</td>
<td>.559(**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Total landscape area(m²)</td>
<td>.462(**)</td>
<td>.401(**)</td>
<td>.978(**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Building footprint(m²)</td>
<td>.829(**)</td>
<td>.735(**)</td>
<td>.747(**)</td>
<td>.660(**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Housing density</td>
<td>.222(**)</td>
<td>.355(**)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Population density</td>
<td>.271(**)</td>
<td>.278(**)</td>
<td>.215(**)</td>
<td>.235(**)</td>
<td>.070(**)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Total water use</td>
<td>.899(**)</td>
<td>.834(**)</td>
<td>.655(**)</td>
<td>.564(**)</td>
<td>.886(**)</td>
<td>.078(**)</td>
<td>.078(**)</td>
<td></td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed). Sample size: 2720 blocks.
### 1.2 Pearson Correlation Coefficients of the Grand Island

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total population</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>.916(</strong>)</td>
</tr>
<tr>
<td>2. Total housing units</td>
<td><strong>.916(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3. Block area (acres)</td>
<td><strong>.735(</strong>)</td>
<td><strong>.654(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4. Total landscape area (m²)</td>
<td><strong>.711(</strong>)</td>
<td><strong>.619(</strong>)</td>
<td><strong>.954(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5. Housing density</td>
<td><strong>.097(</strong>)</td>
<td><strong>.230(</strong>)</td>
<td><strong>.230(</strong>)</td>
<td><strong>.232(</strong>)</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6. Population density</td>
<td><strong>.098(</strong>)</td>
<td><strong>.051</strong></td>
<td><strong>.281(</strong>)</td>
<td><strong>.273(</strong>)</td>
<td><strong>.738(</strong>)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>7. Total water use</td>
<td><strong>.895(</strong>)</td>
<td><strong>.822(</strong>)</td>
<td><strong>.830(</strong>)</td>
<td><strong>.757(</strong>)</td>
<td><strong>-.060(*)</strong></td>
<td><strong>-.113(</strong>)</td>
<td>1</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

Sample size: 1253 blocks.

### 1.3 Pearson Correlation Coefficients of the Sidney

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total population</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>.912(</strong>)</td>
</tr>
<tr>
<td>2. Total housing units</td>
<td><strong>.912(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3. Block area (acres)</td>
<td><strong>.661(</strong>)</td>
<td><strong>.538(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4. Total landscape area (m²)</td>
<td><strong>.664(</strong>)</td>
<td><strong>.539(</strong>)</td>
<td><strong>.928(</strong>)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5. Housing density</td>
<td><strong>.470(</strong>)</td>
<td><strong>.630(</strong>)</td>
<td>-0.155</td>
<td>-0.141</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6. Population density</td>
<td><strong>.547(</strong>)</td>
<td><strong>.598(</strong>)</td>
<td>-0.118</td>
<td>-0.099</td>
<td><strong>.938(</strong>)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>7. Total water use</td>
<td><strong>.839(</strong>)</td>
<td><strong>.672(</strong>)</td>
<td><strong>.800(</strong>)</td>
<td><strong>.824(</strong>)</td>
<td>0.05</td>
<td>0.103</td>
<td>1</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed); Sample size: 102 blocks.
## Appendix 2 Pearson Correlation Coefficients of Commercial, Industrial and Others (CIO) Water Use

### 2.1 Pearson Correlation Coefficients of the City of Lincoln

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Block area (acres)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Building footprint (m²)</td>
<td>.609(**)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Total landscape area (m²)</td>
<td>.985(**)</td>
<td>.549(**)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Consumptive water use</td>
<td>.390(**)</td>
<td>.488(**)</td>
<td>.383(**)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5. Total water use</td>
<td>.122(**)</td>
<td>.310(**)</td>
<td>.104(**)</td>
<td>.714(**)</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 624 blocks.

### 2.2 Pearson Correlation Coefficients of the Grand Island

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Block area (acres)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Total landscape area (m²)</td>
<td>.781(**)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Consumptive water use</td>
<td>0.021</td>
<td>0.038</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4. Total water use</td>
<td>-0.001</td>
<td>0.004</td>
<td>.944(**)</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 405 blocks.
### 2.3 Pearson Correlation Coefficients of the Sidney

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Block area (acres)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Total landscape area (m²)</td>
<td>.985(**)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Consumptive water use</td>
<td>0.106</td>
<td>-0.014</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4. Total water use</td>
<td>-0.069</td>
<td>-0.061</td>
<td>.444(**)</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 35 blocks.
Appendix 3 Pearson Correlation Coefficients of Open Space Water Use

3.1 Pearson Correlation Coefficients of the City of Lincoln

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Block area (acres)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2. Total landscape area(m²)</td>
<td>.997(**)</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3. Consumptive water use</td>
<td>.887(**)</td>
<td>.891(**)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4. Total water use</td>
<td>.887(**)</td>
<td>.891(**)</td>
<td>1.000(**)</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 49

3.2 Correlations of the Grand Island

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
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<td>1. Block area (acres)</td>
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<td>2. Total landscape area(m²)</td>
<td>.972(**)</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3. Consumptive water use</td>
<td>.715(**)</td>
<td>.789(**)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4. Total water use</td>
<td>.715(**)</td>
<td>.789(**)</td>
<td>1.000(**)</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 39

3.3 Correlations of the Sidney

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1. Block area (acres)</td>
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</tr>
<tr>
<td>2. Total landscape area(m²)</td>
<td>.945(**)</td>
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<td>3. Consumptive water use</td>
<td>.683(**)</td>
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<tr>
<td>4. Total water use</td>
<td>.683(**)</td>
<td>.752(**)</td>
<td>1.000(**)</td>
<td>1</td>
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</table>

** Correlation is significant at the 0.01 level (2-tailed); sample size: 19.
Appendix 4 Illustration of Shapfiles’ Attributes Table Titles

<table>
<thead>
<tr>
<th>Title Name</th>
<th>Explanation</th>
<th>Sources</th>
<th>Notes</th>
</tr>
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<td>GIS ID number</td>
<td>Esri</td>
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</tr>
<tr>
<td>Shape *</td>
<td>Polygon</td>
<td>Esri</td>
<td></td>
</tr>
<tr>
<td>GEOID10</td>
<td>census ID</td>
<td>US census</td>
<td></td>
</tr>
<tr>
<td>TAPERSONS</td>
<td>Total person</td>
<td>US census</td>
<td>Residential only</td>
</tr>
<tr>
<td>TAHOUSING</td>
<td>Total housing units</td>
<td>US census</td>
<td>Residential only</td>
</tr>
<tr>
<td>AHS</td>
<td>Average household size</td>
<td>Calculation</td>
<td>TAPERSONS/ TAHOUSING, Residential only</td>
</tr>
<tr>
<td>Landuse</td>
<td>LUCODE(land use code)</td>
<td></td>
<td>1-residential, 2-CIO, 3-open</td>
</tr>
<tr>
<td>Acres</td>
<td>Block area</td>
<td>Esri calculation</td>
<td>US Acres</td>
</tr>
<tr>
<td>Sqm</td>
<td>Block area</td>
<td>Esri calculation</td>
<td>square meters</td>
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<tr>
<td>Count_WM</td>
<td>Water meter numbers</td>
<td>City of Lincoln</td>
<td>Geocoding result</td>
</tr>
<tr>
<td>X</td>
<td>Centroid Coordinate</td>
<td>Esri Calculation</td>
<td>US feet</td>
</tr>
<tr>
<td>Y</td>
<td>Centroid Coordinate</td>
<td>Esri Calculation</td>
<td>US feet</td>
</tr>
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<td>Oct to Dec water use, 2009</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
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<tr>
<td>Dec_Feb</td>
<td>Dec to Feb water use, 2009-2010</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
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<td>Feb_Apr</td>
<td>Feb to April water use, 2010</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
<tr>
<td>Apr_June</td>
<td>Apr to June water use, 2010</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
<tr>
<td>June_Aug</td>
<td>June to Aug water use, 2010</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
<tr>
<td>Aug_Oct</td>
<td>Aug to Oct water use, 2010</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
<tr>
<td>Total_CM</td>
<td>Year water use</td>
<td>City of Lincoln</td>
<td>cubic meters</td>
</tr>
<tr>
<td>Total_or</td>
<td>Year water use</td>
<td>City of Lincoln</td>
<td>1 unit = 100 cubic feet</td>
</tr>
<tr>
<td>Total_CF</td>
<td>Year water use</td>
<td>Grand Island</td>
<td>cubic feet</td>
</tr>
<tr>
<td>Tota_ori</td>
<td>Year water use</td>
<td>Sidney</td>
<td>1 unit = 1000 gallon</td>
</tr>
<tr>
<td>Parcel_num</td>
<td>Parcel numbers within block</td>
<td>Esri Calculation</td>
<td></td>
</tr>
<tr>
<td>Parcel_per</td>
<td>meter numbers/parcel numbers</td>
<td>Calculation</td>
<td>Range from 0 to 1</td>
</tr>
<tr>
<td><strong>HouU_perc</strong></td>
<td>meter numbers/housing units</td>
<td>Calculation</td>
<td>Range from 0 to 2, Residential only</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td><strong>Hous_densit</strong></td>
<td>Housing density</td>
<td>Calculation</td>
<td>TAHOUSING/ Acres, Residential only</td>
</tr>
<tr>
<td><strong>Pop_densit</strong></td>
<td>Population density</td>
<td>Calculation</td>
<td>TAPERSONS/ Acres, Residential only</td>
</tr>
<tr>
<td><strong>Vege_sqm</strong></td>
<td>NDVI&gt;0.15</td>
<td>Esri calculation</td>
<td>square meters</td>
</tr>
<tr>
<td><strong>Vege_perc</strong></td>
<td>Vegetation area percentage</td>
<td>Calculation</td>
<td>Vege_sqm /sqm, Open space only</td>
</tr>
<tr>
<td><strong>WU_densit</strong></td>
<td>Water use density</td>
<td>Calculation</td>
<td>cubic meters/ acres</td>
</tr>
<tr>
<td><strong>OIDemand</strong></td>
<td>Outdoor irrigation demand</td>
<td>Calculation</td>
<td>cubic meters((Etc-precipitation)*Vege_sqm))</td>
</tr>
<tr>
<td><strong>Outwaterus</strong></td>
<td>Outdoor water use</td>
<td>Calculation</td>
<td>April1st to Oct 31st</td>
</tr>
<tr>
<td><strong>OCWU</strong></td>
<td>Outdoor Consumptive use</td>
<td>Calculation</td>
<td>CIO (Commercial, industrial, and others) only</td>
</tr>
<tr>
<td><strong>ICWU</strong></td>
<td>Indoor Consumptive use</td>
<td>Calculation</td>
<td>CIO only</td>
</tr>
<tr>
<td><strong>CWU</strong></td>
<td>Consumptive water use</td>
<td>Calculation</td>
<td>OID/OWU, the smaller one</td>
</tr>
<tr>
<td><strong>PerCap_TWU</strong></td>
<td>Per capita water use</td>
<td>Calculation</td>
<td>Total water use (Cubic meters)/ TAPERSONS, Residential only</td>
</tr>
<tr>
<td><strong>PerCap_CWU</strong></td>
<td>Per capita consumptive water use</td>
<td>Calculation</td>
<td>Total water use (Cubic meters)/ TAPERSONS, Residential only</td>
</tr>
<tr>
<td><strong>PerCap_veg</strong></td>
<td>Parcapita vegetation area</td>
<td>Calculation</td>
<td>Vegetation area/ TAPERSONS, Residential only</td>
</tr>
<tr>
<td><strong>Bf_area</strong></td>
<td>Building footprint area</td>
<td>City of Lincoln</td>
<td>US square feet, City of Lincoln ONLY</td>
</tr>
<tr>
<td><strong>Percap_bf</strong></td>
<td>Per capita building footprints</td>
<td>Calculation</td>
<td>cubic meters/person, City of Lincoln ONLY</td>
</tr>
</tbody>
</table>

Note: 1. this table combines three categories attribute and some of them might not exist in the attributes table of shapefiles and appendix tables. 2. For the water use bill information, in the City of Lincoln, it is bimonthly water billing cycle and the specific information listed above. In the Grand Island and Sidney, their water billing information is charged every month. And they are listed in the shapefile attribute table in the abbreviation of each month.