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Abstract

U.S. water withdrawals have increased slowly since 1980, despite significant growth in the population and economy during this period. This implies that other factors have contributed to offsetting decreases in water withdrawals. The economic input-output life cycle assessment (EIO-LCA) model was used to estimate the total water withdrawal for 135 industrial summary sectors for 1997 and 2002. The change in water withdrawals for the economy from 1997 to 2002 was allocated to changes in five governing factors — population, GDP per capita, water use intensity, production structure, and consumption pattern — using structural decomposition analysis (SDA). The changes in population, GDP per capita and water use intensity increased total water withdrawal, while the changes in production structure and consumption pattern decreased water withdrawals from 1997 to 2002. Consumption pattern change was the largest net contributor to the change in water withdrawals. The counter balancing of these factors is what has kept U.S. water withdrawals relatively constant.

To project U.S. water withdrawal for the next 20 years, four scenarios were developed for each of the five governing factors based upon available predictions or historical trends. The total water withdrawals for U.S. 66 aggregated industrial sectors for 2013-2030 were projected using the EIO-LCA model with fixed and changing economic structure, respectively. The structure and consumption pattern were held constant at the 2012 level and the other three factors were varied across time in the EIO-LCA model with fixed economic structure, while all five governing factors were changed across time with changing economic structure. The maximum projected total water withdrawal is 370 trillion gallons for 2030, which is more than 2.5 times the 2005 U.S. water withdrawal, corresponding to a scenario with maximum growth assumptions for all factors

considered. The medians of total water withdrawals projected by the models with constant vs. evolving economic structure for 2013-2030 follow a continuous increasing trend, and the projected median values by the two models are comparable. The median of total water withdrawal will reach around 180 trillion gallons in 2030, about 1.2 times the 2005 U.S. water withdrawal. The variance in GDP per capita and water use intensity were the two most significant contributors to the uncertainty in projected total water withdrawals for U.S. industrial sectors.

The distinction of consumptive and non-consumptive water use is important for water resource management and assessment of availability and quality of water sources. Consumptive water use coefficients (ratio of consumptive water use to water withdrawal) were estimated by aggregated industrial sectors based on available data. The projected total consumptive water uses for all industrial sectors range from 45-47 trillion gallons in 2013 to 23-51 trillion gallons in 2030 using the EIO-LCA model with fixed economic structure. The median total consumptive water use is projected to grow at an average annual rate of 0.5% during this period. The effects of changes in cooling technology for thermoelectric power generation and irrigation technology for agriculture on changes in consumptive water use for other sectors during 2013-2030 were investigated. Changes in cooling technology do not impact consumptive water use projections for most sectors, but do impact power generation-related sectors. Shifts in irrigation technology do not only affect consumptive water use for agriculture, but also affect significantly the consumptive water use for sectors requiring agricultural products as important supply chain components.

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Chapter 1: Introduction

1.1 Motivation and Problem Statement

This study was motivated by the awareness that potential increases in water demand driven by increasing population and competition for available water resources in the U.S. in the coming decades result in sustainable water use concerns. Water resources in the U.S. have been stressed in many regions during the past few decades, mainly caused by population growth, economic development and climate change (Gleick, 2003; Schnoor, 2010). In 2014, the U.S. population has exceeded 318 million, almost doubling in the past five decades, and it is expected to double again within the following 70 years (U.S. Census Bureau, 2013a; U.S. Census Bureau, 2013b; UN, 2013). The U.S. GDP reached 16.8 trillion dollars in 2013, increasing more than three times over the past 50 years (The World Bank, 2014). Population and economic growth result in more requirements for foods, industrial products, services etc., which could translate into more water demand. Increasing water demand is likely to adversely affect the sustainability of water resources, resulting in the problems of water scarcity and poor water quality (Roy et al., 2012). Nearly every region in the U.S. has experienced the problem of water shortages, and more than 36 states have faced local or regional water shortages by 2013 (U.S. EPA, 2012). Water shortages are projected to occur in 80% of the states in the U.S. in the following decades, especially the western regions will be facing the severe water shortage (U.S. GAO, 2014).

The U.S. Geological Survey (USGS) reported that the total water withdrawals in U.S. peaked in 1980 and have essentially leveled off since then (Kenny et al., 2005). The population has grown and the economy developed since 1980, yet total water withdrawal risen only slightly during this period (U.S. Census Bureau, 2014a; U.S. Census Bureau, 2014b; U.S. Census Bureau, 2014c), which implies that other factors contributed to decreases in U.S. water withdrawals. Understanding the influence of the various factors governing water use in the U.S. can help identify the factors most likely to affect the magnitude of future water stress in the U.S.

It is important to distinguish consumptive and non-consumptive water use for water resource management and assessment of availability and quality of water sources (Solley et al., 1995). The consumptive water coefficient (ratio of consumptive water use to water withdrawal) varies widely across different water uses. The largest industrial water use — thermoelectric power generation — only consumes 2% of the water, while the largest water consumer — agricultural irrigation — consumes 40-100% of agricultural water withdrawal (Solley et al., 1995; Solley et al., 1990; Solley et al., 1980).

In the U.S., much information about water use across region is available, especially for the arid regions. However, very limited information about the indirect water use through the supply chain for the production of goods and services across industrial sector is available (Blackhurst et al., 2010). 60% of water is used indirectly through the supply chain (Blackhurst et al., 2010). Changes in water use for one industrial sector are likely to impact water use for other sectors.

1.2 Research Objectives

The overall goals of this research were to investigate the factors governing changes in water withdrawals for U.S. industrial sectors based upon historical economic and water use data, project the future total water withdrawal and consumptive water use for U.S. industrial sectors across the various scenarios for the governing factors, and identify effects of changes in consumptive water uses for thermoelectric power generation and agricultural irrigation on changes in consumptive water uses for other industrial sectors. To fulfill the main objectives, the following specific objectives were addressed: (1) estimate direct and indirect water withdrawals for U.S. industrial sectors for 1997 and 2002 with the EIO-LCA model (Blackhurst et al., 2010; Hendrickson et al., 2005); (2) quantify the contributions of five factors — population, GDP per capita, water use intensity, production structure, and consumption pattern — to changes in total water withdrawal during 1997-2002; (3) generate future possible scenarios for these five factors governing water withdrawals; (4) project total water withdrawals for U.S. industrial sectors across various scenarios for the five factors from 2013-2030 using the EIO-LCA model with fixed and changing economic structure; (5) evaluate the contributions of the uncertainty in governing factors to the variation in projected water withdrawals across the various scenarios for 2013-2030; (6) distinguish the consumptive and non-consumptive water uses for U.S. industrial sectors based upon the available consumptive water use coefficients during 2013-2030; and (7) investigate effects of changes in cooling technology for thermoelectric power generation and irrigation method for agriculture on changes in consumptive water uses for other industrial sectors. The first two objectives are addressed in Chapter 2, the objectives 3-5 are addressed in Chapter 3, and Chapter 4 addresses the last two objectives.

1.3 Dissertation Preview

The dissertation is organized into five chapters and four appendices. Chapters 2-4 are three main parts of this dissertation, and with each representing individual papers for publication in peer-reviewed journals.

Chapter 2 analyzes five factors — population, GDP per capita, economic production structure, water use intensity and consumption pattern — governing total water withdrawals for U.S. 135 summary industrial sectors from 1997 to 2002. The direct and total water withdrawals for U.S. industrial sectors in 1997 and 2002 were estimated using the EIO-LCA model. The contributions of these five factors to changes water withdrawals during the five years were quantified using structural decomposition analysis (SDA) technology.

Chapter 3 projects the total water withdrawals for 66 aggregated U.S. industrial sectors across the combinations of various scenarios for five governing factors using the EIO-LCA model with fixed and changing economic structure for 2013-2030. The contributions of five governing factors to the uncertainty in projected total water withdrawals were estimated using Analysis of Variance (ANOVA).

Chapter 4 distinguishes the consumptive and non-consumptive water uses for 66 industrial sectors during 2013-2030 based upon the historical consumptive water use coefficients across the combinations of various scenarios for five governing factors using the EIO-LCA model with fixed economic structure for 2013-2030. The consumptive water uses for the 66 industrial sectors were projected under the different scenarios for cooling technology for thermoelectric power generation and irrigation technology for agriculture for 2013-2030, and the effects of changes in cooling technology and irrigation technology on changes in consumptive water uses for industrial sectors were estimated.

Chapter 5 provides a summary of the important conclusions and main contributions of this work, and recommendations for future work.

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Chapter 2: Factors Governing Change in Water Withdrawals for U.S. Industrial Sectors from 1997 to 2002

This chapter, written by Hui Wang and co-authored by Mitchell J. Small, and David A. Dzombak, has been published on *Environmental Science & Technology, 2014, 48, 3420-342*9.

Abstract

The United States Geological Survey (USGS) reports that U.S. water withdrawals have been steady since 1980, but the population and economy have grown since then. This implies that other factors have contributed to offsetting decreases in water withdrawals. Using water withdrawal data from USGS and economic data from Bureau of Economic Analysis (BEA), direct and total water withdrawals were estimated for 134 industrial summary sectors in the 1997 U.S. economic input-output (EIO) table and 136 industrial sectors in the 2002 EIO table. Using structural decomposition analysis (SDA), the change in water withdrawals for the economy from 1997 to 2002 was allocated to changes in population, GDP per capita, water use intensity, production structure, and consumption patterns. The changes in population, GDP per capita and water use intensity led to increased water withdrawals, while the changes in production structure and consumption patterns decreased water withdrawals from 1997 to 2002. Consumption patterns change was the largest net contributor to the change in water withdrawals. The model was used to predict aggregate changes in total water withdrawals from 2002 to 2010 due to known changes in population and GDP per capita; a more complete model assessment must await release of updated data on USGS water withdrawals and EIO data.

2.1 Introduction

United States (U.S.) water resources have been increasingly stressed over the past decades. Nearly every region in the U.S. has experienced water shortages in the past five years, and more than 36 states are projected to face local or regional water shortages by 2013 (U.S EPA, 2013a). Roy at al. predict that substantial portions of California, Nevada, Arizona, Texas, Florida are at high or extreme high risk of insufficient water supply due to climate change in 2050 (Roy et al., 2012). Water shortages in some of these areas are now (or could be in the future) alleviated by the sustainable water use strategies such as water recycling and reuse, stormwater capture, water transfer from more water-rich areas and desalination of seawater. For example, water from the Colorado River and from the Central Valley of California is transferred to the water-short area of Southern California to meet demand (Schnoor, 2010).

Water withdrawal refers to the total amount of water withdrawn from the water sources. Total water withdrawals in the U.S. experienced a continuous growth between 1950 and 1980, and peaked in 1980 (157 trillion gallons), with an average annual growth rate of 3.3% over these 30 years (Huston et al, 2000; Kenny et al., 2005; Solley et al., 1995; USGS, 2012). U.S. total water withdrawal leveled off during 1985-2005 (Kenny et al., 2005). Thermoelectric power generation is the largest water withdrawal category and irrigation is ranked at the second place (Kenny et al., 2005). However, the information on water withdrawals for U.S. industrial sectors is very limited. Blackhurst et al. found that more than 50% of the U.S. water withdrawals in 2002 are associated with the sectors of agricultural activities, power generation, and food manufacturing; and that 60% of the total water withdrawal occurs through the supply chain (Blackhurst et al., 2010).

Population growth and economic development have been considered the principal factors causing changes in water quality, quantity and availability (Schnoor et al., 2010). By September 2013, the U.S. residential population exceeded 316 million, almost doubling in the past 50 years and it is projected to double again within the next 70 years (U.S. Census Bureau, 2013a; U.S. Census Bureau, 2013b; UN, 2013), while the U.S. per capita GDP increased about three times from 1950 to 2005 (The World Bank, 2012). As the population has grown and the economy developed since 1980, there has been a need to grow more food, more industries, more services, etc., which could, all else held constant, translate into increased water consumption (U.S Census Bureau, 2012a; U.S. Census Bureau, 2012b); yet total water withdrawal has stayed stable over the same period (Kenny et al., 2005). This implies that other factors contributed to decreases in U.S. water withdrawals. The trends in U.S. population and GDP per capita, and water withdrawals reported by USGS are indicated in Appendix A.

In this work, the contribution of five factors to changes in U.S. water withdrawal for industrial sectors between 1997 and 2002 were evaluated: changes in population, GDP per capita, water use intensity, production structure, and consumption patterns. Specific objectives were (1) Determine the factors affecting the change in water withdrawal for U.S. industrial sectors from 1997 to 2002; (2) Quantify the contribution of each factor to the change in total water withdrawal for U.S. industrial sectors during 1997-2002, using the technique of structural decomposition analysis (SDA); (3) Determine the industrial summary sectors with the largest water withdrawal changes during the period 1997 to 2002; and (4) Predict 2010 water withdrawals using the 2002 technology and production structure assumptions with only population and GDP per capita updated (databases for subsequent periods are not yet released).

2.2 Data Sources and Methods

2.2.1 Data Sources

2.2.1.1 Economic input-output tables

The U.S. Bureau of Economic Analysis (BEA) has released its benchmark economic input-output (EIO) table every five years up to 2002. EIO tables for the two most recently reported years (1997 and 2002) were used. The 491 detailed sectors in the 1997 EIO table were grouped into 134 summary sectors, and the 428 detailed sectors in 2002 were classified into 136 summary sectors (U.S. BEA, 2012a; U.S. BEA, 2012b). In this study, we focused on U.S. water withdrawals for the summary sectors for both years.

Some of the BEA definitions for the summary sectors changed from 1997 to 2002: the new sector *Internet publishing and broadcasting* and three new government industry sectors (*General federal defense government services*, *General federal nondefense government services* and *General state and local government services*) were created in the 2002 EIO table. These three new government industry sectors in the 2002 EIO table were merged into one sector, *General government industry*, by summing economic activities. A new sector *Internet publishing and broadcasting* with all zero economic activities was added to the 1997 I-O table. Both the 1997 and 2002 EIO table have 135 summary sectors in common with the consolidation and addition of sectors, and both were adjusted for inflation to 2000 prices. The detailed information about 1997 and 2002 summary sectors is provided in Appendix A.

2.2.1.2 Water withdrawal data

The USGS has developed inventories of major-category water withdrawal in the U.S. every five years from 1950 to 2005. To match the EIO data, the water withdrawals data for 1995, 2000 and 2005 were used to estimate water withdrawals for the same categories in 1997 and 2002 using interpolation. USGS reported water withdrawals for the categories *Thermoelectric power generation*, *Mining*, *Industrial*, *Irrigation*, *Residential*, *Public supply*, and *Livestock* for 1995, 2000 and 2005, and for a new category, *Aquaculture*, in 2000 and 2005. Water withdrawals for *Livestock* and *Aquaculture* in 2000 and 2005 were aggregated to keep consistent with the reported water withdrawal for livestock in 1995. The water withdrawals for mining, industrial, residential, and livestock & aquaculture were self-supplied, which were not delivered from a public supplier (Kenny et al., 2005).

Six of the USGS category-water withdrawals for 1997 and 2002 were allocated to the 1997 and 2002 industrial sectors based on economic activities, process activities and the number of employees, respectively. Residential water withdrawal (~6% of total water withdrawal) representing the final consumption was not allocated to any industrial sectors for both years (Blackhurst et al., 2010). We mainly followed the methods of allocation provided by Blackhurst et al (Blackhurst et al., 2010). The methods of allocation for the industrial sectors *Power generation*, *Agriculture*, *Animal production* and some detailed mining sectors were modified. Water withdrawals for *Power generation* were mapped to three sectors associated with electricity generation and utilities according to the industrial output; water withdrawals for *Agriculture* and *Livestock & Aquaculture* were directly allocated to the sector *Crop production* and *Animal production*, respectively. The detailed allocation methods are described in Appendix A.

2.2.1.3 Population and GDP per capita data

In addition to EIO data and water withdrawals data, two years of data (1997 and 2002) for population and GDP per capita were used in this study. The population for 1997 was 268 million and for 2002 was 288 million (U.S Census Bureau, 2012a; U.S Census Bureau, 2012b); the 1997 and 2002 GDP per capita were $30,000 and $37,000 (current dollars) respectively (The World Bank, 2012).

2.2.2 Methodology

2.2.2.1Economic input-output life cycle assessment (EIO-LCA)

The EIO-LCA model uses U.S. BEA data on the intersectoral purchases of materials by industries, and the water withdrawal per dollar of output to estimate the total water withdrawal by tracing the flow of goods and services among the sectors for 1997 and 2002 (Blackhurst et al., 2010; Hendrickson et al., 2005). Total water withdrawal is the sum of direct and indirect water withdrawal. Direct water withdrawal is the water taken for the sector itself, and indirect water withdrawal refers to water withdrawn in their supply chain (Blackhurst et al., 2010). The supply chain includes all component suppliers which are required for the production of the sector's goods or services (Hendrickson et al., 2005). For example, *Automobile manufacturing* needs to purchase the raw materials from *Painting and coating manufacturing*, *Iron and steel mill,* and other numerous suppliers. The water withdrawn for *Automobile manufacturing* itself is direct water withdrawal, and water withdrawn for all supplier sectors such as *Painting and coating manufacturing,* and *Iron and steel mill* to support *Automobile manufacturing* is counted as indirect water withdrawal (supply chain water withdrawal) for the *Automobile manufacturing* sector. The EIO-LCA method was used to estimate the total and supply chain water withdrawals for the industrial sectors for 1997 and 2002 (Hendrickson et al., 2005). The EIO-LCA model is built upon Equation [2-1]:

$$\mathbf{W}=\mathbf{F}*\mathbf{L}*\mathbf{Y} \quad [2 - 1]$$

where W is a vector of total water withdrawal for each industrial sector; F is a square matrix with diagonal elements representing the water withdrawal per dollar of output for each sector, referred to as the water use intensity matrix [gallons/dollar]. For example, 340 billion gallons of water are needed to generate 420 billion dollars of output for *Food manufacturing* sector, which results in a water use intensity of 0.8 gallons/dollar for this sector; L is the total requirement matrix representing production structure (also called Leontief inverse matrix), in which entries represent the total dollars of inter-industry purchases per dollar of final use of commodity [dollars] (Horowitz et al., 2009). It is an industry by commodity total requirement matrix, and the columns show the total requirement of inputs from the industries to generate one dollar of commodity. For example, the element $L_{ij}=0.5$ in the matrix indicates that $0.5 of product from industry i is needed for every dollar of commodity j that is produced; and Y is a vector of final use representing the consumption of goods and services by personal consumption expenditures, imports and exports of goods and services, etc. [dollars].

The gross domestic product (GDP) is the sum of all the final uses (Hendrickson et al., 2005). The final use Y can be decomposed into components associated with population (P), GDP per capita (Yg), and consumption patterns (Yc). A similar decomposition was applied to CO_2 emission estimates in China by Guan et al. EIO-LCA model equation [2-1] considering such decomposition is given by Equation [2-2] (Guan et al., 2008).

$$\mathbf{W}=P*Yg*\mathbf{F}*\mathbf{L}*\mathbf{Yc} \quad [2 - 2]$$

where W, F and L are the same as in Equation [2-1]; P is population; Yc is the consumption pattern vector representing the GDP share by each of the industrial sectors [non-dimensional]. For example, the element for the food manufacturing sector in the consumption pattern vector is 0.03, which represents that the GDP from this sector accounts for 3% of total GDP; and Yg is the GDP per capita [dollars].

2.2.2.2 Structural decomposition analysis (SDA)

Structural decomposition analysis (SDA) is a technique that decomposes the changes in one variable into the changes in its determinants, and the determinants are assumed to be independent (Dietzenbacher et al., 2000). This method has been used to analyze the factors affecting energy use, CO_2-emissions, water use and other pollutants and resources (Cazcarro et al., 2011; Guan et al, 2008; Hoekstra et al., 2002; Wood, 2009). Guan et al. employed a similar method to that used in this study to evaluate the drivers of CO_2 emissions in China from 1980 to 2003 (Guan et al, 2008). Cazcarro et al. applied SDA to water use changes in Spain, though without considering the effects of population and economic growth considered in our research (Cazcarro et al., 2011). In this study, the SDA method was used to quantify the contribution of five factors to the change in total water withdrawal for industrial sectors during 1997-2002: population (P), GDP per capita (Yg), water use intensity (F), production structure (L), and consumption patterns (Yc) (Guan et al, 2008). In this application of SDA, there are totally 5!=120 possible decompositions (Dietzenbacher et al., 1998). As the results from different decomposition forms may vary greatly, the average effects and standard deviations are typically reported (Dietzenbacher et al., 1998). Two example decomposition forms are shown in the following equations.

$$\begin{aligned}\Delta W &= W2002 - W1997\\ &= [\Delta P * F2002 * L2002 * Yc2002 * Yg2002\ ] + [P1997 * \Delta F * L2002 * Yc2002 * Yg2002]\\ &\quad + [P1997 * F1997 * \Delta L * Yc2002 * Yg2002] + [P1997 * F1997 * L1997 * \Delta Yc * Yg2002]\\ &\quad + [P1997 * F1997 * L1997 * Yc1997 * \Delta Yg\ ] \qquad [2-3]\end{aligned}$$

$$\begin{aligned}&= [\Delta P * F1997 * L1997 * Yc1997 * Yg1997] + [P2002 * \Delta F * L1997 * Yc1997 * Yg1997]\\ &\quad + [\mathrm{P2002 * F2002 * \Delta L * Yc1997 * Yg1997}] + [\mathrm{P2002 * F2002 * L2002 * \Delta Yc * Yg1997}]\\ &\quad + [\mathrm{P2002 * F2002 * L2002 * Yc2002 * \Delta Yg}\ ] \qquad [2\text{ - }4]\end{aligned}$$

In both Equations [2-3] and [2-4] there are five terms in brackets; each represents water withdrawal change due to one governing factor. Each term is the product of five variables: a single ΔX variable denoting the change from 1997 to 2002 for the variable considered, and four remaining variables representing the values of the other factors in 1997 or 2002. As indicated, the terms in the brackets represent different combinations of the state variables in 1997 and 2002, multiplied by the respective change term for each. The terms in the brackets represent the change in water withdrawal due to population change, the water use intensity change, production structure change, consumption pattern change and the GDP per capita change, respectively. We averaged all 120 decompositions and computed the standard deviation across the 120 forms to obtain the results.

The principal steps employed in the analysis conducted here were as follows, and the detailed flow chart for this methodology is shown in Figure 2-1.

Step 1: Estimate 1997 and 2002 water withdrawals for USGS six major categories.

Step 2: Allocate USGS category water withdrawals to EIO industrial sectors and compute water use intensity for both years.

Step 3: Use EIO-LCA model to estimate total and direct water withdrawals for each sector for both years.

Step 4: Quantify the contributions of population, per capita GDP, water use intensity, production structure and consumption patterns to changes in total water withdrawal between 1997 and 2002 using the SDA method.

2.3 Results

2.3.1 Estimation of Water Withdrawals in 1997 and 2002

The results from the analysis show that the U.S. economy exhibited a 3% increase in total water withdrawal, and a 1% increase in direct water withdrawal between 1997 and 2002. The total water withdrawal is estimated to have increased from approximately 133 to 137 trillion gallons, with the indirect water withdrawal responsible for 63% and 64% of the total water withdrawal in 1997 and 2002, respectively.

Table 2-1 shows the 10 largest water withdrawal summary sectors in 1997 and 2002. Nine of these 10 sectors in 1997 remained in the top 10 in 2002. The sector *General government industry* took the place of *Natural gas and distribution* to be one of the 10 largest water users in 2002. The change in definition of the government industry sector resulted in an apparent increase in water withdrawal for *General government industry* from 1997 (121^{st}) to 2002 (4^{th}). The sector *General government industry* was presented an intermediate industry in the 2002 EIO table that produces goods and services for final users while this sector was a final user in 1997 (Horowitz et al., 2009; Stewart et al., 2002). *Power generation and supply, Food manufacturing* and *Crop production* were the three largest water users for both years, together accounting for about 50% of total water withdrawal for both years, which is consistent with the results obtained by Blackhurst et al. (Blackhurst et al., 2010). Eight of the 10 largest water withdrawal sectors used more water indirectly than directly in both 1997 and 2002, but *Power generation and supply* and *Crop production* took more than 95% of their water withdrawal directly. Total water withdrawal decreased from 1997 to 2002 in some of the top sectors including *Power generation and supply*, *Food*, *Natural gas distribution*, and increased in the sectors representing *Agriculture*, *Construction*, *Hospitals* and *Government industry*. *Power generation and supply* had the largest absolute decrease in total water withdrawal (2.8 trillion gallons). The detailed direct and indirect water withdrawals for the 10 largest water withdrawal sectors are shown in Table A-3 and A-4 in Appendix A.

2.3.2 Estimation of Water Withdrawal for Different Categories of Final Use

The final use of commodities consists of personal consumption expenditures, private fixed investment, change in private inventories, exports and imports of goods and services, government consumption expenditures and investment (Horowitz et al., 2009). The changes in water withdrawal for the six final use categories during 1997-2002 are shown in Figure 2-2. During this period, the increase in water withdrawal (~4 trillion gallons) was mainly attributed to water withdrawal for increased personal consumption. The increased government consumption and private investment caused increases in water withdrawal by 11% and 9% respectively. Increased imports reduce U.S. water withdrawals, while increased exports increase U.S. water withdrawals. Since imports increased and exports decreased during this period (U.S. BEA, 2012a; U.S. BEA, 2012b), both changes contributed to a decrease in U.S. water withdrawal. Water withdrawals associated with exportation decreased by 2.1 trillion gallons. With the assumption that the imported products were produced using the same technology as in the U.S. (Guan et al., 2008), U.S. total water withdrawals are estimated to have decreased by 3 trillion gallons during

1997-2002, due to the water withdrawals displaced offshore by increasing imports. The changes in significant amounts of water withdrawals were associated with the food-related sectors: *Crop production* and *Food manufacturing*, which was the largest increased and decreased water withdrawal sector due to changed imports from 1997-2002, respectively. The decrease in imported products, especially the high water use intensity products, facilitated increase in water withdrawal in U.S. For example, the decrease in 13% imports of crop productions caused the increase in 0.73 trillion gallons of water withdrawal. The five largest increased and decreased water withdrawal sectors due to changed imports are shown in Appendix A.

2.3.3 SDA Results for Water Withdrawal Change from 1997 to 2002

Figure 2-3 shows the five governing factors and their contribution to the change in total water withdrawal for the economy from 1997 to 2002. The industrial sectors took about 4 trillion gallons (3% of 1997 water withdrawal) more water in 2002 than 1997. Three factors contributed to an increase in total water withdrawal: population growth, increased GDP per capita, and the change in water use intensity. In contrast, changes in production structure and changes in consumption patterns caused a decrease in total water withdrawal. The absolute change in total water withdrawal resulting from the consumption pattern change was the largest absolute change in water withdrawal caused by any of the five factors. The change in consumption patterns reduced more than 20 trillion gallons of water withdrawal in the U.S. economy from 1997 to 2002, with the decrease in water withdrawal from 1997 to 2002 caused by production structure change comprising about half of this value. The change in water use intensity contributed an increase of 15 trillion gallons in water withdrawal from 1997 to 2002 followed by the increased GDP per capita (12 trillion gallons) and population growth effect (10 trillion gallons).

2.3.3.1 Sector-specific water withdrawal changes due to population growth and increase in GDP per capita from 1997 to 2002

Figure 2-4 presents the five largest increased water withdrawal sectors and the estimated change in total water withdrawal attributed to population growth and increased GDP per capita during 1997-2002 with other factors held constant. The sectors with the largest population and GDP per capita associated increases in water withdrawal are the same: *Power generation*, *Retail trade* and three food-related sectors. With the continuous growth of population from 1997 to 2002, an additional 10 trillion gallons of water was withdrawn in 2002 compared to 1997. The water withdrawal change for *Power generation*, *Food manufacturing* and *Crop production*, represent 50% of the total water withdrawal increase caused by population growth from 1997 to 2002.

The mean SDA estimate of this increase in GDP per capita on total water withdrawal through the economy is about a 12 trillion gallon increase due to the 10% increase in GDP per capita during 1997-2002. The five largest increased water withdrawal sectors were responsible for 60% of the total rise of water withdrawal due to the GDP per capita increase from 1997 to 2002. The largest water user *Power generation* withdrew 7% more water in 2002 than 1997 due to per capita GDP growth, which represents 20% of the GDP-associated increase in water withdrawal.

2.3.3.2 Sector-specific water withdrawal changes due to changes in water use intensity

Figure 2-5 shows the five largest increased and the largest decreased water withdrawal sectors due to water use intensity changes (in this case a net change in gallons water per dollar of production as a weighted average across the economy) from 1997 to 2002. The water withdrawal for *State and local government enterprises* dropped 0.3 trillion gallons, which was the largest decrease in water withdrawal resulting from water use intensity changes across all sectors in the economic system from 1997 to 2002. The decreases in water withdrawal for other sectors were too small to be indicated. The change in total water withdrawal due to water use intensity change from 1997 to 2002 was dominated by the increased water withdrawal sectors; the decrease in total water withdrawal was less than 10% of the increase in total water withdrawal. The five largest increased water withdrawal sectors account for 80% of the total water withdrawal increase due to water use intensity changes, and the increased water withdrawal for *Food manufacturing* and *Crop production* exceeded twice the increase in water withdrawal for the other three largest sectors. Possible reasons for the major sectoral increases in water use intensity are presented in the discussion section.

2.3.3.3 Sector-specific water withdrawal changes due to changes in production structure

Figure 2-6 indicates the five largest increased and decreased water withdrawal sectors and the total net water withdrawal change due to the change in input-output requirements for production in each sector. Production structure represents the interrelationship of purchases across the sectors, and it reflects changes in production technology. The change in production structure caused a net reduction of 10 trillion gallons of water withdrawal from 1997 to 2002. The change in production structure across the sectors resulted in an increase in water withdrawal for 30% of the industrial sectors, and the increase in water withdrawal for more than 95% of these sectors was less than 1 trillion gallons, except for *General government* industry. Compared to the increased water withdrawal for the sectors due to production structure change, the decline in water withdrawal was more significant, especially the decrease in water withdrawal for *Food manufacturing* and *Food services and drinking places*. Each of these two sectors experienced a decline in the water withdrawal of 5 trillion gallons due to production structure change. The other three sectors *Natural gas distribution*, *Retail trade* and *Real estate* in total reduced water withdrawal by 10% due to production structure change.

2.3.3.4 Sector-specific water withdrawal changes due to changes in consumption patterns

Figure 2-7 presents the five largest increased and decreased water withdrawal change sectors and the change in total water withdrawal due to changes in consumption patterns. These consumption pattern changes are reflected in relative changes in final use among the sectors, with the total final use (GDP) divided differently among the different sectors of goods and services. The decrease in water withdrawal for the majority of sectors (70%) dominated the change in total water withdrawal, resulting in a reduction of more than 20 trillion gallons water withdrawal, which caused the change in consumption pattern to be the largest absolute contributor to total water withdrawal change from 1997 to 2002. *Power generation*, *Crop production* and *Food manufacturing* were the three most important sectors with decreases in water withdrawal associated with changing consumption patterns yielding more than 15 trillion gallons of water withdrawal reduction, accounting for 80% of the decrease in water withdrawal change due to different consumption patterns in 2002 versus 1997. The change in consumption patterns increased water withdrawal for 38 sectors with *General government industry*, *Hospital* , *New residential construction, Educational services and Owner-occupied dwellings* exhibiting the largest water withdrawal increases, but the increase in water withdrawal for each of these sectors did not exceed 1.5 trillion gallons.

2.3.4 Projection of U.S. Water Withdrawals in 2010

The U.S. total water withdrawal for the industrial sectors in 2010 was projected using the same methodology as the estimation of water withdrawal for 1997 and 2002. Lacking reported data upon which to base our estimates, we assumed that the water use intensity, consumption pattern and production structure in 2010 remained at the 2002 level, while population and GDP per capita increased (based on available data) to 309 million and 46,610 current dollars in 2010 (UN, 2013; The World Bank, 2012), respectively. The projection based on the above assumptions was that U.S. total water withdrawal reached 156 trillion gallons in 2010, 14% more than the water withdrawal in 2002. Direct water withdrawal in the 2010 projection accounted for 36% of total water withdrawal, the same proportion as 2002 because of the constant production structure assumed for both years. A further projection of total water withdrawal up to 2030 under various scenarios of population, economic and technology change is being pursued in our ongoing research.

2.4 Uncertainty

Based on the data and methods we applied, the uncertainty of our results can be assessed. Uncertainty and variability exist in the original water withdrawal data, EIO data, the aggregation of industrial sectors, allocation of USGS water withdrawal to the industrial sectors, and in the structural decomposition analysis (SDA), but most are difficult to quantify. The basic water withdrawal data for seven categories were compiled from various sources by USGS, and different sources and methods could result in different levels of precision (Kenny et al., 2005). For example, water withdrawals for aquaculture in 2005 increased by 60% as compared to the estimated value in 2000, this large increase might be due to a difference in estimation methods rather than an actual change (Kenny et al., 2005). USGS did not produce water withdrawal data for 1997 and 2002; rather we used interpolation to obtain the various water category withdrawals for both years based upon the USGS water withdrawal data for 1995, 2000 and 2005. The interpolation was applied with the assumption that the water withdrawals between 1995-2000 and 2000-2005 follow a linear relationship, but this assumption likely introduced some error. The method of allocation plays a key role in the estimation of water withdrawal for the industrial sectors, and the associated assumptions used in the method of allocation explained in the SI are likely to introduce some uncertainty. The data limitations for some sectors also yield further uncertainty in our results. For instance, process data are preferable for allocation of water withdrawal to the mining sectors for the calculation of water use intensity, but in the absence of such data we estimated allocated water withdrawal of some mining subsectors by scaling relative to other subsectors by the number of employees (e.g., we allocated the water withdrawal for *Drilling oil and gas wells* by scaling allocated *Oil and gas extraction* water withdrawal by the number of employees). The changes in classification and definition in the economic input-output table from 1997 to 2002 introduced some uncertainty to our results as well. The non-uniqueness of decomposition forms of SDA introduces variability in our results as depicted in Figures 3-7 (error bars in the figures). In addition, the possible inter-dependence among the five factors is not easy to evaluate. The assumption of full dependence among the factors for the SDA method may cause some bias in the results. Assessing and incorporating such interdependencies in SDA is an appropriate target for future research.

Although interpolation and some assumptions were used in the estimation, our estimations were checked against various published data and were found to be comparable. For example, the water withdrawals allocated to *Crop production* and *Livestock* for both 1997 and 2002 were about 52 trillion gallons, as shown in Tables S1-S2 in the SI, which is consistent with the water withdrawals for these two sectors reported by the World Bank (52.5 trillion gallons for 1997 and 51.9 trillion gallons for 2002) (The World Bank, 2013a; The World Bank, 2013b); our estimated largest water withdrawal sectors and indirect water withdrawal for 2002 are consistent with those published by Blackhurst et al. (Blackhurst et al., 2010)

2.5 Discussion

Increases in population, GDP per capita and water use intensity all resulted in a net increase in water withdrawal across the U.S. economy from 1997 to 2002. Water use intensity was the largest positive contributor to the increase in water withdrawal from 1997 to 2002, whereas the overall contributions of increases in population and GDP per capita to change in water withdrawal were modest. The growth of population and GDP per capita during 1997-2002 resulted in similar increases in water withdrawal for the major industrial sectors related to food, power generation, and retail trade. With the growth of population and the economy, the demand for the products supporting individual consumption increased, especially for elementary needs of people such as food, energy and household products. The production and use of food and energy are interconnected with many other factors, such as water consumption (U.S EPA, 2013b). Increased requirements for such products translated into an increase in water withdrawal for the corresponding industries.

The increase in water withdrawal due to changed water use intensity was primarily caused by the increased water use intensity of agricultural activities. Agricultural water withdrawal is mainly used for irrigation for crop production. The annual average temperature in the U.S in 1997 (53.02 F) was lower than 2002 (54.01 F) and the average precipitation in 1997 (79.5cm) was significantly higher than in 2002 (72.8cm) (NOAA, 2012). The year 2002 was thus generally hotter and drier than 1997, which may have resulted in increased demand for water use for irrigation. In addition, although harvest cropland decreased from 31.9 million acres in 1997 to 30.9 million acres in 2002 (USDA, 2002), the average irrigation rate did not vary greatly (1.7-1.8 acre-feet/acre) during this period (USDA, 2003), and the output of the sector *Crop production* in 2002 was about 20% less than its output in 1997 (U.S. BEA, 2012a; U.S. BEA, 2012b), which also might account for a portion of the increase in water use intensity for agricultural products from 1997 to 2002.

The increase in water withdrawal for power generation resulted from increase in water use intensity for the industry. In this analysis, power generation specifically refers to thermoelectric power generation (Huston et al., 2000; Kenny et al., 2005; Solley et al., 1995), that is, water withdrawal for fossil-fuel, nuclear, or geothermal power generation. Most of the water withdrawn by thermoelectric plants is used for condenser and reactor cooling (Kenny et al., 2005). The amount of water withdrawn for power plant cooling varies across power plant generating technologies and cooling systems. Most U.S. thermoelectric power plants use once-through cooling or a wet recirculating cooling tower system, with about 43% of the generating capacity being once-through cooling and 42% wet recirculating cooling towers (Feeley III et al., 2008). Recent national average water withdrawal data indicate that nuclear power generation plants generally need more water to generate every megawatt-hour of electricity compared to coal power generation and natural gas plants using once-through and recirculating cooling systems (Feeley III et al., 2008). The U.S reliance on nuclear power experienced growth from 1997 to 2002 (WNA, 2012); nuclear power plants produced 629 billion KWh representing 20% of the country's electricity generation in 1997, growing to 780 billion KWh and nearly 22% of electricity in 2002 (U.S. EIA, 2012). This contributed to more water withdrawal for thermoelectric power generation in 2002 as compared to 1997. In addition, the output of power generation declined by 3% from 1997 to 2002 (U.S. BEA, 2012a; U.S. BEA, 2012b), which could also have contributed to more water withdrawal for every dollar of output in 2002 versus 1997.

The changes in production structure and consumption patterns reduced the total water withdrawal for the U.S. economy from 1997 to 2002. The change in consumption patterns reflects changes in preferences for goods and services. The trend in consumption during 1997-2002 indicates more emphasis on service-producing sectors such as health-care related sectors and education services rather than goods-producing sectors. The service-producing sectors generally have less intensive water consumption than the goods-producing sectors (Blackhurst et al., 2010), resulting in a net decrease in water withdrawal due to changes in consumption patterns. The private goods-producing industries GDP share decreased by 3%, while the private services-producing industries increased their GDP share from 66% in 1997 to 69% in 2002. The health-care related sectors increased their share of GDP by 2% as compared to 1997. Personal consumption expenditures for *Educational services* increased by 45%, and there was a 40% increase for *Recreation* from 1997 to 2002 (U.S. BEA, 2012a; U.S. BEA, 2012b), resulting in an increase in final use and water withdrawal for these sectors. In addition, the private fixed investment for *New residential construction* rose by 70% in 2002, as reflected in the average of floor area in new single-family houses increasing from 200 m^2 in 1997 to 215 m^2 in 2002 (U.S. Census Bureau, 2012c), contributing to an increase in water withdrawal for new residential construction. In contrast, decreases in total water withdrawal due to changes in consumption patterns were significantly influenced by the decline in GDP share of agricultural products and power generation. Although an increase in private consumption of agricultural products caused increased water withdrawal, decreases in exports of agricultural products by 20% and a reduction in private inventories of agricultural products by 200% reduced associated water withdrawal from 1997 to 2002 (U.S. BEA, 2012a; U.S. BEA, 2012b). The export of major agricultural products, including soybeans, corn, and wheat decreased by 25%, 6% and 15% respectively during this period (USDA, 2012). The 60% decrease of government consumption and investment for power generation from 1997 to 2002 likewise reduced its water withdrawal. As a critical part in the supply chain, the decreased relative final use for agricultural products and power generation in 2002 significantly reduced the quantity of indirect water withdrawal in the supply chain for food manufacturing and two other energy-related sectors. The SI provides a more detailed demonstration of how changes in water withdrawal associated with changing consumption patterns reflect changes in final use for these sectors.

Our results highlight how the change in water withdrawal is a consequence of factors associated with, and jointly influenced by population, GDP per capita, water use intensity, production structure and consumption patterns. The growth of population and the economy does not necessarily imply an overall increase in water withdrawals. Therefore, further attention should be paid to other driving factors, especially changes in consumption patterns. Additional shifts to consumption patterns that have low water requirements might continue to slow the pace of increasing water demand in the U.S. and relieve a portion of the water stress in the future. More information on water use and economic activities over multiple years would be particularly helpful in improving models for water use management and prediction. We intend to extend the analysis method presented here to project U.S. water withdrawals under alternative water technology, population and economic growth scenarios, and determine the contribution of the five factors studied above across the different scenarios. This will include an update of the 2010 predictions presented above, once official USGS water and economic structure data are reported for the U.S., as well as projections into the future.

While water withdrawal provides a measurement of overall water use, it is not sufficient to evaluate water quality impacts based solely on total water withdrawal data. This study did not divide water withdrawals into consumptive and non-consumptive water use. Consumptive water use is the portion of water withdrawal consumed and not returned to the regional water environment, and non-consumptive water use is the portion returned to the water body after use (Solley et al., 1995). The quantity and quality of return flow differs across industries with differing water quality impacts and effects on reuse potential (Pebbles, 2003). Distinction between consumptive and non-consumptive water use for the EIO industrial sectors will be considered for estimating water quality impacts and water management in future studies. The factors affecting consumptive water uses for U.S. industrial sectors will be investigated as well. In addition, the five factors studied here are proposed based on the EIO-LCA model highlighting sectoral economic activities, which do limit the ability to identify some underlying factors such as water price and direct water use efficiency, e.g., total water (rainfall plus irrigation) withdrawal per field for *Crop production*.

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Table 2-1. Estimated total and direct water withdrawal for the 10 largest use summary sectors in 1997 and 2002

Summary Sector	Rank		Ratio of Direct/Total		Total Water Withdrawal (trillion gallon)		
Name	**1997**	**2002**	**1997**	**2002**	**1997**	**2002**	**change**
Power generation and supply	1	1	0.96	0.97	29	26	-2.8
Food manufacturing	2	2	0.11	0.16	22	22	-0.24
Crop production	3	3	0.98	0.97	16	18	1.7
Food services and drinking place	4	5	0.014	0.024	8.5	6.5	-2.0
Retail trade	5	6	0.037	0.024	5.1	5.0	0.10
Natural gas distribution	6	18	0.0011	0.0018	3.5	1.4	-2.1
Real estate	7	10	0.086	0.053	2.8	2.4	-0.40
New residential construction	8	7	0.019	0.014	2.5	3.8	1.3
New nonresidential construction	9	9	0.022	0.027	2.4	2.8	0.32
Hospitals	10	8	0.062	0.029	2.3	3.6	1.3
General government industry	121	4	0	0.18	0	11	11

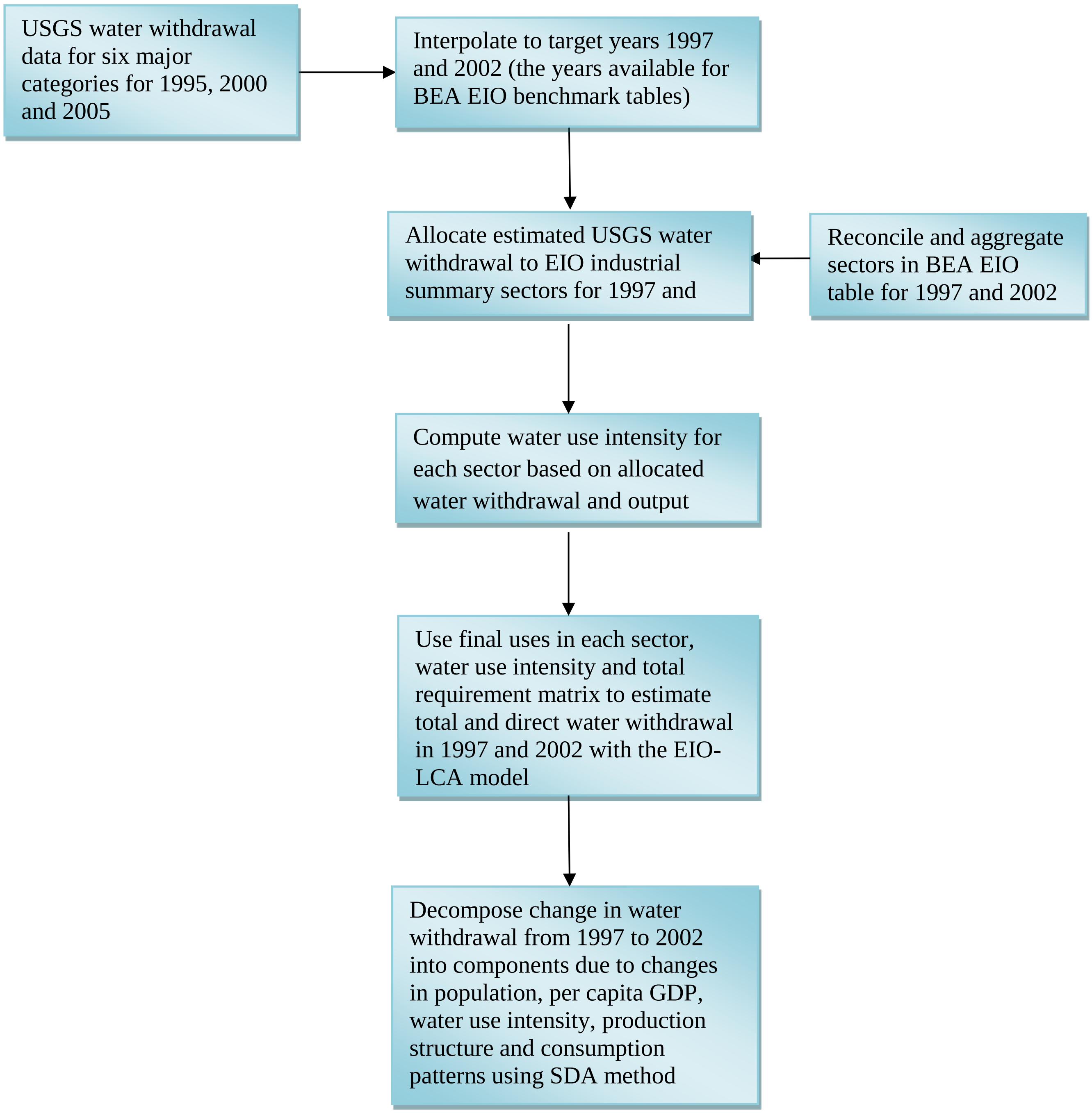

Figure 2-1. Flow chart for estimation of U.S. water withdrawal and quantification of factors to change in total water withdrawals between 1997 and 2002

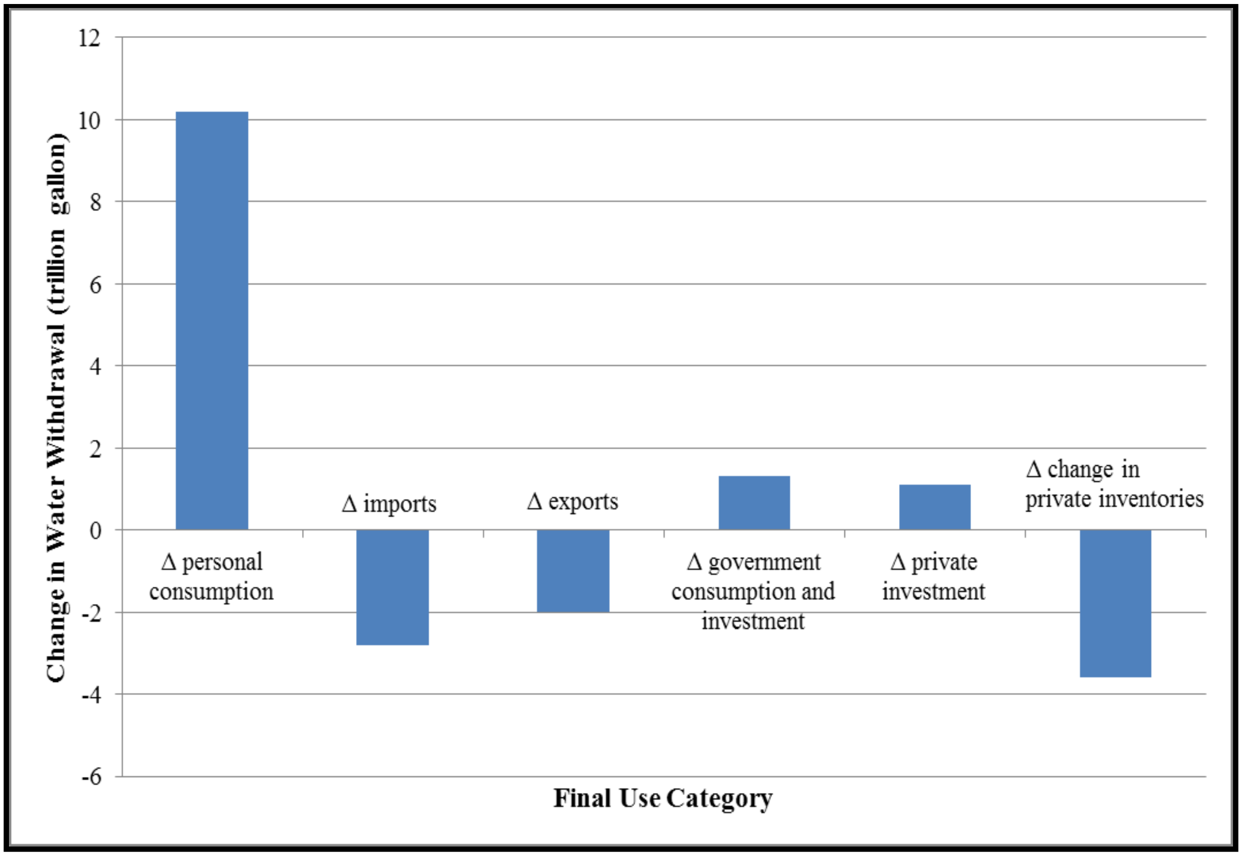

Figure 2-2. Contribution of final uses to change in U.S. water withdrawals from 1997 to 2002

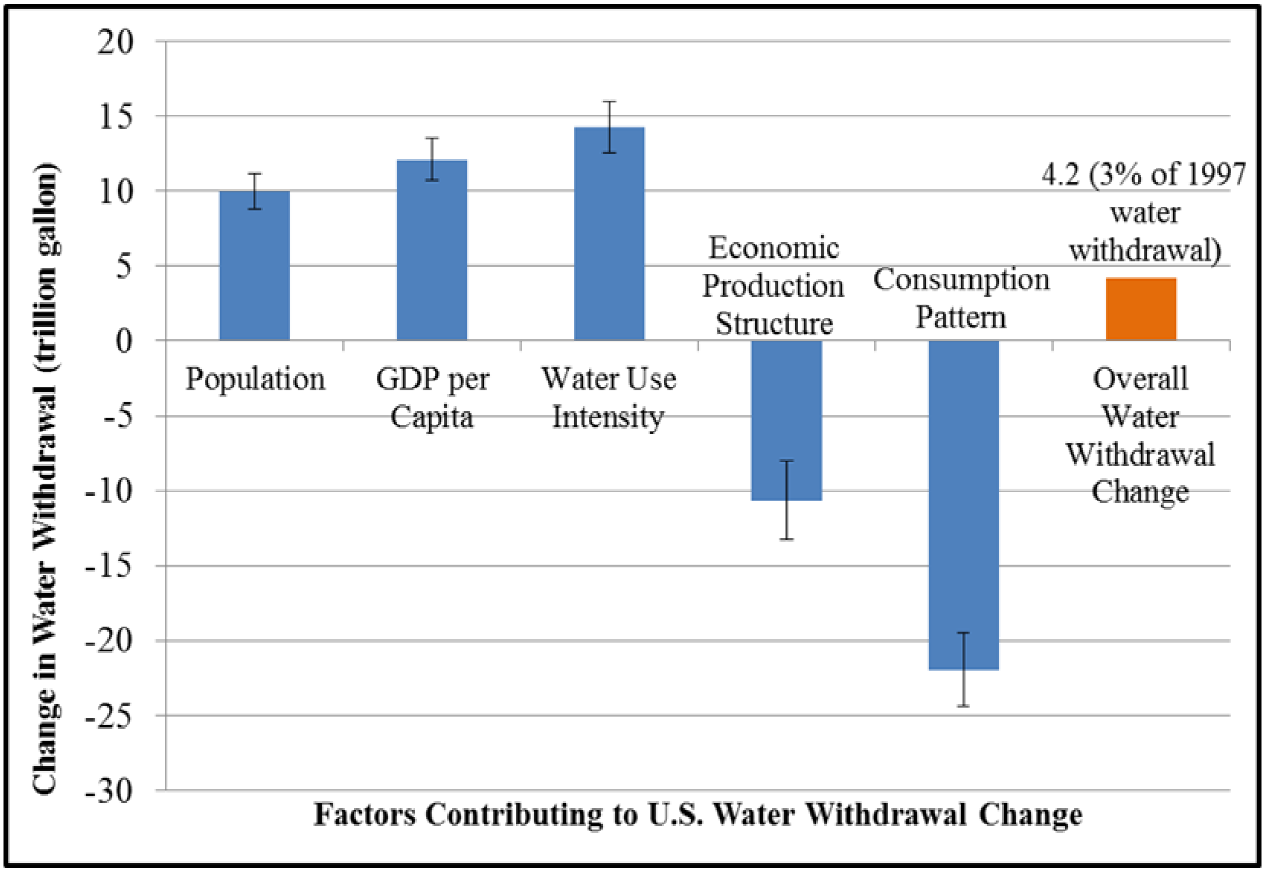

Figure 2- 3. Total water withdrawal change in the U.S. from 1997 to 2002 due to five governing component factors. The results indicate the mean across the 120 decomposition forms, while the bars present the associated standard deviation across the 120 decompositions.

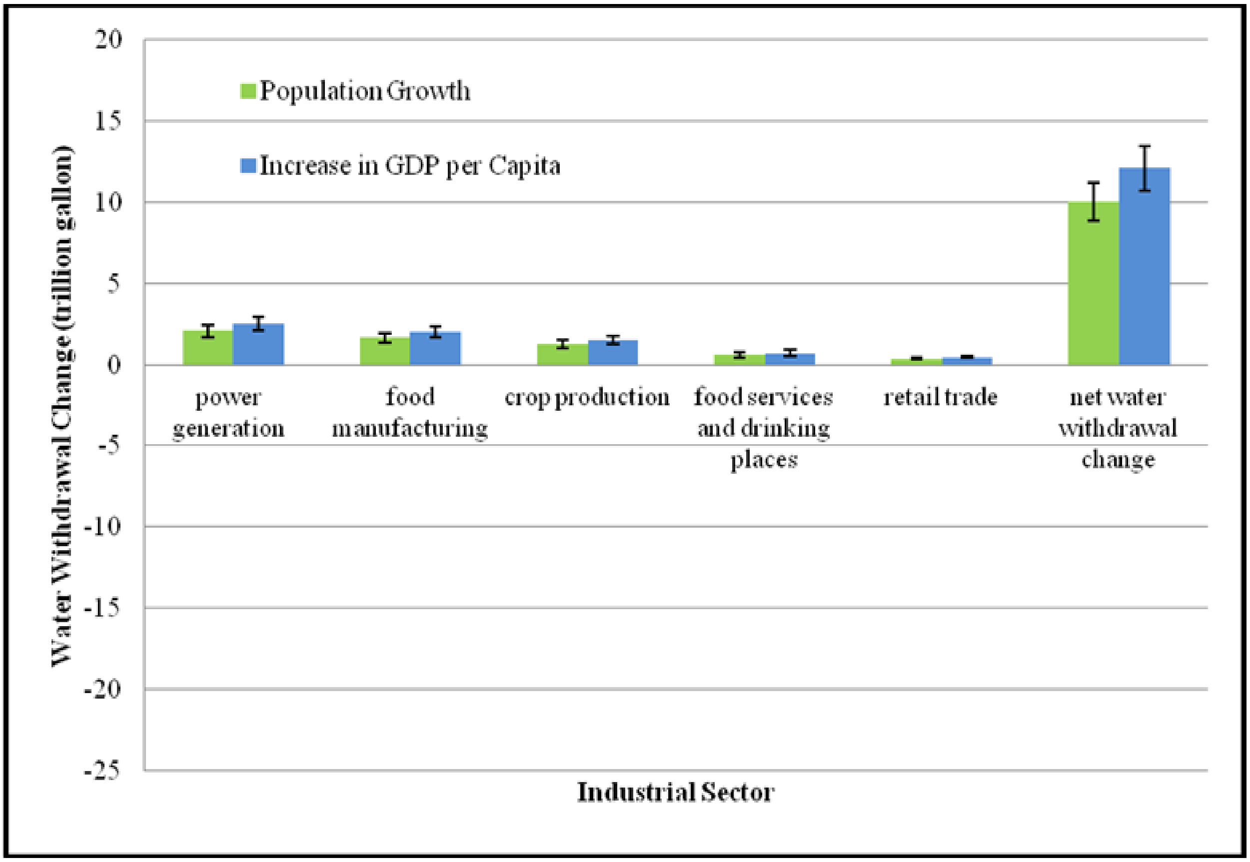

Figure 2-4. Five largest increased water withdrawal sectors between 1997 and 2002 *due to population and GDP per capita growth*. The bars present the mean of water withdrawal changes with increased population and GDP per capita across 120 decompositions, with ± one standard deviation across 120 decompositions also shown.

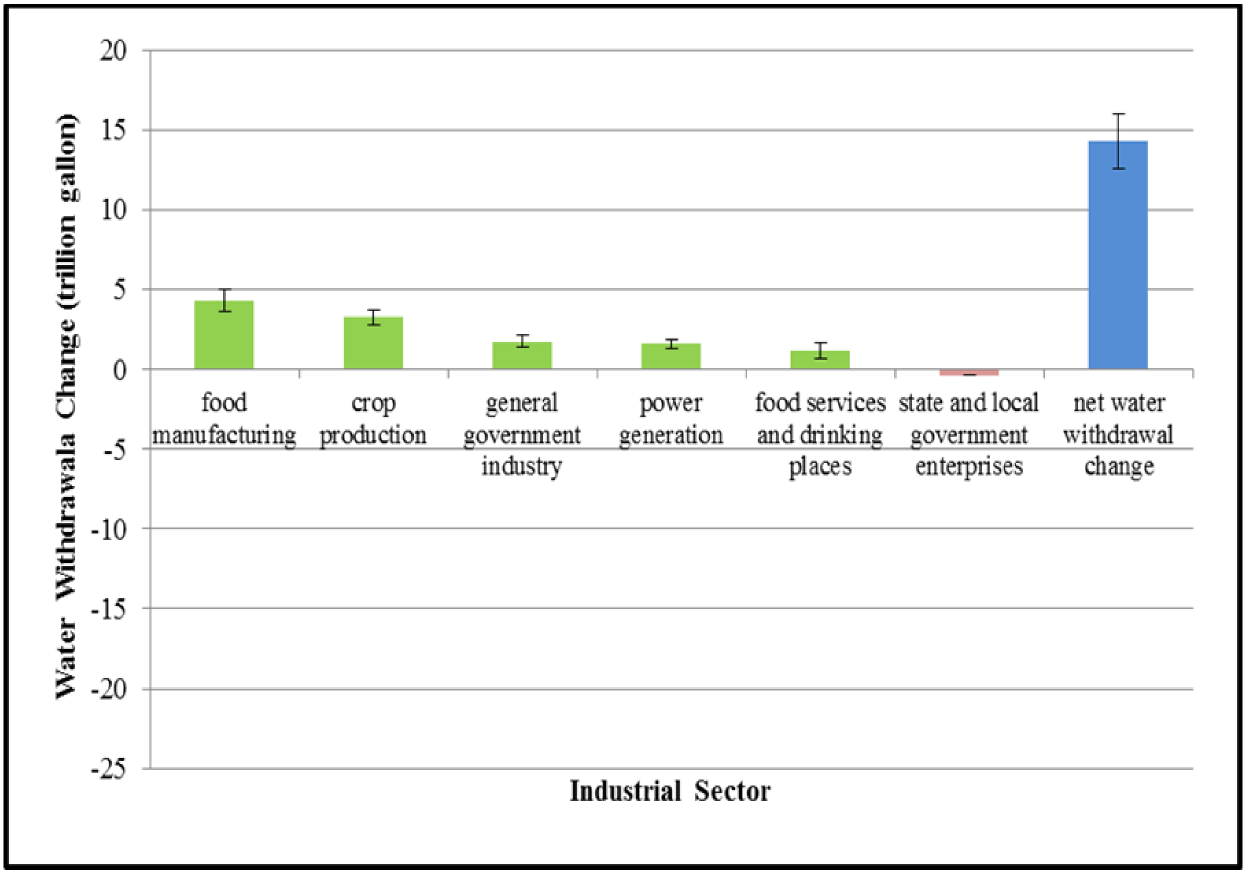

Figure 2-5. The largest increased and decreased water withdrawal sectors between 1997 and 2002 *due to change in water use intensity*. The bars present the mean of water withdrawal changes with changed water use intensity across 120 decompositions, with ± one standard deviation across120 decompositions also shown.

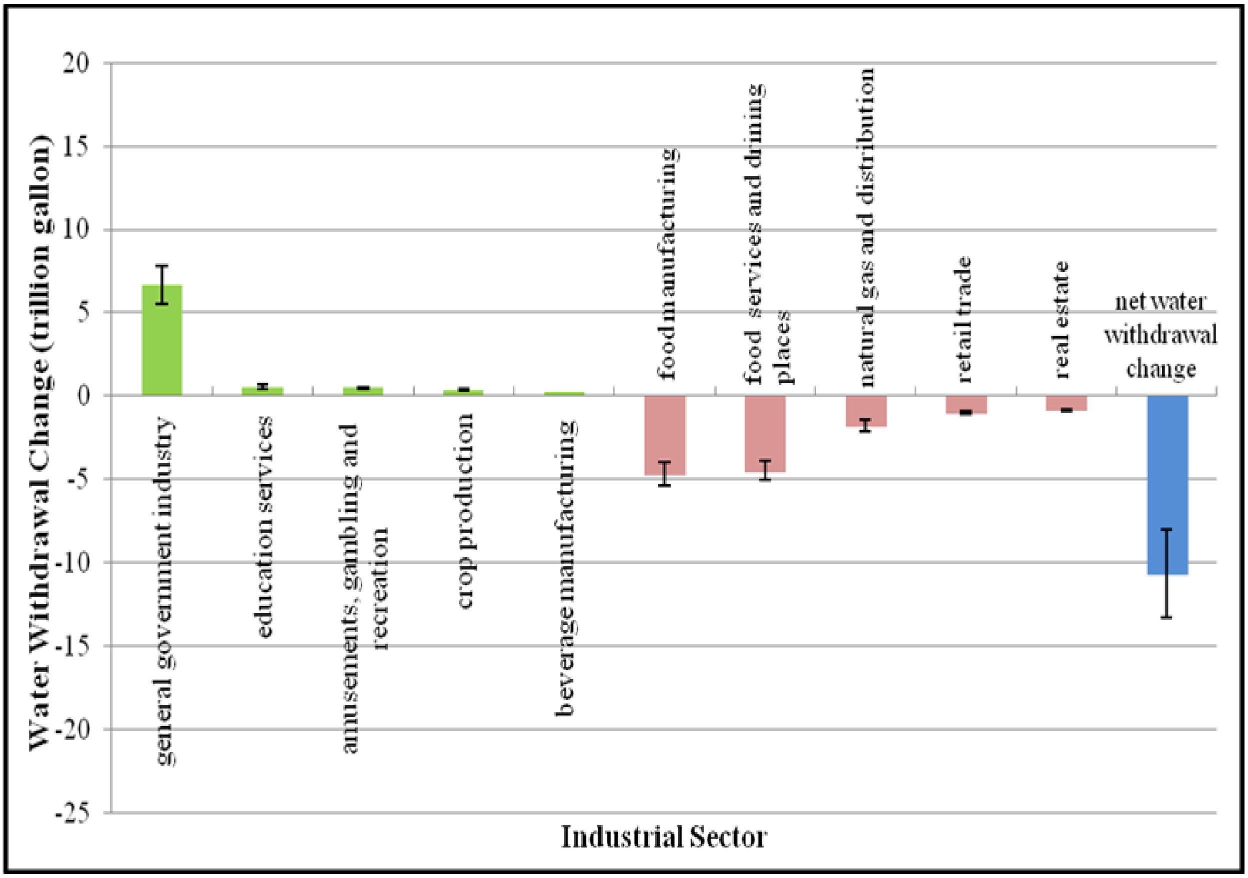

Figure 2-6. Five largest increased and decreased water withdrawal sectors between 1997 and 2002 *due to change in production structure*. The bars present the mean of water withdrawal changes with changed economic production structure across 120 decompositions, with ± one standard deviation across 120 decompositions also shown.

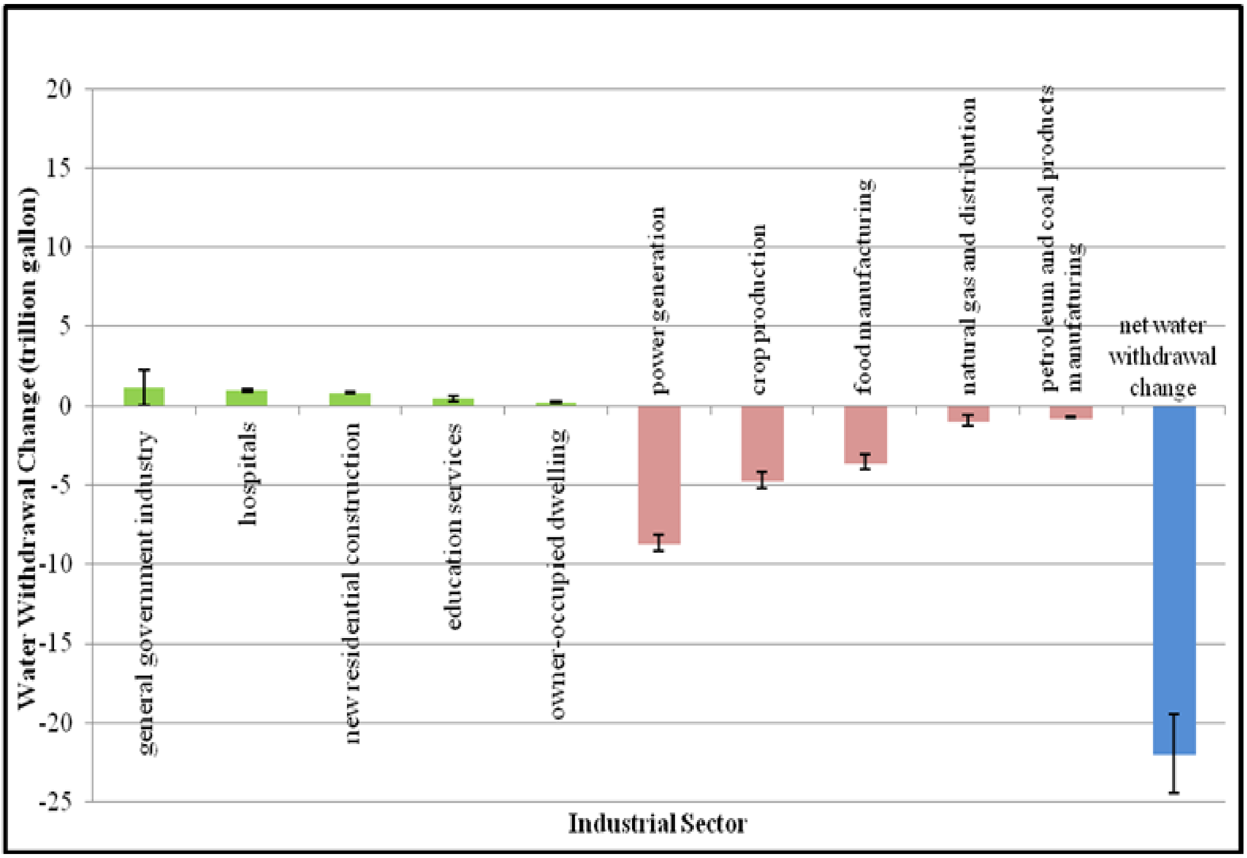

Figure 2-7. Five largest increased and decreased water withdrawal sectors between 1997 and 2002 *due to change in consumption patterns*. The bars represent the mean of water withdrawal changes with changed consumption patterns across 120 decompositions, with ± one standard deviation of water withdrawal changes based on 120 decompositions also shown.

Chapter 3: Projection of Total Water Withdrawals for U.S. Industrial Sectors across Various Scenarios for 2013-2030

This chapter, written by Hui Wang and co-authored by Mitchell J. Small, and David A. Dzombak, will be submitted for publication.

Abstract

The sustainability of U.S. water resources is facing challenges due to increasing water demand and decreasing water availability. Population, GDP per capita, water use intensity, production structure, and consumption pattern are primary factors governing total water withdrawal across industrial sectors. In this study, four future scenarios were developed for each of the five factors based on available predictions or historical data. The total water withdrawals for U.S. industrial sectors for 2013-2030 were projected using an economic input-output life cycle assessment (EIO-LCA) model with (1) fixed economic structure in which the production structure and consumption pattern were held constant at the 2012 level and the other three factors were varied across time; and (2) changing economic structure in which all five governing factors were changed across time. The EIO-LCA model with fixed economic structure introduced smaller uncertainty in the projected water withdrawal for U.S. industrial sectors than the EIO-LCA model with changing economic structure. The maximum projected total water withdrawal for 2030, corresponding to a scenario with maximum growth assumptions for all factors considered is 370 trillion gallons, which is more than 2.5 times the 2005 U.S. water withdrawal. The median of total water withdrawal will reach 180 trillion gallons, about 1.2 times the 2005 U.S. water withdrawal. The medians of total water withdrawals projected by the models with constant vs. evolving economic structure for 2013-2030 follow a continuous increasing trend, and the projected median values by the two models are comparable. The uncertainty in GDP per capita and water use intensity were the two most significant contributors to the uncertainty in projected total water withdrawals for U.S. industrial sectors.

3.1 Introduction

The sustainability of U.S. water resources is affected by a number of factors related to climate, land use and land cover, population, water quality, technological innovation, and social and economic changes (Roy et al., 2012; Shen et al., 2008). Water resource sustainability in the coming decades in many areas will face particular challenges from increasing water demand and decreasing water availability due to population growth, economic development, landscape alteration, and climate change (Schnoor, 2010).

This study focuses on projected water withdrawals for United States (U.S) industrial sectors from the present (2013) until the year 2030. Water withdrawals may be for water uses that are either non-consumptive – where the water is returned (often with modified water quality) to the local hydrologic system; or consumptive – where the water is lost to evaporation or captured in products or related long-term storage. In addition to *direct* water withdrawal for non-consumptive or consumptive use, production inputs to different sectors of the economy can be traced back through their supply chains and the cumulative water used to produce these upstream goods and services summed to estimate the indirect water use for the downstream sector. Here we refer to the withdrawal for direct use by each sector of the economy as "water withdrawal", while the sum of the direct and indirect water use by each sector is referred to as the "total water withdrawal".

Projections of water withdrawal for the U.S. at the national level have been performed by some agencies and researchers (Roy et al., 2012; Schnoor, 2010; Brown, 2000; Roy et al., 2005; Guldin, 1989; Chen et al., 2013). The previous studies have mainly focused on the forecast of

U.S. freshwater withdrawal. U.S. freshwater withdrawal projections generally have been made for the water use categories reported by the U.S. Geological Survey (USGS), based upon the historical water withdrawal trends, or water withdrawal per capita trends in combination with future population projections. Typically, high, medium, and low projections for these factors are developed and combined to represent alternative future scenarios of water demand and withdrawal. The published fresh water withdrawal projections show a wide range of variation due to the different assumptions associated with these scenarios. The USGS water use survey considers both freshwater and saline water. According to USGS historical data, freshwater use accounts for 85 percent of all water use. Like USGS, the water withdrawal studied here includes both freshwater and saline water withdrawal (Kenny at al., 2005; Huston et al., 2000; Solley et al., 1995; Solley et al., 1990; Solley et al., 1985). It is difficult to forecast future water withdrawal accurately, as there is too limited knowledge and forecasting ability for many of the key factors affecting future water withdrawals, such as the structure and size of the economy and the level of innovation in water-efficient technology (Brown et al., 2000). Interactions among the contributing factors of climate change, population growth, economic growth, technological innovation, and water use efficiency are also difficult to anticipate.

In this study, an economic input-output life cycle assessment (EIO-LCA) model (Hendrickson et al., 2005) with fixed economic structure and an EIO-LCA model with changing economic structure were applied and compared for their projections of the total water withdrawal for U.S. industrial sectors across combinations of various scenarios of population, economic growth and water efficiency for 2013-2030. The overall model incorporates the effects of population, GDP per capita, water use intensity, economic structure, and consumption patterns, on changes in U.S.

water withdrawal for each industrial sector (Wang et al., 2014). The EIO-LCA model with changing economic structure was used to project future water withdrawal for U.S. industrial sectors based on the alternative scenarios for the five governing factors, while production structure and consumption patterns were held constant the at 2012 level in the EIO-LCA model with fixed economic structure.

This study had the following specific objectives: (1) Develop feasible future scenarios for the governing factors affecting total water withdrawal for U.S. industrial sectors for 2013-2030 based upon the available predictions and historical data for population, GDP per capita, water use intensity, production structure, and consumption patterns; (2) project total water withdrawals across U.S. industrial sectors during the time period of 2013-2030 with two EIO-LCA model configurations (fixed economic structure vs. dynamic economic structure) for combinations of various scenarios for the governing factors, and compare the projections obtained from these two models; (3) evaluate the contributions of the uncertainty in governing factors to the variation in projected water withdrawals across the various scenarios; (4) obtain insight into the relative importance of the factors governing U.S. water use in the future.

3.2 Data and Methods

3.2.1 Economic Input-Output Life Cycle Assessment (EIO-LCA) Model

The EIO-LCA model was used to estimate U.S. total water withdrawal across all industrial sectors using information on water use intensity (water withdrawal per dollar of output) for each industrial sector and the matrix of inter-industry economic transactions (Blackhurst et al., 2010; Hendrickson et al., 2005; Wang et al., 2014). The EIO-LCA model enables estimation of the total water withdrawn by industrial sectors including the direct and supply chain water withdrawal based on the flow of goods and services across the sectors (Hendrickson et al., 2005; Wang et al., 2014; Blackhurst et al., 2010). The estimated water withdrawal obtained from this model excludes residential water withdrawals, which are not represented by any industrial sector (Wang et al., 2014; Blackhurst et al., 2010).

In the EIO-LCA model, the total water withdrawal can be represented as the product of five governing factors: population, GDP per capita, water use intensity, production structure, and consumption pattern (Wang et al., 2014; Guan et al., 2008).

$$\mathbf{W} = P * Yg * \mathbf{F} * \mathbf{L} * \mathbf{Yc} \qquad [3 - 1]$$

where W is a vector of total water withdrawal for the industrial sectors [gallons], P is U.S. resident population, Yg is GDP per capita [dollars/person], and F is the water use intensity matrix [gallons/dollar]. F is a diagonal matrix, and its diagonal entries are the water withdrawal per dollar of output for each sector (Blackhurst et al., 2010; Hendrickson et al., 2005; Wang et al., 2014). L, the production structure matrix, is a square matrix, and its elements represent the total requirement of intersectoral purchases per dollar of final consumption [dollars] (Wang et al., 2014; Horowitz et al., 2009). Yc is the vector of the national consumption pattern [non-dimensional]. Its elements describe the proportion of GDP produced by each industrial sector (Wang et al., 2014).

3.2.2 Scenario Development and Data Sources

Four scenarios were developed for each of the five governing factors in the EIO-LCA model: population, GDP per capita, water use intensity, production structure, and consumption pattern.

The 2012 data for these five factors were used as a constant baseline (current level) for comparison of the other scenarios. Three additional scenarios for each factor were developed based upon reported predictions or historical trends.

3.2.2.1 Population (P)

The U.S. Census Bureau has projected U.S. resident population based on the projected fertility rates, mortality rates and net international migration through 2060 for four scenarios: low series, middle series, high series and constant series (U.S. Census Bureau, 2012; U.S. Census Bureau, 2013). The four scenarios for population projections result from varying assumptions of net international migration, but all other assumptions and methodology for these four scenarios are the same (U.S. Census Bureau, 2012). The population projections under the low series, middle series and high series scenarios during 2013-2030 from the U.S. Census Bureau and 2012 population were used in this study. The population under the low series scenario is projected to reach 354 million in 2030, representing a 0.66% average annual growth rate. In the middle series, the average annual change in population is projected to be 0.74%, with the population increasing to 358 million in 2030. The population under the high series scenario is projected to increase to 363 million in 2030. The low, middle, and high series projected population and the 2012 real population were the four population scenarios used for the projections of water withdrawal for U.S. industrial sectors during 2013-2030.

3.2.2.2 GDP per capita

Sources of projected long-term GDP per capita are limited. The U.S. real GDP per capita and annual growth rates for 2013-2030 have been forecast by the Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA), with a 1.9% average annual growth rate projected during this period (U.S. ERS, 2014). The predicted GDP and population for 2013-2030 were used to generate other scenarios for GDP per capita. Four scenarios of future GDP for 2013-2030 were projected based on the real GDP in 2012 (The World Bank, 2014a) and three scenarios of GDP growth rate proposed by the U.S. Energy Information Administration (EIA) (U.S. EIA, 2013), including constant economic growth (0% annual growth rate), low economic growth (2% annual growth rate), medium economic growth (2.5% annual growth rate), and high economic growth (2.9% annual growth rate). The GDP projected under these four scenarios and four possible scenarios of projected population (2012 population, low, middle and high series projected population) (U.S. Census Bureau, 2013) were used to develop the scenarios of GDP per capita for 2013-2030.

These four scenarios of projected population and GDP generated 16 possible scenarios of GDP per capita for 2013-2030. The estimated average annual growth rate of these 16 possible scenarios of GDP per capita during 2013-2030 ranged from -0.9% to 2.9%, which provided a guide to set -0.95% as the low economic growth scenario, which is negative 0.5 times the average annual growth rate projected by the UDSA. The USDA projected annual growth rate of GDP per capita, representing a 1.9% average annual growth rate, was used as the medium economic growth scenario. The USDA projected annual growth rate multiplied by 1.5, resulting in 2.9% average annual growth rate of GDP per capita, was designated as the high economic growth scenario from 2013 to 2030. The U.S. 2012 GDP per capita was used for the projection of water withdrawal as the constant scenario (The World Bank, 2014b).

3.2.2.3 Water use intensity (F)

Water use intensity represents the amount of water withdrawn for every dollar of output (Hendrickson et al., 2005; Wang et al., 2014; Blackhurst et al., 2010). Three scenarios for water use intensity were generated mainly based upon the historical water productivity during 1992-2011 (The World Bank, 2014c). The water productivity measures the dollars of GDP produced with every gallon of freshwater withdrawal (The World Bank, 2014c). Due to data limitations, we assumed that all the industrial sectors have the same annual growth rate of water use intensity as the overall water use intensity during 2013-2030. The overall water use intensity refers to the total water withdrawn for every dollar of total industry output produced in the U.S. economy. The ratio of GDP to total industry output, and the percentage of freshwater withdrawal to total water withdrawal were assumed to be constant for 2013-2030. The change rate of the inverse of water productivity (total freshwater withdrawal per dollar of GDP) is equal to the rate of change of the overall water use intensity (total water withdrawal per dollar of total industry output) under these two assumptions. The annual growth rate of the inverse of water productivity approximately ranged from -3% to -1% during 1992-2011, with the growth rate exhibiting an increasing trend during this period (The World Bank, 2014c), which suggests that a positive growth rate should be considered. -3%, -1% and 0.5% were selected to be the average annual change rate for water use intensity for the high reduction, low reduction and low increase scenarios for 2013-2030, respectively, based on the historical trends in water productivity. The Appendix B provides the details for scenario designs for water use intensity. The water use intensity for the three scenarios for 2013-2030 was projected based on 2012 water use intensity and the three annual growth rate scenarios. The water use intensity for U.S. industrial sectors in 2012 was considered as the constant baseline scenario. It was estimated based upon 2002 water use intensity, the latest available water use intensity for the industrial sectors (Wang et al., 2014), with the average annual growth rate of the inverse of water productivity -2.3% during 2002-2007 and -1% during 2007-2012 (The World Bank, 2014c).

3.2.2.4 Production structure (L)

The production structure is derived from the economic make and use tables provided by the U.S. Bureau of Economic Analysis (BEA) (U.S. BEA, 2013). The make table represents the production of commodities by industries, and the use table indicates the commodities used by intermediate industries and final consumers (Horowitz et al., 2009).

3.2.2.4.1 Production structure in the EIO-LCA model with fixed economic structure

The production structure was assumed to remain constant at the 2012 level in the EIO-LCA model with fixed economic structure, which results in only one scenario for production structure in this model. The aggregated make and use tables in 2012 were used to compute the 2012 production structure (U.S. BEA, 2013). To match the industrial sectors available for analysis in the most recent water use intensity database (for the year 2002), four sectors *Motor vehicle and parts dealers*, *Food and beverage stores*, *General merchandise stores*, and *Other retail* were merged into one sector *Retail trade*. The modified make and use table for 2012 include 66 industries and 68 commodities after the combination of sectors.

3.2.2.4.2 Production structure in the EIO-LCA model with changing economic structure

Scenarios with changing economic structure were also considered. Four scenarios for production structure were included in the EIO-LCA model with changing economic structure. The 2012 production structure was considered as the constant scenario in this model, and the other three scenarios were generated based upon the annual make and use tables from 1997 to 2012 at the aggregated level. The sectors in the 1997-2012 make and use tables were merged to match the industrial sectors in 2002, which resulted in 66 industries and 68 commodities included in the 1997-2012 make and use tables.

We assumed that all total industry outputs and intermediate industry outputs for the 66 industries, and all total commodity outputs and intermediate commodity outputs for the 68 commodities follow a log-linear relationship with time during 1997-2012. Three scenarios for total industry outputs and intermediate industry outputs for 66 industries, and total commodity outputs and intermediate commodity outputs for 68 commodities for 2013-2030 were projected based upon 0.75 times, 1.0 times, and 1.5 times estimated annual growth rates obtained from the log-linear relationship versus time during 1997-2012, with the three scenarios of predicted GDP (low economic growth (2% annual growth rate), medium economic growth (2.5% annual growth rate) and high economic growth (2.9% annual growth rate)) as the constraints. Scenarios for the make and use tables for 2013-2030 were developed based upon the scenarios for the four economic variables described above.

Three scenarios for make tables for 2013-2030 were projected based on the 2012 make table, three scenarios of projected total industry outputs (row totals of the make table), and total commodity outputs (column totals of the make table) for 2013-2030 calculated using the RAS method. The RAS method is a bi-proportional technique and was employed to forecast an EIO table based on the EIO table of a base year, with the given row and column totals of the EIO table for a predicted year (Lahr, et al., 2004). It is an iterative proportional fitting procedure that uses the row and column adjustment coefficients "R" and "S" to adjust the table until the adjusted table is balanced (Lahr et al., 2004). Three scenarios for use tables for 2013-2030 were projected based on the intermediate portion of the 2012 use table, three scenarios of projected intermediate industry outputs (column totals of the intermediate portion of the use table), and intermediate commodity outputs (row totals of the intermediate portion of the use table) for 2013-2030 calculated with the RAS method as well. The production structures under three scenarios for 2013-2030 were obtained from the three scenarios of the projected make and use tables according to the mathematical derivation of the total requirements tables for input-output analysis (U.S. BEA, 2013). Information about the fitting of log-linear trend curves to the elements of the input-output matrix and subsequent specification of scenarios for production structure change is presented in the Appendix B.

3.2.2.5 Consumption pattern (Yc)

The consumption pattern refers to the share of GDP produced by the various industrial sectors. The consumption pattern is derived from the use table, which implies that the consumption pattern follows the same scenarios as the production structure.

Summaries of the scenarios for governing factors in the EIO-LCA model with fixed economic structure and changing economic structure are shown in Tables 3-1 and 3-2, respectively.

3.3 Results and Discussion

Various scenarios for population, GDP per capita, water use intensity, production structure, and consumption pattern were used to develop the projections of total water withdrawal for industrial sectors for 2013-2030, employing the EIO-LCA model, first with fixed economic structure and then with projected changes in economic structure. The projections of water withdrawal in this study are not intended to provide an exact (or even a probabilistic) estimate of the amount of water needed for U.S. industrial sectors in the future, but rather to present a view of potential future water demand across a combination of different possible conditions of population, economic growth, and technological change.

This study is intended to provide insight into the influence of the various factors governing water use sustainability in the future, and to help identify the factors most likely to affect the magnitude of future water stress in the U.S. The scenarios developed in this study are not intended to provide a probabilistic assessment of future economic, technological, and water use outcomes. While the probabilities associated with each future scenario are surely not equal, estimation of these probabilities is beyond the scope of this study. The purpose is instead to lay out a set of possible future outcomes and to explore how the various causative factors interact to fashion the scenario.

3.3.1 Projected Total Water Withdrawal for U.S. Industrial Sectors by the EIO-LCA Model with Fixed Economic Structure for 2013-2030

Figure 3-1 shows the total projected water withdrawal for U.S. industrial sectors for all scenarios and the median of these projections computed using the EIO-LCA model with fixed economic structure for the period 2013-2030. Four different scenarios were assigned to each of population, GDP per capita, and water use intensity, while production structure and consumption pattern were held at the 2012 level in this model. This yielded 64 scenarios of projected water withdrawal for each year during 2013-2030. The range in the water withdrawal projections for all industrial sectors grows wider over time as the effects of scenario differences in population, economic, and technological change accumulate over the 18-year period. The total water withdrawal for U.S. industrial sectors was projected to be in the range of 155-167 trillion gallons in 2013. The projected minimum water withdrawal decreased by 50% in 2030 relative to 2013, while the maximum water withdrawal doubled between 2013 and 2030. The projected total water withdrawals for all industrial sectors range from 80 to 340 trillion gallons in 2030. The projected median value across scenarios experiences a slight growth, increasing from 161 trillion gallons in 2013 to 176 trillion gallons in 2030 with an annual average growth rate of 0.5%. The maximum total water withdrawal for each year was projected to occur when both population and GDP per capita experience high growth rates, and water use intensity increases at a low rate.

As shown in Figures 3-2 and 3-3 the effects of various scenarios for GDP per capita and water use intensity on the projected water withdrawal are more pronounced than the different scenarios for population. Figure 3-2a shows that the highest water withdrawal scenarios tend to be associated with a high GDP per capita growth rate (pink curves), followed by those with a medium GDP per capita growth rate (blue curves). Figure 3-2b indicates that the lowest water withdrawal scenarios tend to be associated with high reductions in water use intensity (red curves) followed by those with a medium reduction in water use intensity (green curves).

Figure 3-3 indicates no discernible relationship between high or low water withdrawal scenarios and the population growth. Variations in the factors in the model, in particular, GDP per capita and water use intensity mask the effects of population growth differences on water withdrawals across the scenarios considered. Extreme increases in GDP per capita and water use intensity generated extreme projected water withdrawals. The high growth scenario of GDP per capita (3% annual growth rate) caused projected water withdrawal to range from 155-340 trillion gallons in 2030, while its low growth scenario resulted in a much lower range for the water withdrawal (80-170 trillion gallons) in 2030. The projected water withdrawals resulting from the scenarios of water use intensity were distinctly different as well. The water withdrawal under the high reduction scenario for water use intensity (with a decrease rate of 3% every year) was forecast to vary from 80-180 trillion gallons in 2030, while the low increase scenario for water use intensity (0.5% annual growth rate) caused a doubling of water withdrawal projections compared to the high reduction scenario of water use intensity, ranging from 150-340 trillion gallons in 2030.

3.3.2 Projected U.S. Total Water Withdrawal for Industrial Sectors by EIO-LCA Model with Changing Economic Structure for 2013-2030

Figure 3-4 indicates the total projected water withdrawal for U.S. industrial sectors for all scenarios and the median of these projections as generated using the EIO-LCA model with changing economic structure and the same combinations of scenarios for population, GDP per capita, and water use intensity as in the previous section (where a fixed economic structure was assumed). In this model, production structure and consumption pattern were assumed to change under four possible scenarios during this time period. With the same 64 scenarios for combinations of population, GDP per capita, and water use intensity as in the EIO-LCA model with fixed economic structure, this case for a changing economic structure yields 256 scenarios for the projected water withdrawal for U.S. industrial sectors for each year.

The medians of total water withdrawal for all industrial sectors during 2013-2030 follow a continuously increasing trend, from 161 to 181 trillion gallons with an average annual growth rate of 0.70% during these 17 years. The median growth rate is somewhat higher than in the case with fixed economic structure (0.5%). The total water withdrawal across different scenarios was projected to range from 154-167 trillion gallons in 2013, while the range of projected total water withdrawal widens to 80- 380 trillion gallons in 2030. More than 50% of the projected total water withdrawal scenarios are in the range of 100-200 trillion gallons in 2030. The maximum total water withdrawal for U.S. industrial sectors was predicted to result from a combination of scenarios with both population and GDP per capita at a high growth rate, the water use intensity at a low growth rate, and the current production structure and consumption pattern during 2013-2015. The maximum water withdrawal was associated with the 1.5 times the 15-year log-linear baseline trend scenario for production structure and consumption pattern, GDP per capita at a high growth rate, and the water use intensity at a low growth rate starting from 2016.

Figures 3-5 and 3-6 present the total water withdrawal projected by the EIO-LCA model with changing economic structure under the various scenarios for GDP per capita, water use intensity, population and, economic production structure, individually. As Figure 5 shows, the differences in the projected water withdrawals under various scenarios for both GDP per capita and water use intensity are distinct. The projected water withdrawals under the medium and high growth scenarios for GDP per capita vary from 130-380 trillion gallons in 2030, while ranging from 80-

220 trillion gallons under the constant and low reduction scenarios. The medium and high reduction scenarios for water use intensity were projected to cause a lower range of total water withdrawal (80-280 trillion gallons) than the constant and low increase scenarios (135-380 trillion gallons). However, the varying scenarios for population and economic production structure are unable to distinguish the ranges of projected water withdrawals clearly. The variations in projected water withdrawal for U.S. industrial sectors under the two extreme growth scenarios (constant scenario and high growth scenario) for population are 80-330 trillion gallons and 90-380 trillion gallons respectively, and this difference is not significant. The ranges of projected water withdrawals for industrial sectors under the four scenarios for production structure almost overlap, with the lowest range of 80-340 trillion gallons under the constant scenario for production structure and the highest range of 80-380 trillion gallons predicted for the 1.5 times the 15-year log-linear trend scenario for the economic production structure.

The largest water withdrawals for U.S. industrial sectors projected by the EIO-LCA model with fixed and changing economic structure occur under the scenarios for high growth of population, GDP per capita and water use intensity. As Figures 3-1 and 3-4 show, the largest projected water withdrawals for U.S. industrial sectors by both models shows a dramatic increase from 2013-2030, more than 300 trillion gallons in 2030, exceeding 2.5 times the 2005 level. Although this extreme projection accelerates the trend in increases in total water withdrawal for current years (during the period of 1980 to 2005) and is much larger than most previous projections, a similar growth rate of water withdrawal was found in the historical data (from 1950 to 1975) (Kenny et al., 2005). The increases in the median of projected total water withdrawal across time are not significant. Both models predict that the median of total water withdrawal will reach about 180 trillion gallons in 2030, which is comparable to the projections in previous studies (Roy et al., 2012; Brown et al., 2000; Roy et al., 2005).

As shown in Figures 3-1 and 3-4, the projected maximum water withdrawals in 2030 are very large relative to current values and would certainly stress water supply systems significantly. Water managers would likely react and adapt to such stresses long before they reached such high levels. As mentioned earlier, the scenarios evaluated are not intended to provide a probabilistic assessment of potential future outcomes. Scenario "switching" might also occur, in which adaptations to water shortages (as described above) or other outcomes could together affect population, economic growth, technology, and/or water use. In addition, water shortages could stimulate the development of technological innovations that reduce water use intensity in different sectors. Severe water shortages might also cause a contraction in the economy, reducing economic growth (and plausibly population growth, for example, due to reductions in resources for health care or reduced economic opportunity for new immigrants). To account for such adaptations and feedback mechanisms, the modeling approach could be modified by adjusting the scenarios to allow population growth, economic growth, and technological innovation rates to change during periods of water shortage (or surplus). Models allowing for such adaptations should be explored in future studies.

3.3.3 Analysis of Variance in Projected Total Water Withdrawal for U.S. Industrial Sectors for 2013-2030

An analysis of variance (ANOVA) was used to evaluate the relative contributions of the governing factors in the EIO-LCA models (with fixed economic structure and with changing economic structure) to the uncertainty in the projected total water withdrawals for 2013-2030.

Total water withdrawals for U.S. industrial sectors projected by both EIO-LCA models show significant variations across various scenarios during the period from 2013 to 2030. The variations in projected total water withdrawal result from the uncertainty in future conditions of population, GDP per capita, technology, and consumption patterns.

Figure 3-7 summarizes how much of the variance across scenarios in the total water withdrawals projected by the EIO-LCA model with fixed economic structure is accounted for by the different values and effects of changes in population, GDP per capita and water use intensity. As shown in this figure, the variance caused by each factor experiences a continuous increase during 2013-2030, and the total variance in the projected total water withdrawal increases by 500 times during this time period. The contribution of variations in future population to variance in the total projected water withdrawal is the smallest, and the effects of variations in the GDP per capita and water use intensity on the variations in projected total water withdrawals are dominant. More than 95% of the variance in the projected water withdrawal comes from the uncertainty in future conditions of GDP per capita and water use intensity.

Figure 3-8 shows the variances in total water withdrawal for U.S. industrial sectors projected by the EIO-LCA model with changing economic structure resulting from variation in the five governing factors in this model: population, GDP per capita, water use intensity, production structure and consumption patterns. The variance in projected water withdrawal across scenarios in 2030 is 530 times the variation in 2013. The high variance in the projections mainly results from the uncertainty in future GDP per capita and water use intensity, and the effects of variation in the other three factors (population, production structure and consumption patterns) are much smaller. More than 50% of the uncertainty in projected total water withdrawal results from the various scenarios of GDP per capita, and the uncertainty in future water use intensity accounts for approximate 40% of the variance in the projection.

As shown in Figures 3-7 and 3-8, the uncertainties in GDP per capita and water use intensity are the two most significant factors affecting the variance of the projected total water withdrawals for 2013-2030. Although the consideration of changes in production structure and consumption pattern in the EIO-LCA model with changing economic structure leads to a greater variance in the projection, the effects of uncertainties in production structure and consumption pattern on the uncertainty in projected total water withdrawal are relatively small during this time period. The generation of scenarios for production structure and consumption patterns is based upon the assumptions of log-linear trends in industry output, commodity output, intermediate industry output and intermediate commodity output for all industrial sectors, but the correlation between changes in these four economic variables and changes in production structure and consumption patterns was not strong during the calibration period (1997-2012). The variations in production structure and consumption patterns could result in a larger effect on future water withdrawals, which will depend on the direction and pace of evolution in the economy.

An overall implication of the scenario analysis is that limits or decreases in the growth of GDP per capita and water use intensity allow for reductions in water withdrawal. GDP per capita is an indicator of economic conditions in a country, and it is generally used to measure the standard of living. As such, while decreases in GDP per capita can reduce water withdrawal rates (and environmental impact in general), this route is generally not preferred. Water use intensity is an indirect measurement of water use efficiency, and improvements in water use efficiency can promote reductions in total water withdrawal for all industrial sectors. For example, the use of more recirculating cooling systems in power generation plants can yield reductions in direct water use for the electricity sector (NETL, 2009), as well as a reduction in indirect water use for those sectors that use electricity in their supply chain (virtually all sectors of the economy). Similarly, improvements in water use efficiency in the agricultural and food manufacturing sectors (e.g., with more efficient irrigation) will percolate through the economy, reducing indirect (and total) water use significantly (Wang et al., 2014). While our scenarios assume equal rates of change in water use efficiency across all sectors of the economy, important differences between sectors could occur and further studies to assess and anticipate these differences are needed.

Due to the limitations of EIO-LCA modeling, this study has ignored additional factors which are likely to affect future water demand and withdrawals, such as water price and changing education and awareness among industry and consumers. Two simple models that could serve as a first platform for assessing these effects (an IPAT model and a simplified IPAT model) are presented in Appendix B and are used there to project the total water withdrawal (including total water withdrawal for all industrial sectors) as well as residential water withdrawal. U.S. long-term water withdrawal (2013-2100) projected by the IPAT model is also shown in Appendix B.

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Table 3-1. Summary of various scenarios for governing factors in the EIO-LCA model with fixed economic structure

Scenario	Population	GDP per capita	Water Use Intensity	Production Structure	Consumption Pattern
1	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)
2	*Low growth* (0.66% annual growth rate)	*Low reduction* (negative Half USDA projected annual growth rate during 2013-2030: 0.95% average annual decrease rate)	*High reduction* (3% annual decrease rate during 2013-2030)	NA	NA
3	*Medium growth* (0.74% annual growth rate)	*Medium growth* (USDA projected annual growth rate during 2013-2030: 1.9% average annual increase rate	*Medium reduction* (1% annual decrease rate during 2013-2030)	NA	NA
4	*High growth* (0.82% annual growth rate)	*High growth* (1.5 times USDA projected annual growth rate during 2013-2030: 2.9% average annual increase rate)	*Low increase* (0.5% annual increase rate during 2013-2030)	NA	NA

Table 3-2. Summary of production structure and consumption pattern scenarios for governing factors in the EIO-LCA model with changing economic structure (Note: in scenarios 1-4 the assumptions for population, GDP per capita, and water use intensity are the same in this model as those in the model with fixed economic structure shown in Table 3-1.)

Scenario	Production Structure	Consumption Pattern
1	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)
2	*0.75 times 15-year log-linear trend* (0.75 times annual growth rate of estimated commodity output, commodity intermediates, industry output, industry intermediates based on logarithm linear relationship versus time during 1997-2012)	*0.75 times 15-year log-linear trend* (0.75 times annual growth rate of estimated commodity output, commodity intermediates based on logarithm linear relationship versus time during 1997-2012)
3	*15-year log-linear trend* (estimated commodity output, commodity intermediates, industry output, industry intermediates based on logarithm linear relationship versus time during 1997-2012)	*15-year log-linear trend* (estimated commodity output, commodity intermediates based on logarithm linear relationship versus time during 1997-2012)
4	*1.5 times 15-year log-linear trend* (1.5 annual growth rate of estimated commodity output, commodity intermediates, industry output, industry intermediates) based on logarithm linear relationship versus time during 1997-2012)	*1.5 times 15-year log-linear trend* (1.5 times annual growth rate of estimated commodity output, commodity intermediates based on logarithm linear relationship versus time during 1997-2012)

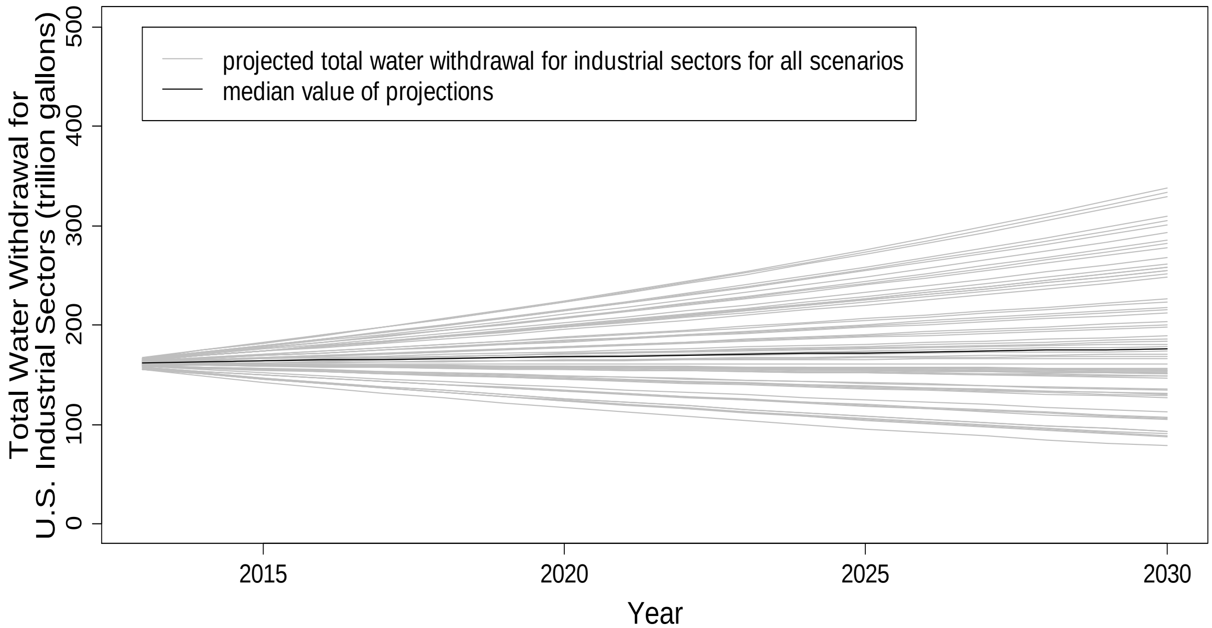

Figure 3-1. Projected total water withdrawals for U.S. industrial sectors for 2013-2030 under 64 scenarios by the EIO-LCA model with *fixed economic structure*.

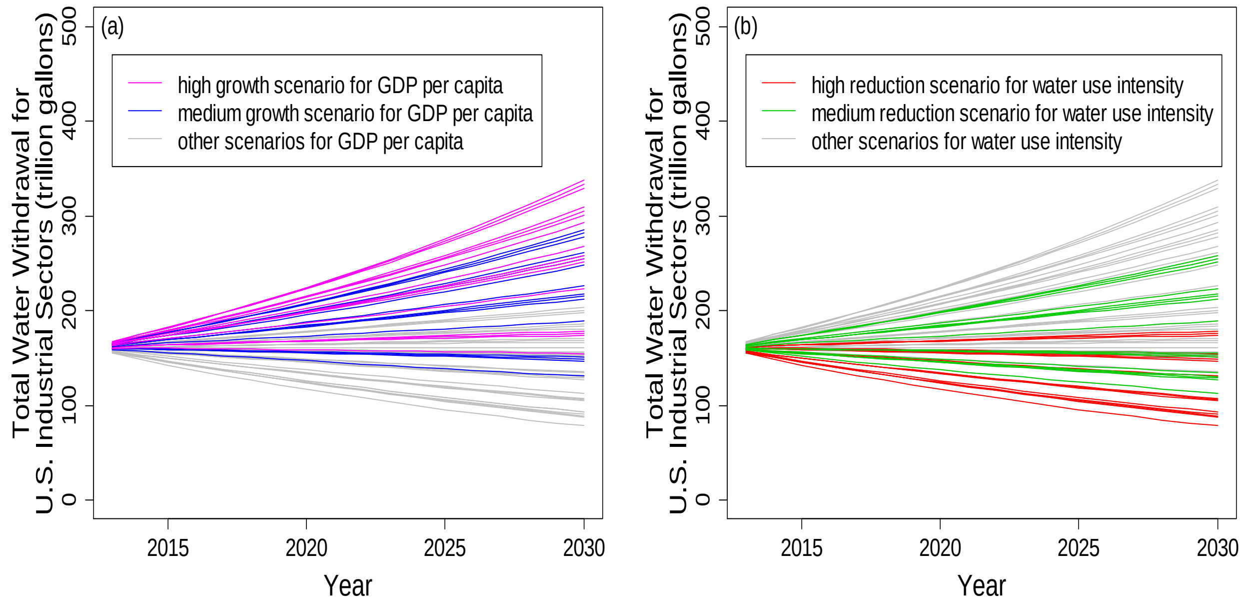

Figure 3-2. Projected total water withdrawal for U.S. industrial sectors for 2013-2030 by EIO-LCA model with *fixed economic structure* under various cenarios of GDP per capita and water use intensity. (a) Effect of GDP per capita. Figure highlights the projected water withdrawal for industrial sectors under medium and high growth scenarios for GDP per capita. (b) Effect of water use intensity. Figure highlights the projected water withdrawal for industrial sectors under medium and high reduction scenarios for water use intensity.

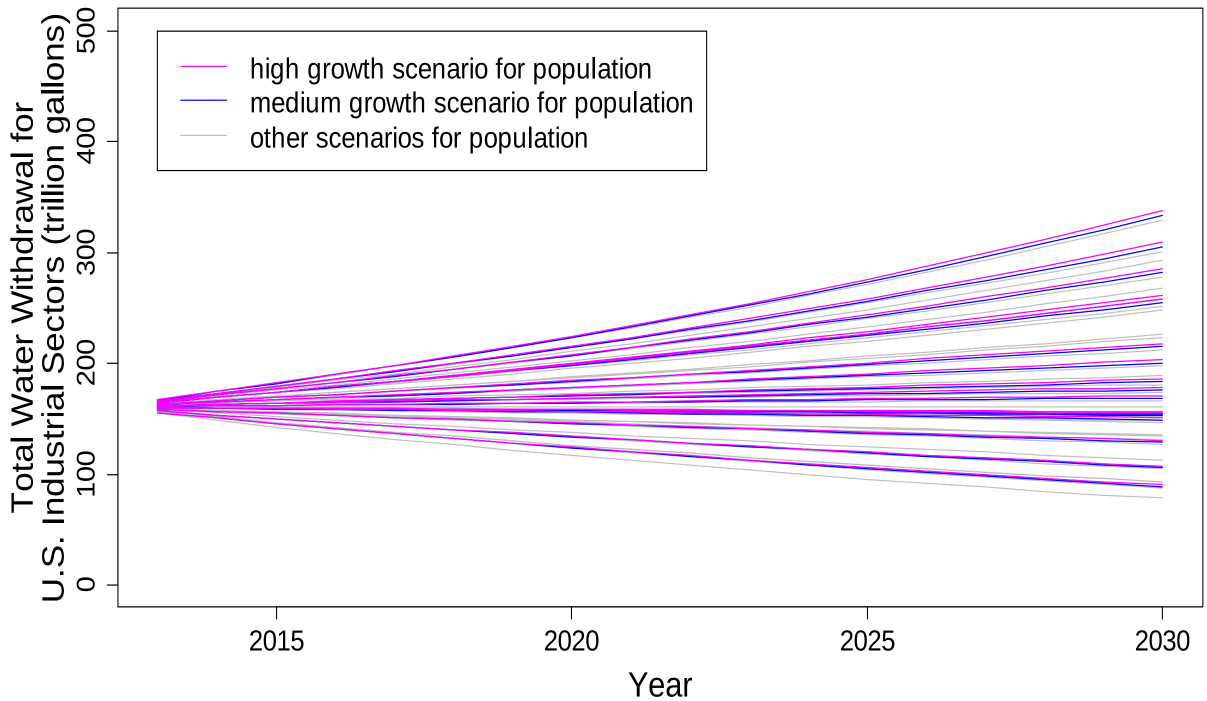

Figure 3-3. Projected total water withdrawal for U.S. industrial sectors for 2013-2030 by the EIO-LCA model with *fixed economic structure* under various scenarios for population growth

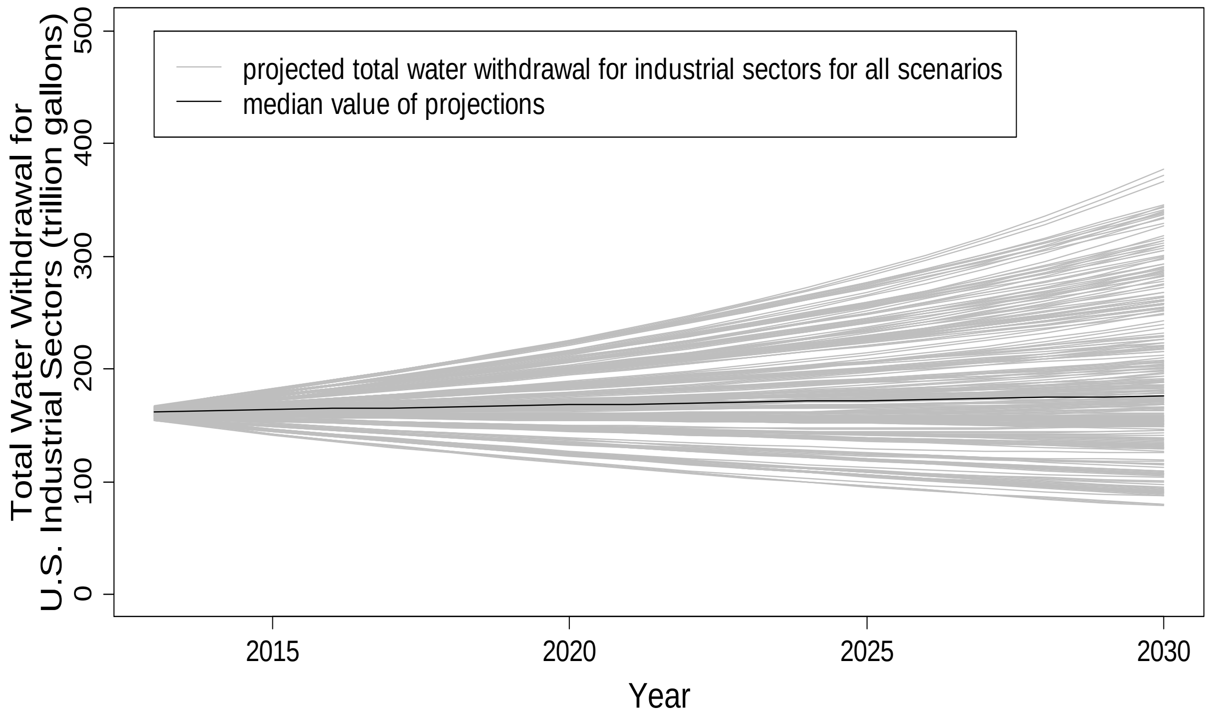

Figure 3-4. Projected total water withdrawals for U.S. industrial sectors for 2013-2030 under 256 scenarios by the EIO-LCA model with *changing economic structure*

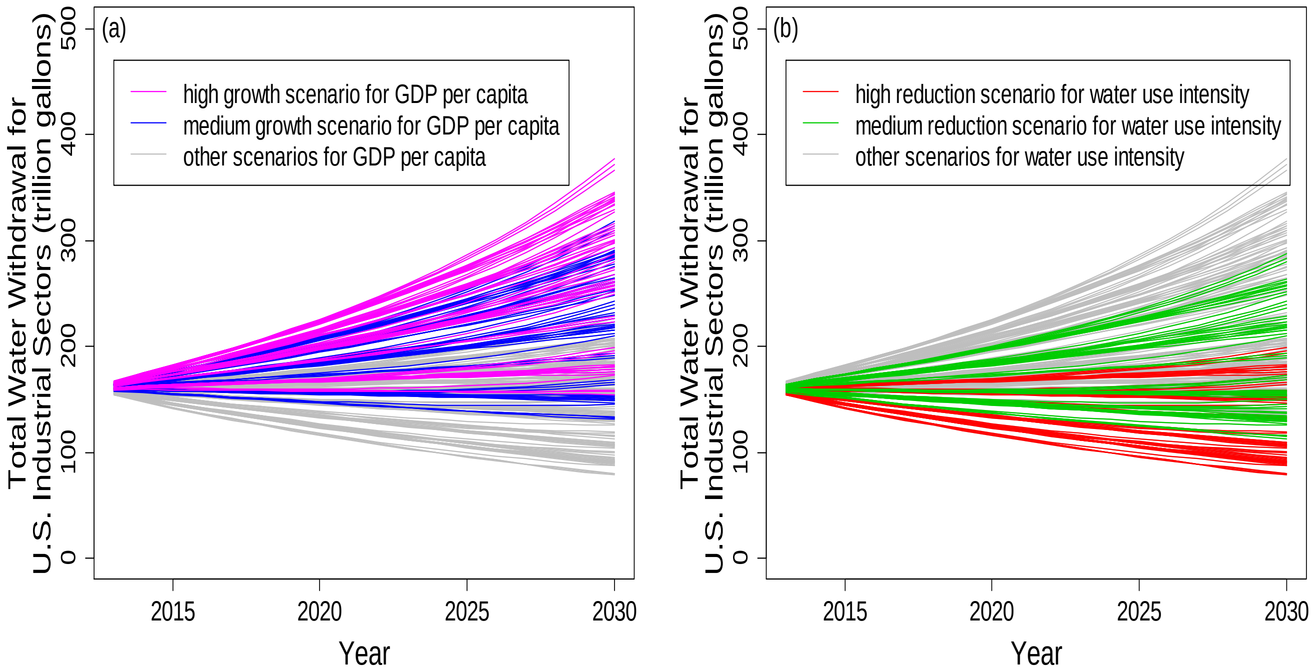

Figure 3-5. Projected total water withdrawal for U.S. industrial sectors for 2013-2030 by the EIO-LCA model with *changing economic structure* under various scenarios for GDP per capita and water use intensity. (a) Effect of GDP per capita. Figure highlights the projected water withdrawal for industrial sectors under medium and high growth scenarios for GDP per capita. (b) Effect of water use intensity. Figure highlights the projected water withdrawal for industrial sectors under medium and high reduction scenarios for water use intensity.

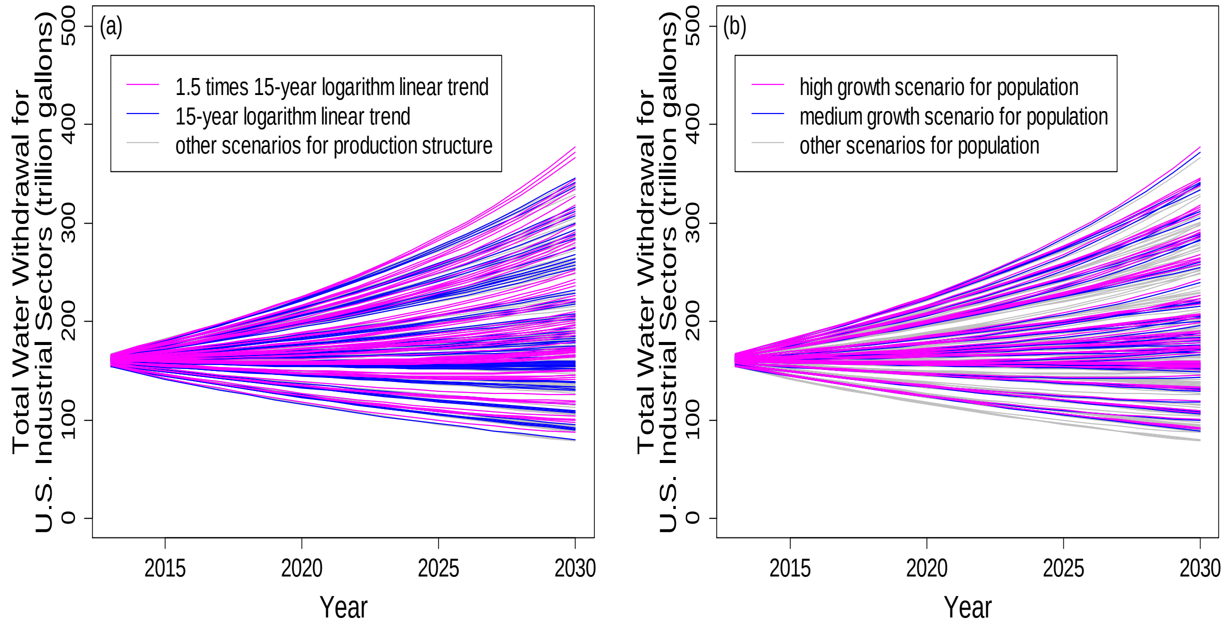

Figure 3-6. Projected total water withdrawal for U.S. industrial sectors for 2013-2030 by the EIO-LCA model with *changing economic structure* under various scenarios for population and production structure. (a) Effect of economic production structure. Figure highlights the projected water withdrawal for industrial sectors under 1.5 times the 15-year log-linear trend and 15-year log-linear trend scenario for production structure. (b) Effect of population. Figure highlights the projected water withdrawal for industrial sectors under medium and high growth scenarios for population.

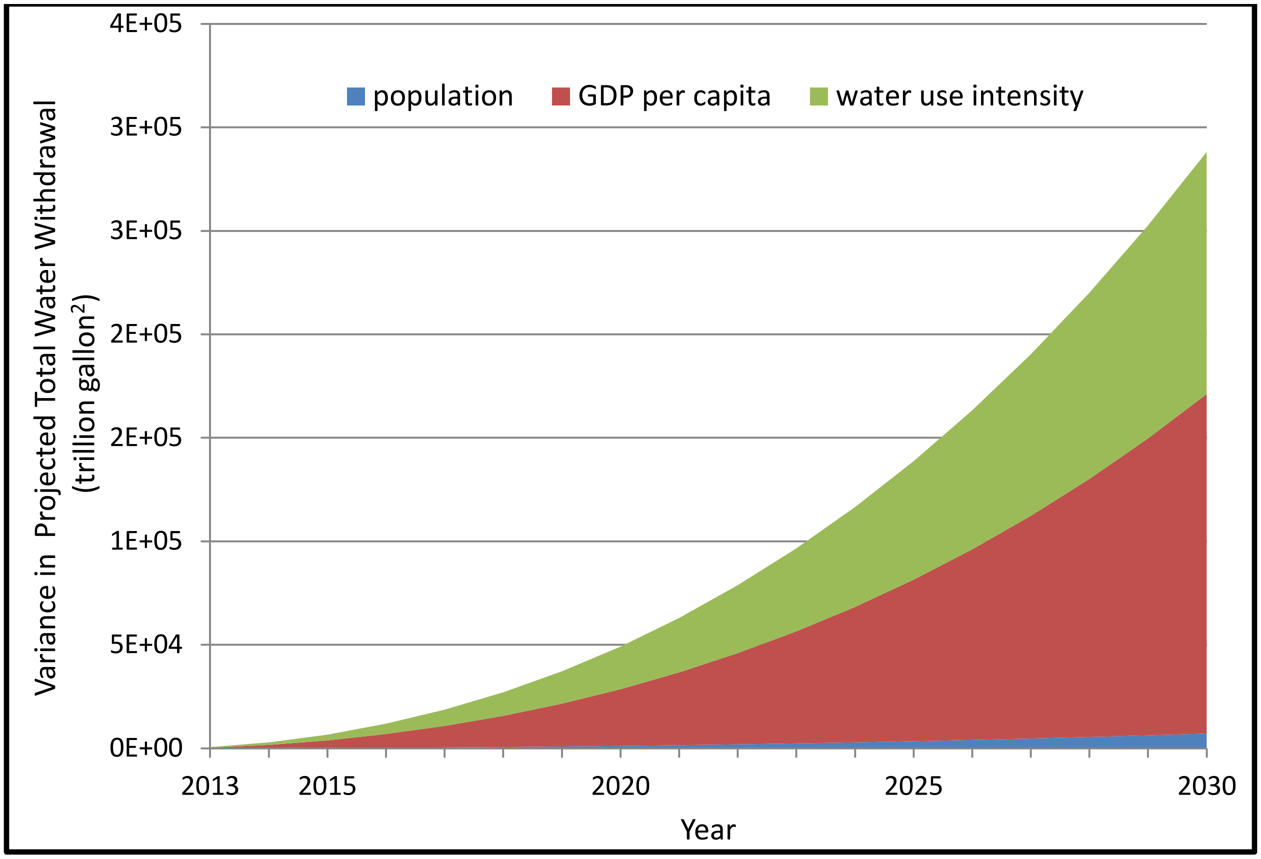

Figure 3-7. Contribution of uncertainty in governing factors to variation in water withdrawal projected by the EIO-LCA model with fixed economic structure

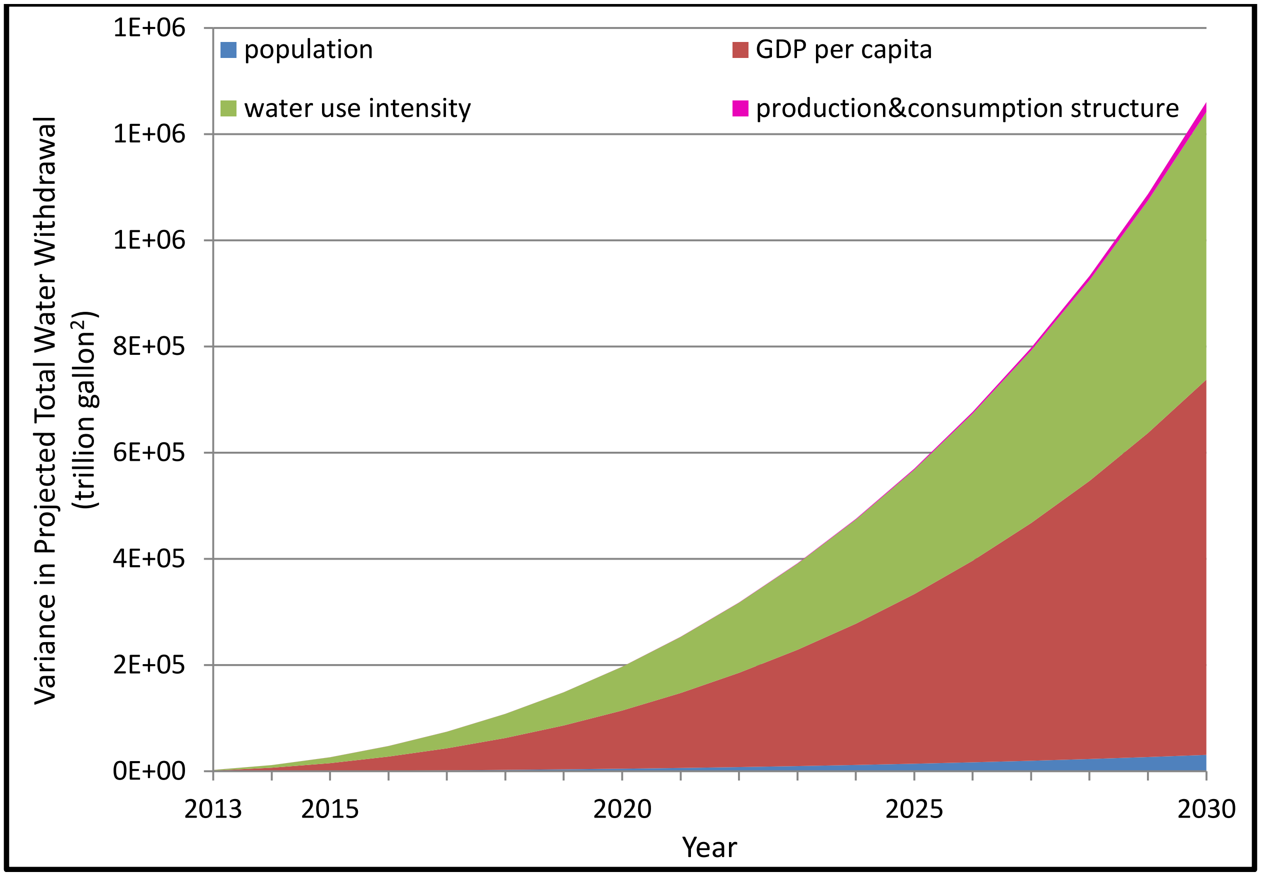

Figure 3-8. Contribution of uncertainty in governing factors to variation in water withdrawal projected by the EIO-LCA model with changing economic structure

Chapter 4: Projecting Changes in Consumptive Water Use for Industrial Sectors and Effects of Changes in Water Consumption for Power Generation and Agricultural Irrigation

This chapter, written by Hui Wang and co-authored by Mitchell J. Small, and David A. Dzombak, will be submitted for publication.

Abstract

The distinction of consumptive and non-consumptive water use is important for water resource management and assessment of availability and quality of water sources. The consumptive water coefficient (ratio of consumptive water use to water withdrawal) varies widely across different water use. Consumptive water use coefficients were estimated for 66 aggregated industrial sectors based on available data. In this study, the total consumptive uses for all industrial sectors (sum of direct and supply chain consumptive water use) were projected based on the available consumptive water use coefficients across 64 combinations of dynamic scenarios for population, GDP per capita and consumptive water use intensity using the EIO-LCA model with fixed economic structure for 2013-2030. The projected consumptive water use for all industrial sectors ranges from 45-47 trillion gallons in 2013 to 23-51 trillion gallons in 2030 across 64 scenarios; the median total consumptive water use is projected to grow at an average annual rate of 0.5% during this period. Thermoelectric power generation is the largest industrial water use, but only about 2% of the water is consumed in the operational process. Agricultural irrigation is the second largest water user, but 40-100% of agricultural water withdrawal is consumed, making it the largest water consumer. The effects of changes in cooling technology for thermoelectric power generation and irrigation technology for agriculture on changes in consumptive water use for other sectors during 2013-2030 were investigated. Changes in cooling technology do not impact consumptive water use projections for most sectors, but do impact power generation-related sectors themselves. Shifts in irrigation technology do not affect consumptive water use for agriculture, and also affect consumptive water use for sectors requiring agricultural products as important supply chain components.

4.1 Introduction

Water withdrawal (water use) data can be classified as consumptive water use and non-consumptive water use. Consumptive water use refers to the part of withdrawn water that is not returned to the water source because of evaporation, infiltration into the ground, transpiration, consumption by people or livestock, etc. (Solley et al., 1995). Non-consumptive water use is the portion of water withdrawn that is returned to the water source after use and is available for reuse (Solley et al., 1995). The distinction of consumptive and non-consumptive water use is important for water resource management and assessment of availability and quality of water source. Used water returned to a source often is a source of water quality impairment (Pebbles, 2003). For example, the agricultural irrigation return flows often contain high concentrations of nitrogen and phosphorus due to the usage of fertilizer for crops (Pebbles, 2003).

The consumptive water use coefficient representing the ratio of water consumption to water withdrawal varies by water use category. Although power generation is the largest water user among industrial sectors (Kenny et al., 2005; Huston et al., 2000), the consumptive water use coefficient for power generation is small compared to other water use categories, i.e., approximately 2% of the water is evaporated in the thermoelectric power plants (Solley et al., 1995). In the United States (U.S.), about 91% of electricity is generated by the thermoelectric generation plants, with hydroelectric power plants producing the remaining 9% of electricity (Torcellini et al., 2003). The amount of water consumption in hydroelectric power generation is very small, and the consumptive water use can be considered negligible (Solley et al., 1995). In this study, we only focus on water consumption for the thermoelectric power generation fueled with coal, oil, natural gas and nuclear. The type of cooling system used to generate electricity is the primary factor affecting the amount of water consumed in the thermoelectric power plants (Kenny et al., 2005; NETL, 2009; Macknick et al., 2011).

The consumptive water use coefficient for agricultural irrigation is the largest across the industrial water use categories, ranging from 40-100% of water withdrawal (Huston et al., 2000; Kenny et al., 2005; Solley et al., 1995). Agriculture is also the second largest water user (Huston et al., 2000; Kenny et al., 2005; Solley et al., 1995). The large water withdrawal and the high water use coefficient lead agricultural irrigation to consume the largest quantity of water in the U.S., accounting for about 80% of total consumptive water use. Water consumption for irrigation mainly includes the water loss in evaporation, transpiration, incorporation in crops or plants (Solley et al., 1995). Due to climate conditions and crop planting patterns, water consumed for irrigation in the western states represents 90% of the U.S. water consumption (USDA, 2008). In the U.S., more than 50% of irrigated lands are still irrigated by the low efficiency irrigation technologies (Schaible et al., 2012). The profile of future irrigation technology deployment will largely determine water use and consumption for agriculture in the coming decades.

Technological innovations or changes in cooling systems for thermoelectric power generation and agricultural irrigation not only affect water consumption for their related industrial sectors in the economic system, but also affect indirectly many other sectors that use the output of the thermoelectric power generation and agricultural sectors as component suppliers in the supply chain. The direct and indirect effects of technological innovations in these two largest water using sectors on overall water consumption in the economy have not been evaluated heretofore.

In this study we examined water consumption across the U.S. economy, projected water consumption for the coming decades, and evaluated potential effects of changes in water management technology for the two largest water using sectors. We pursued the following specific research objectives: (1) project the total consumptive use for the industrial sectors (sum of direct and supply chain consumptive water use) in the economic system based on the available consumptive water use coefficients for the six major water use categories from USGS (e.g. public supply, agricultural irrigation, and thermoelectric power generation, etc.) for 2013-2030 for various scenarios of population, GDP per capita, water use intensity, production structure and consumption pattern; (2) estimate the effects of changes in consumptive water use for thermoelectric power generation-related sectors on changes in consumptive water use for other aggregated industrial sectors during 2013-2030 for different cooling technology scenarios; (3) estimate the effects of changes in consumptive water use for agricultural irrigation-related sectors on changes in consumptive water use for other aggregated industrial sectors from 2013 to 2030 for different irrigation technology scenarios.

4.2 Data and Methods

4.2.1 Economic Input-Output Life Cycle Assessment (EIO-LCA)

The EIO-LCA model used for projecting the consumptive water uses for U.S. industrial sectors during the period of 2013-2030 is shown in Equation 4-1.

$$\mathbf{CW} = P * Y_g * \mathbf{CF} * \mathbf{L} * \mathbf{Y_c} \qquad [4 - 1]$$

The vector and matrix terms in this model are shown as bold. CW is a vector representing total consumptive water use for the industrial sectors [gallons]; P is the population of the U.S., Yg is the U.S. GDP per capita [dollars/person], CF is a diagonal matrix, and the entries represent the consumptive water use intensity [gallons/dollar]. The consumptive water use intensity is the water consumed for every dollar of output production. The computation of consumptive use intensity is modified based upon the method from Blackhurst et al. and Wang et al. for water use intensity estimation (Blackhurst et al., 2010; Wang et al., 2014a). The detailed approach for consumptive water use intensity is described below. L is the production structure matrix, which describes the value of total production needed across the industrial sectors for one dollar of final demand [dollars]. Yc is the consumption pattern vector, elaborating the fraction of GDP produced by each industrial sector [non-dimensional].

4.2.2 Projection of Consumptive Water Use for Industrial Sectors for 2013-2030

The total consumptive water use for all U.S. industrial sectors for the period of 2013-2030 was projected for various specified scenarios developed with combinations of values for the five governing terms (population, GDP per capita, consumptive water use intensity, economic production structure and consumption pattern) in the EIO-LCA model with fixed economic structure (Wang et al., 2014a; Wang et al., 2014b). The economic structure and consumption pattern were assumed to remain constant at 2012 level in this model. Four scenarios were designated to each of the other three factors based upon the reported predictions and historical trends, which results in 64 scenarios for total consumptive water use. 2012 data were used as the baseline constant scenario for these three factors. The low, medium and high growth scenarios for population forecast by U.S. census bureau during 2013-2030 were used as the future scenarios for population (U.S Census Bureau, 2013; Wang et al., 2014b). According to the available predicted GDP and population, the GDP per capita was assumed to increase annually at -0.95%, 1.9% and 2.9% for the low reduction, medium growth and high growth scenarios for

2013-2030, respectively (U.S. Census Bureau, 2013; U.S. EIA, 2013; Wang et al., 2014b). The generation of scenarios for consumptive water use intensity relied on the historical annual growth rate of water productivity between 1997-2011 (The World Bank, 2014). The water productivity reflects the value of GDP produced with every gallon of freshwater use. Due to data limitations, we assumed that all the industrial sectors have the same annual growth rate of consumptive water use intensity as the overall water use intensity during 2013-2030 (Wang et al., 2014b).The overall water use intensity was assumed to grow by -3%, -1% and 0.5% every year for the high reduction, low reduction and low increase scenarios for 2013-2030, respectively (Wang et al., 2014b). The scenarios for these three governing factors are summarized in Table 4-1.

4.2.2.1 Estimation of consumptive water use intensity

The consumptive water use intensity for an industrial sector represents the amount of water consumption associated with one dollar of industry output. To determine the consumptive water use intensity for each industrial sector, water consumption needs to be estimated for each sector. This was accomplished by allocation of water consumption for each of six major USGS water use categories (*Thermoelectric power generation*, *Mining*, *Industrial*, *Irrigation*, *Residential*, *Public supply*, and *Livestock)* to each industrial sector (Kenny et al., 2005). Consumptive water use coefficients by category and the industry output for industry output were employed to estimate the consumptive water use intensity. Water consumption for the major water use categories was calculated based on the water withdrawal data in 2002 and average consumptive water use coefficient for each category (Solley et al., 1985; Solley et al.,1990; Solley et al., 1995). The water withdrawals for the two most current years of 2000 and 2005 were used to estimate the water withdrawal for 2002 by interpolation to match the industry output reporting year (Kenny et al., 2005; Hutson et al., 2000; Wang et al., 2014a). The water consumption amounts were allocated to the 66 industrial sectors using the methodology of Wang et al. (Wang et al., 2014a) which is based on economic activities, process activities, and number of employees.

4.2.2.2 Estimation of consumptive water use coefficients for industrial sectors

The consumptive water use coefficient represents the percentage of water consumed from the total water withdrawal. The consumptive water use coefficients for 66 aggregated U.S. industrial sectors were estimated based on both water withdrawal by industrial sector (Wang et al., 2014b) and consumptive water use by industrial sector projected by the EIO-LCA model with fixed economic structure for 2013-2030. The consumptive water use coefficients for industrial sectors were computed under the same scenarios for both water withdrawal and water consumption, resulting in 64 scenarios for consumptive water use coefficients for industrial sectors. Since very similar methods and data were applied to generate the five factors for projection of both water withdrawal and water consumption for 2013-2030 and the average consumptive water use coefficient for 1985-1995 from USGS was used to project water consumption across time (Solley et al., 1985; Solley et al., 1990; Solley et al., 1995), the consumptive water use coefficients for industrial sectors are almost constant across scenarios and time. The consumptive water use coefficients for all 66 aggregated industrial sectors were listed in Appendix C.

4.2.3 Projection of Consumptive Water Use Intensity for Thermoelectric Power Generation-Related Sectors for 2013-2030

In this study, we focused on 66 aggregated industrial sectors in the U.S. economic system. There are three aggregated sectors related to thermoelectric power generation: *Utilities*, *Federal* *government enterprises*, and *State and local government enterprises* (U.S. BEA, 2014). The consumptive water use intensity for these three power generation-related sectors is determined by the allocated water consumption to these sectors and the industry output for the three sectors. Four scenarios for cooling technology in thermoelectric power plants were developed, yielding four scenarios for water consumption for thermoelectric power generation. Four scenarios for industry output for power generation-related sectors were assigned as well based upon the 1997-2012 annual historical data (U.S. BEA, 2014), resulting in 16 scenarios for consumptive water use intensity for three power generation-related sectors.

4.2.3.1 Scenarios for cooling technology for thermoelectric power generation

Three types of cooling technology are mainly used for thermoelectric power generation: once-through, wet-recirculating, and dry-cooling (NETL, 2009). In the once-through cooling system, water taken from nearby rivers, lakes or other water sources is used to pass through the condensers, and the warm cooling water is immediately discharged back to the original water body. A large amount of water is needed for power plants equipped with the once-through cooling systems, but a small amount of water is consumed in such systems (NETL, 2009; Solley et al., 1995). Because of the large water requirements and thermal impacts of the discharges, regulations in the U.S. discourage once-through cooling for new power plants (NETL, 2009; paddock et al., 1978; Li et al., 2011). In a wet-recirculating system involving a cooling tower, the cooling water is reused, and only the portion of water lost through evaporation needs to be replaced by makeup water withdrawal. Hence, the wet-recirculating systems need lower water withdrawals but have more consumptive water use than once-through systems (NETL, 2009;

Solley et al., 1995). Air is used to condense the steam instead of water for dry cooling systems, and no water is consumed in these cooling systems (NETL, 2009; Solley et al., 1995).

The first two scenarios for future cooling technology were developed following those suggested by the NETL (NETL, 2009), and the other two scenarios were modifications of NETL scenarios (NETL, 2009). The consumptive water use for thermoelectric power generation is expected to have an increasing trend from scenario 1 through scenario 4. Four scenarios for cooling technology used for thermoelectric power generation are shown as follows:

Scenario 1 (*baseline case*): distribution of technologies for power plant additions and retirements for 2013-2030 is proportional to the current distribution of types of cooling systems.

Scenario 2 (*low consumptive water use growth*): all power plant additions for 2013-2030 use wet recirculating cooling, while the distribution of cooling technologies for power plant retirements is proportional to the current distribution of types of cooling systems.

Scenario 3 (*medium consumptive water use growth*): all power plant additions for 2013-2030 use wet recirculating cooling, while all power plant retirements use once-through cooling systems.

Scenario 4 (*high consumptive water use growth*): all power plant additions for 2013-2030 use wet recirculating cooling, while all power plant retirements use once-through cooling system. Further, 2% of existing once-through cooling capacity for each generation type is retrofitted with recirculating cooling technology every year starting from 2013-2030.

4.2.3.2. Projection of consumptive water use for thermoelectric power generation under four scenarios for cooling technology for 2013-2030

The 2012 consumptive water use for thermoelectric power generation was used as the baseline to project the water consumption in thermoelectric power generation for the four scenarios above during 2013-2030. The consumptive water use for thermoelectric power generation in 2012 was estimated by the current distribution of cooling technology and generation type (coal, fossil non-coal, combined cycle and nuclear) (NETL, 2009), 2012 net electricity generating capacity (U.S. EIA, 2014a), capacity factors (U.S. EIA, 2014b), and the consumptive freshwater use factor by generation type (NETL, 2009; Macknick et al., 2011), as shown in Equation [4-2]. We assumed that freshwater consumption accounts for 70% of total water consumption (including fresh and saline water) according to the historical data (Solley et al., 1995; Solley et al., 1990; Solley et al., 1985; Solley et al., 1980).

$$\begin{aligned}&\textit{Cosnumptive water use for thermoelectric power generation in } 2012 = \sum \textit{electricity generating capacity} \\ &\textit{by generation type in } 2012 \times \textit{capacity factor by generation type in } 2012 \times 8760 \times \textit{current distribution of} \\ &\textit{cooling system by generation type} \times \textit{freshwater consumption factor by generation type} / 70\% \qquad [4-2]\end{aligned}$$

Consumptive water use for thermoelectric power generation in 2012 is in [gallons]; electricity generating capacity represents the electric output that a generator can produce [watts]; capacity factor measures how often an electric generator runs for a specific period, and is a ratio of actual operation hours to the full time of an entire year (8760 hours) [%]; current distribution of cooling system by generation type shows the percentage of cooling technology used across the generation type [%];freshwater consumption factor measures the amount of freshwater consumed per watt hour of electricity generated [gallons/watt hour].

The consumptive water use for thermoelectric power generation for 2013-2030 was projected mainly based on the 2012 consumptive water use and predicted additions and retirements of electricity generating capacity for 2013-2030 under four scenarios for cooling technology. Due to data limitations, the capacity factors and freshwater consumption factors by generation type were assumed to remain constant as the 2012 level for 2013-2030. The projection of 2013-2030 water consumption for thermoelectric power generation is shown in Equation [4-3]-[4-5].

$$\textit{Consumptive water use for thermoelectric power generation for year } t = \textit{consumptive water use for thermoelectric power generation in 2012} + \textit{consumptive water use for new thermoelectric power generation plants for year } t - \textit{consumptive water use for retired thermoelectric power generation plants for year } t \qquad [4-3]$$

$$\textit{Consumptive water use for new thermoelectric power generation plants for year } t = \textit{cumulative electricity generating capacity additions by generation type for year } t \times \textit{capacity factor by generation type in } 2012 \times 8760 \times \textit{distribution of cooling system by generation type (according to the scenario)} \times \textit{freshwater consumption factor by generation type} / 70\% \qquad [4-4]$$

$$\textit{Consumptive water use for new thermoelectric power generation plants for year } t = \textit{cumulative electricity generating capacity retirements by generation type for year } t \times \textit{capacity factor by generation type in } 2012 \times 8760 \times \textit{distribution of cooling system by generation type (according to the scenario)} \times \textit{freshwater consumption factor by generation type} / 70\% \qquad [4-5]$$

4.2.3.3 Projection of consumptive water use intensity for power generation-related sectors for 2013-2030

The consumptive water use intensity for power generation-related sectors (*Utilities, Federal electric utilities*, and *State and local government electric utilities*) is the water consumption for producing every dollar of industry output for the sectors. The consumptive water use intensity for each power generation-related sectors was obtained from the ratio of allocated consumptive water use from each sector to the corresponding industry output. 16 scenarios for consumptive water use intensity for each power generation-related sector were yielded from four scenarios for cooling technology and industry output for these three power generation-related sectors.

4.2.3.3.1 Allocation of water consumption for thermoelectric power generation to thermoelectric power generation-related sectors

The projected consumptive water use for thermoelectric power generation was allocated to three industrial sectors – *Utilities, Federal electric utilities,* and *State and local government electric utilities* – based on the proportion of their industry output. *Federal electric utilities* and *State and local government electric utilities* are two detailed sectors included in the aggregated sectors *Federal government enterprises* and *State and local government enterprises,* respectively (U.S. BEA, 2002). The industry outputs for *Federal electric utilities,* and *State and local government electric utilities* have not been available since 2002; we assumed that the proportion of industry output for *Utilities, Federal electric utilities,* and *State and local government electric utilities* stayed constant at the 2002 level for 2013-2030. The water consumption for thermoelectric power generation under four scenarios was allocated to these three sectors following this proportion.

4.2.3.3.2 Projection of industry output for power generation-related sectors for 2013-2030

The industry outputs for three power generation-related sectors – *Utilities, Federal government enterprises,* and *State and local government enterprises* – for 2013-2030 were projected based on the historical annual data from 1997-2012 (U.S. BEA, 2002). We assumed that the industry outputs for all three sectors follow a log-linear relationship with time during the period of 1997-2012. The three scenarios for industry outputs for 2013-2030 were projected with the 0.5 times, one times and 2 times annual growth rate estimated from this log-linear relationship from 1997-2012. The 2012 industry outputs were set as the constant baseline scenario for 2013-2030.

Scenario 1 (*constant baseline*): the industry outputs for the three power generation-related sectors remain at the 2012 level for 2013-2030, with an average annual growth rate of 0% for three sectors.

Scenario 2 (*low economic growth*): the industry outputs for the three power generation-related sectors are 0.5 times the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 0.3% for *Utilities*, -0.2% for *Federal government enterprises*, and 1.55% for *State and local government enterprises*.

Scenario 3 (*medium economic growth*): the industry outputs for the three power generation-related sectors follow the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 0.6% for *Utilities*, -0.1% for *Federal government enterprises*, and 3.1% for *State and local government enterprises*.

Scenario 4 (*high economic growth*): the industry outputs for the three power generation-related sectors are 2.0 times the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 1.2% for *Utilities*, -0.05% for *Federal government enterprises*, and 6.2% for *State and local government enterprises*.

4.2.4 Projection of Consumptive Water Use Intensity for Agricultural Irrigation-Related Sectors for 2013-2030

In the 66 aggregated industrial sectors, *Farms* is the only sector related to the agricultural irrigation. Two summary sectors *Crop production* and *Animal production* are included in the *Farms* sector. Comparing the consumptive water use related to irrigation for *Crop production* and *Animal production*, the portion of consumptive water use for *Animal production* such as pasture irrigation is very small. In this study, we only focused on the consumptive water use for *Crop production* under the varying scenarios for irrigation technology for 2013-2030. The consumptive water use for *Animal production* was assumed to stay at the 2012 level during 2013-2030. The consumptive water use for *Farms* is the sum of water consumption for both *Crop production* and *Animal production*.

The consumptive water use intensity for *Farms* is the amount of water consumed for producing one dollar of industry output for this sector. Four scenarios for irrigation technology for 2013-2030 were designed, generating four scenarios for consumptive water use for irrigation. Four scenarios for industry output for *Farms* were assigned as well based upon the annual historical data during 1997-2012, resulting in 16 scenarios for consumptive water use intensity for *Farms*.

4.2.4.1 Projection of consumptive water use for irrigation for 2013-2030

The consumptive water use for irrigation for 2013-2030 was projected based on the irrigated acreage for major crops, distribution of irrigation technology by crop, and consumptive water use rate by irrigation technology. The major crops planted in the U.S. include corn, sorghum, barley, oats, wheat, soybeans and products, rice, cotton, sugar beet, sugarcane, fruit and tree nuts, and vegetables (USDA, 2014a).

4.2.4.1.1 Projection of irrigated croplands for 2013-2030

The irrigated croplands for the major crops during 2013-2030 were estimated based on the available projected harvested acreage for the major crops for 2013-2023 (USDA, 2012) and the fraction of irrigated cropland (% of total harvested cropland) in 2012 (USDA, 2014a). Due to data limitation, we assumed that the fraction of irrigated cropland for all major crops remained constant at the 2012 level for 2013-2030, and the harvested croplands for major crops were held constant at the 2023 level for 2024-2030. The irrigation rate for sugarcane was not available and assumed to be identical to sugar beet.

4.2.4.1.2 Estimation of distribution of irrigation technology for major crops

The current distribution of irrigation methods for the major crops was estimated based on their irrigated acreage and primary method of irrigation in 2008 (USDA, 2008). The distribution of irrigation technology refers to the proportion of irrigated acreage by each irrigation method across major crops. Three basic types of irrigation systems are currently employed in the U.S.: gravity system, sprinkler system, and drip (trickle) system (USDA, 1998; USDA, 2003; USDA, 2008). Available data provide the acreages for *Cotton*, *Vegetable*, and *Fruit and tree nuts* irrigated by sprinkler and drip system separately, but give the combined irrigated acreages for sprinkler and drip system for other crops (USDA, 2008). To obtain the distribution of these three irrigation methods for each major crop, the proportion of cropland irrigated by sprinkler and drip irrigation technology for the crops excluding *Cotton*, *Vegetable*, and *Fruit and tree nuts* was assumed identical to the overall proportion of cropland irrigated by sprinkler and drip irrigation method (USDA, 2008). In addition, the distribution of irrigation technology used for sugarcane was assumed to the same as sugar beet because of the lack of data for irrigated acreages by irrigation method (USDA, 2008). The distribution of irrigation technology by crop for 2013-2030 was projected based on the estimated current distribution and the developed scenarios for future irrigation technologies.

4.2.4.1.3 Estimation of consumptive water use rate for irrigation by irrigation technology

The consumptive water use rate for irrigation refers to the amount of water consumed per acre of field for irrigating crops or plants. The consumptive water use for irrigation mainly includes the water consumption by evaporation, transpiration and incorporation into the crops or plants.[5] Due to data limitations, we estimated the consumptive water use rate by irrigation technology mainly based upon the water application rate (USDA, 2008) and application efficiency by irrigation technology (Howell, 2003). The water application rate measures the water applied to every acre of field. The application efficiency (%) relates to the irrigated water needed by the crops or plants and the water applied to the field (Howell, 2003).

4.2.4.2 Scenarios for irrigation technology for 2013-2030

Flooding of fields by gravity-induced flow (gravity system) is the most traditional irrigation method used for crops and plants (USGS, 2014). While this method involves no pumping, it is more labor intensive than other irrigation methods, and it is not easy to distribute water uniformly for high slope fields (U.S. EPA, 2003). The sprinkler irrigation system generally delivers water through pipes under pressure, and the water is sprayed on the land similar to artificial precipitation (USGS, 2014). This irrigation method is not affected by topography and labor cost is low; but climate conditions significantly impact its irrigation efficiency and its operation cost is high (USDA, 2014b). The drip irrigation method, also called trickle irrigation, applies water directly to the root zone of plants by dripping water on the surface of soil very slowly. This method is the most efficient irrigation technology, as the water losses through evaporation and surface runoff are very low (U.S. EPA, 2003).

The acres irrigated by sprinkler and drip technology have increased by 45% and 115% from 1994-2008, respectively, while the croplands irrigated by gravity have declined by 10% during this time period (USDA, 1994; USDA, 1998; USDA, 2003; USDA, 2008). More than 50% of croplands are currently irrigated by the sprinkler technology in the U.S. The acreages irrigated by the gravity system approximately accounts for 40%, and about 7% of croplands are irrigated by the drip irrigation method (USDA, 1994; USDA, 1998; USDA, 2003; USDA, 2008). Based on the historical trends, the following four scenarios for irrigation technology for 2013-2030 were developed:

Scenario 1 (*baseline case)*: the distribution of irrigation method for major crops for 2013-2030 is the same as the current distribution.

Scenario 2 (*low water consumption decrease*): 2% of gravity irrigation method is replaced by the drip irrigation method for all major crops every year from 2013 to 2030.

Scenario 3 (*medium water consumption decrease*): 2% of the gravity irrigation method is replaced by the sprinkler irrigation (1%) and drip irrigation method (1%) for all major crops every year from 2013 to 2030.

Scenario 4 (*high water consumption decrease*): 2% of the gravity irrigation method is replaced by the sprinkler irrigation method for all major crops every year from 2013 to 2030.

4.2.4.3 Projection of industry output for irrigation-related sectors for 2013-2030

Four scenarios for industry output of *Farms* for 2013-2030 were developed with the same approach as those for thermoelectric generation-related sectors. The industry output in 2012 was used as the constant baseline scenario. The industry output projected based upon the 0.5 times, one times and 2.0 times annual growth rate estimated from the log-linear relationship from 1997-

2012 were assumed be to the economic low, medium and high scenario, respectively (U.S. BEA, 2014). The four scenarios are shown as follows:

Scenario 1 (*constant baseline*): the industry outputs for *Farms* remain at the 2012 level for 2013-2030, with an average annual growth rate of 0%.

Scenario 2 (*low economic growth*): the industry outputs for *Farms* are 0.5 times the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 1.2%.

Scenario 3 (*medium economic growth*): the industry outputs for *Farms* follow the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 2.4%.

Scenario 4 (*high economic growth*): the industry outputs for *Farms* are 2.0 times the 15-year log-linear trend (1997-2012) for 2013-2030, with an average annual growth rate of 4.8%.

4.3 Results and Discussion

Various scenarios for population, GDP per capita, water use intensity, production structure, and consumption pattern were developed to project total consumptive water use for industrial sectors for 2013-2030, employing the EIO-LCA model with fixed economic structure. A primary goal was to distinguish consumptive and non-consumptive water use across combinations of different possible conditions of population, economic growth, and technological change, to help identify the potential quantity and availability of water resource in the future. Another goal was to investigate the relationship of changes in cooling technology for thermoelectric power generation and agricultural irrigation technology with changes in consumptive water use for U.S. industrial sectors, and to identify the impacts of indirect consumptive water uses through supply chain.

4.3.1 Projected Total Consumptive Water Use for All Industrial Sectors for 2013-2030

Figure 4-1 indicates the total consumptive water use for U.S. industrial sectors across all scenarios, and its median values projected by the EIO-LCA model with fixed economic structure for 2013-2030. Four varying scenarios for each of population, GDP per capita, and consumptive water use intensity, and fixed scenario for production structure and consumption pattern at the 2012 level yielded 64 scenarios for total consumptive water use each year during 2013-2030. The variance in projected consumption water use gets larger over time: the projected consumptive water use for all industrial sectors ranges from 45-47 trillion gallons in 2013 and 23-51 trillion gallons in 2030. The minimum total consumptive water use was projected to occur when population and GDP per capita grow at low growth rates, and consumptive water use intensity decreases at a high rate; while the maximum consumptive water use was projected to occur under the high growth scenario for population and GDP per capita, and low increase scenario for consumptive water use intensity. The growth trends in the median value of projected total consumptive water use during 2013-2030 was very steady, from 47 trillion gallons in 2013 to 51 trillion gallons in 2030 with an average annual growth rate of 0.5%.

Due to the similarity of scenarios for estimation of consumptive water use with those for water withdrawal in the EIO-LCA model with fixed economic structure (Wang et al., 2014b), the total consumptive water use uniformly accounts for about 30% of total water withdrawal for all industrial sectors across the 64 scenarios during 2013-2030. It implies that although the total water withdrawal across the industrial sectors is high for the extreme cases, most of the water withdrawal has potential for water reuse with suitable water use management. This would relieve the stress for available water supply.

4.3.2 Projected Consumptive Water Use for Thermoelectric Power Generation for 2013-2030

As Figure 4-2 shows, the consumptive water use for thermoelectric power generation for 2013-2030 was projected under four scenarios for cooling technology used in thermoelectric power plants. The consumptive water use for thermoelectric power generation was used as the baseline. Scenarios 1 through 4 for cooling technology involve an increasing trend in usage of wet recirculating cooling system and decreasing trends in usage of once-through cooling system, which resulted in increases in consumptive water use for thermoelectric power generation across scenarios for cooling technology because of higher water consumption rate for recirculating cooling system than once-through cooling. The water consumed for thermoelectric power generation under both scenario 1 and 2 experienced a slight decrease from 2013-2030, and the amounts of water consumed for these two scenarios were very similar. The consumptive water use for thermoelectric power generation decreased from 1.22 trillion gallons in 2013 to around 1.15 trillion gallons in 2030. The consumptive water use for thermoelectric power generation under scenario 3 was projected to increase by 0.05% every year during 2013-2030, and reach 1.26 trillion gallons in 2030. Scenario 4 involves replacement of 2% of existing once-through cooling systems by recirculating cooling each year, resulting in the largest quantity of water consumption compared to the other three scenarios. Scenario 4 results in a 1.7% decline per year, from 1.35 to 1.80 trillion gallons during the time period of 2013-2030.

4.3.3 Projected Consumptive Water Use for Thermoelectric Power-Related Sectors and Other Sectors under Scenarios for Cooling Technology for 2013-2030

The consumptive water uses for industrial sectors under various scenarios for cooling technology and industry output for thermoelectric power generation-related sectors during 2013-2030 were projected using the EIO-LCA model with fixed economic structure. Four scenarios for cooling technology and four scenarios for industry output for three power generation-related sectors yielded 16 scenarios for water consumption intensity for these three sectors. The water consumption intensities for other industrial sectors were projected based on the medium reduction scenario (1% annual reduction rate). Population and GDP per capita were projected under the medium growth rate. Figures 4-3a-4-3d show the normalized consumptive water uses for three sectors — *Utilities* (thermoelectric power generation), *Farms*, and *Food and beverage products*— across various scenarios for cooling technology for thermoelectric power generation under four scenarios for industry output for *Utilities* for 2013-2030.

Figures 4-3a shows the projected consumptive water uses for *Utilities*, *Farms* and *Food and beverage products* under four scenarios for cooling technology with constant industry output for the *Utilities* sector, which were normalized by the consumptive water use under baseline case for cooling technology representing current distribution of cooling technology. *Utilities* shows dramatic changes in water consumption across four scenarios for cooling technology during 2013-2030, increasing by about 50% from the baseline case through high water consumption increase scenario for cooling technology in 2030. All normalized consumptive water uses for *Farms* and *Food and beverage products* for four scenarios for cooling technology are about 1.0, which implies that these two sectors consume very similar amount of water across four scenarios for cooling technology.

Figures 4-3b-4-3d show the normalized water consumption for *Utilities*, *Farms* and *Food and beverage products* across four scenarios for cooling technology, with the low, medium, and high economic growth scenario for industry output for the Utilities sector. These three figures present similar trends in changes in water consumption for *Utilities*, *Farms* and *Food and beverage products* across various scenarios for cooling technology as those with constant output for thermoelectric power generation (Figure 4-3a). Figures 4-3a-4-3d indicate that changes in cooling technology and industry output for *Utilities* do not affect the water consumption for the other sectors such as *Farms* and *Food and beverage products* significantly, while primarily impacting the consumptive water use for the thermoelectric power generation-related sectors themselves.

According to the current and future trends in regulations and industry practice, more recirculating cooling technology will be used in the thermoelectric power plants instead of once-through cooling technology (NETL, 2009). As a result, the consumptive water use for thermoelectric power generation is likely to increase significantly in the future due to more water evaporation in the recirculating cooling systems. The extreme scenario for cooling technology (scenario 4) shows that the consumptive water use for thermoelectric power generation will reach about 1.80 trillion gallons at the national level, which is still relatively low as compared with agricultural irrigation. However, the water consumption for thermoelectric power generation in some regions will be significantly different from the national average value due to different population density and growth rate. The thermoelectric power generation capacity is projected to increase by 10% across the U.S., while increasing by 30% in the western U.S. and 20% in the southeast areas (U.S. EIA, 2014a). Some regions requiring higher consumptive water use for thermoelectric power generation will face challenges with respect to available water resources. In addition, increases in consumptive water use for thermoelectric power generation due to shifts in cooling technology have negligible impacts on water consumption for other sectors in the supply chain.

4.3.4 Projected Consumptive Water Use for Agricultural Irrigation under Scenarios for Irrigation Technology for 2013-2030

Figure 4-4 shows the projected consumptive water use for agricultural irrigation under four scenarios for future irrigation technology for 2013-2030. The consumptive water use for irrigation in 2012 was used as the baseline. The consumptive water use for irrigation under scenarios 1 through 4 exhibits a decreasing trend. The consumptive water uses for irrigation for all four scenarios peak in the year 2014 because of the occurrence of projected maximum irrigated cropland in 2014, more than 14.20 trillion gallons. The water consumption for irrigation with the current distribution of irrigation technologies (scenario 1) decreases approximately 0.7% per year during 2014-2018 (13.95-14.10 trillion gallons), increases annually 0.3% from 2018-2023, and then levels off and remains constant until 2030. With replacement of 2% of gravity irrigation system by the drip irrigation system every year (scenario 2), the consumptive water use for irrigation decreases from 14.30-13.80 trillion gallons during 2014-2018, and increases slightly in the following four years (0.1% annual growth rate), and then experiences a continuous decline with an annual decrease rate of 0.1% during 2023-2030. In scenario 3, 2% of gravity irrigation is replaced with drip irrigation (1%) and sprinkler irrigation (1%), respectively. The consumptive water use for irrigation under this scenario decreases annually at 1% from 2014-2019, stays constant between 2019 and 2024, and then declines continuously with an average decrease rate of 0.1%. The change trends in consumptive water use for irrigation under scenario 4 are similar to those for scenario 3, but the irrigation consumes less water in scenario 4 than scenario 3.

4.3.5 Projected Consumptive Water Use for Irrigation-Related Sectors and Other Sectors under Scenarios for Irrigation Technology for 2013-2030

Consumptive water uses for industrial sectors across the different scenarios for irrigation technology and industry output for irrigation-related sectors during 2013-2030 were projected by the EIO-LCA model with fixed economic structure. *Farms* is the only sector related to irrigation in the 64 aggregated U.S. industrial sectors. Four scenarios for future irrigation technology and four scenarios for industry output for *Farms* yielded 16 scenarios for consumptive water use intensity for *Farms*. The consumptive water use intensities for other industrial sectors were projected based upon the medium reduction scenario (1% annual reduction rate) and 2012 water consumption intensity. Population and GDP per capita were assumed to grow at the medium rate.

Figures 4-5a-4-5d show the normalized projected consumptive water uses for *Farms, Utilities* and *Food and beverage products* across four scenarios for irrigation technology, with constant, low, medium and high economic growth scenarios for industry output for *Farms*, respectively. Increases in sprinkler irrigation technology and decreases in gravity irrigation in scenarios 1 through 4 cause a decreasing trend in consumptive water use for irrigation, which results in declines in water consumption for *Farms* with a fixed industry output produced by *Farms* from scenarios 1 to 4 for irrigation technology. These four figures show similar trends in changes in consumptive water uses for *Farms, Utilities* and *Food and beverage products* under four scenarios for irrigation technology. Shifts in irrigation technology resulted in changes in water consumption for *Farms* directly, as well as, *Food and beverage product* indirectly through the supply chain from 2013-2030. The pattern and extent of changes in consumptive water use for *Food and beverage product* are similar to that for *Farms* across various scenarios for irrigation technology for *Farms* over time. The consumptive water uses for both *Farms* and *Food and* *beverage product* decrease by about 5.5% from the baseline case to the high water consumption decrease scenario for irrigation technology in 2030. However, changes in irrigation technology do not have dramatic impacts on consumptive water use for *Utilities* during 2013-2030 under any scenario for industry output of *Farms*, which implies that *Utilities* is a low irrigation water consumption-intensity sector.

In this study, we estimated consumptive water use for agricultural irrigation for scenarios with different combinations of irrigation technology. In fact, consumptive water use for irrigation by is affected by many natural factors such as temperature, precipitation, wind speed, soil conditions and other factors including the types of crops, planting season etc., which were not considered here. In addition, the assumptions we made in order to deal with data limitations also introduce uncertainty in estimation of consumptive water use for irrigation. For example, only the major crops were considered for projection of consumptive water use, resulting in underestimation of consumptive water use for irrigation.

Agricultural irrigation is the largest water consumer in the U.S (Kenny et al., 2005). Water conservation in agricultural irrigation has become an increasingly important focus to relieve stresses on available water supplies. Although the efficiency of irrigation has been increased via the technological innovation in the past decades, more than 50% of cropland in the U.S. is still irrigated using the traditional irrigation technology with less efficiency (Schaible et al., 2012). The transition from gravity irrigation systems to pressure irrigation systems (such as drip irrigation and sprinkler irrigation) has been a shifting trend across the U.S, which was is reflected in the scenarios for irrigation technology developed in this study. Efficient irrigation technology and improved water management can help conserve water, reducing water applied per acre of cropland. However, conservation of water for agricultural irrigation generally cannot satisfy increases in yield of agricultural production (Schaible et al., 2012).

Changes in consumptive water use for agricultural irrigation do not only affect water consumption in agricultural sectors, but also impact the consumptive water use for the sectors which need agricultural products as components in their supply chains. Due to increases in pressure on water resources, agricultural irrigation is facing growing competition in water use from other industrial sectors (Schaible et al., 2012). Decreases in consumptive water use for agricultural irrigation can help decrease water consumption with other industrial sectors, reducing competition for water supply. In addition to improving efficiency of water use and water management practices, importation of agricultural products is another way to reduce water use in the U.S., which also can decrease water footprint for other sectors through decreases in embedded water use in agricultural production.

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Table 4-1. Summary of various scenarios for governing factors in the EIO-LCA model for consumptive water use with fixed economic structure

Scenario	Population	GDP per Capita	Consumptive Water Use Intensity
1	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)	*Constant baseline* (2012 level)
2	*Low growth* (0.66% annual growth rate)	*Low reduction* (negative Half USDA projected annual growth rate during 2013-2030: 0.95% average annual decrease rate)	*High reduction* (3% annual decrease rate during 2013-2030)
3	*Medium growth* (0.74% annual growth rate)	*Medium growth* (USDA projected annual growth rate during 2013-2030: 1.9% average annual increase rate	*Medium reduction* (1% annual decrease rate during 2013-2030)
4	*High growth* (0.82% annual growth rate)	*High growth* (1.5 times USDA projected annual growth rate during 2013-2030: 2.9% average annual increase rate)	*Low increase* (0.5% annual increase rate during 2013-2030)

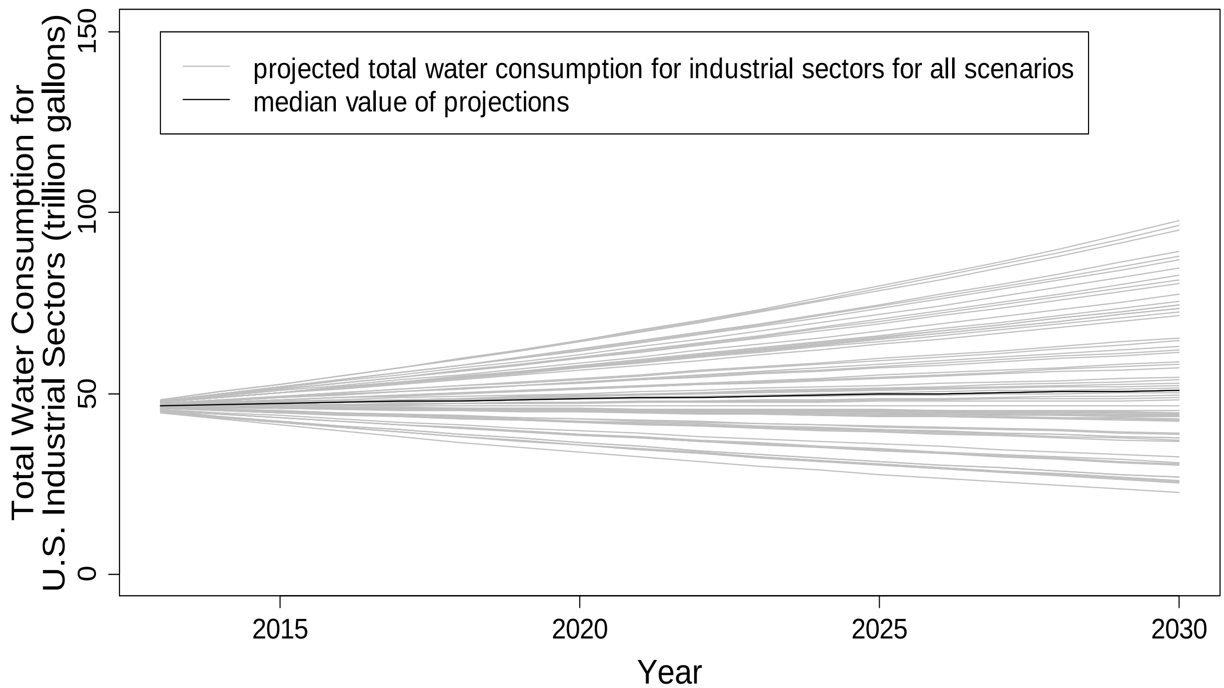

Figure 4-1. Projected total consumptive water use for U.S. industrial sectors for 2013-2030 under 64 scenarios

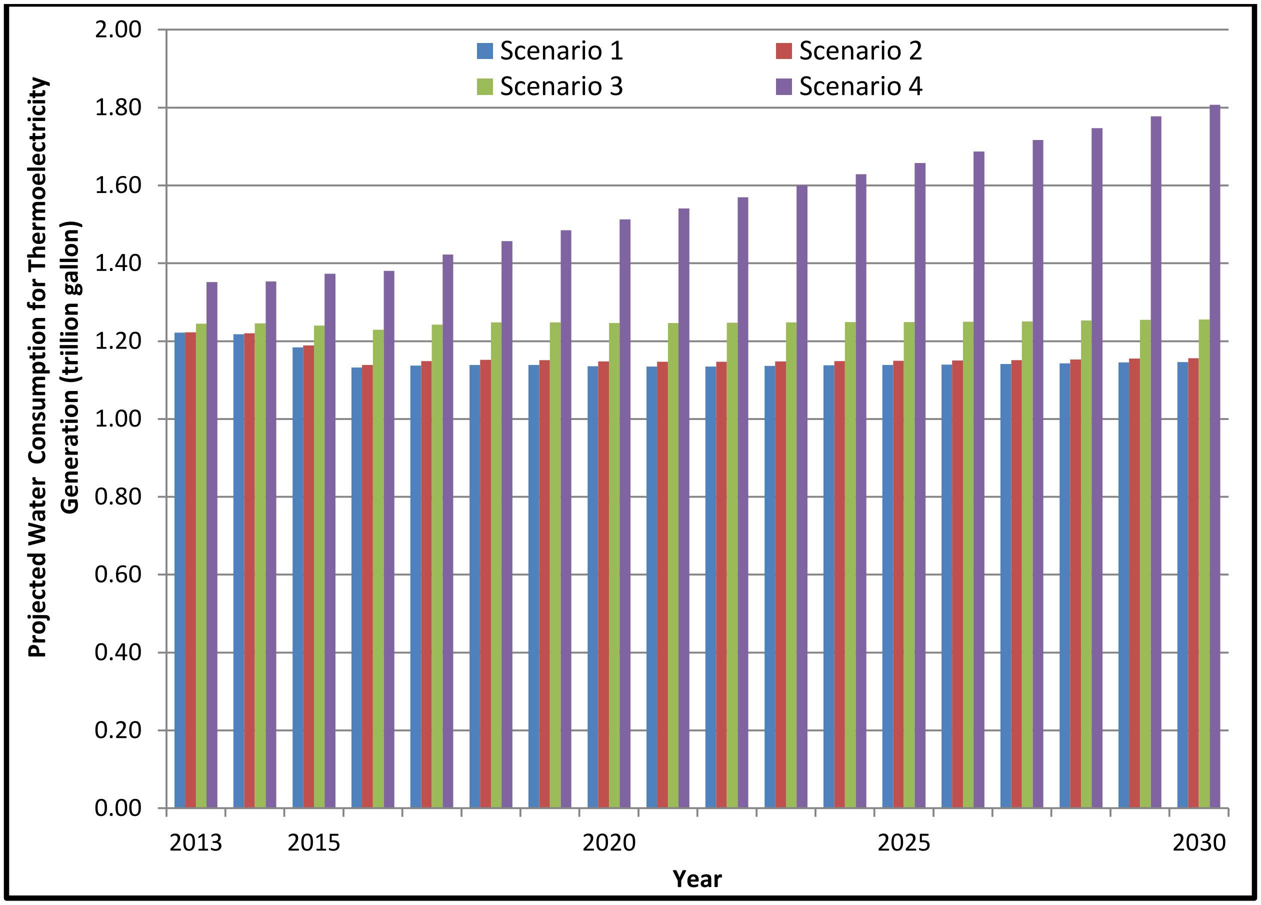

Figure 4-2. Projected consumptive water use for thermoelectric power generation for 2013-2030 under four scenarios for cooling technology for thermoelectric power generation

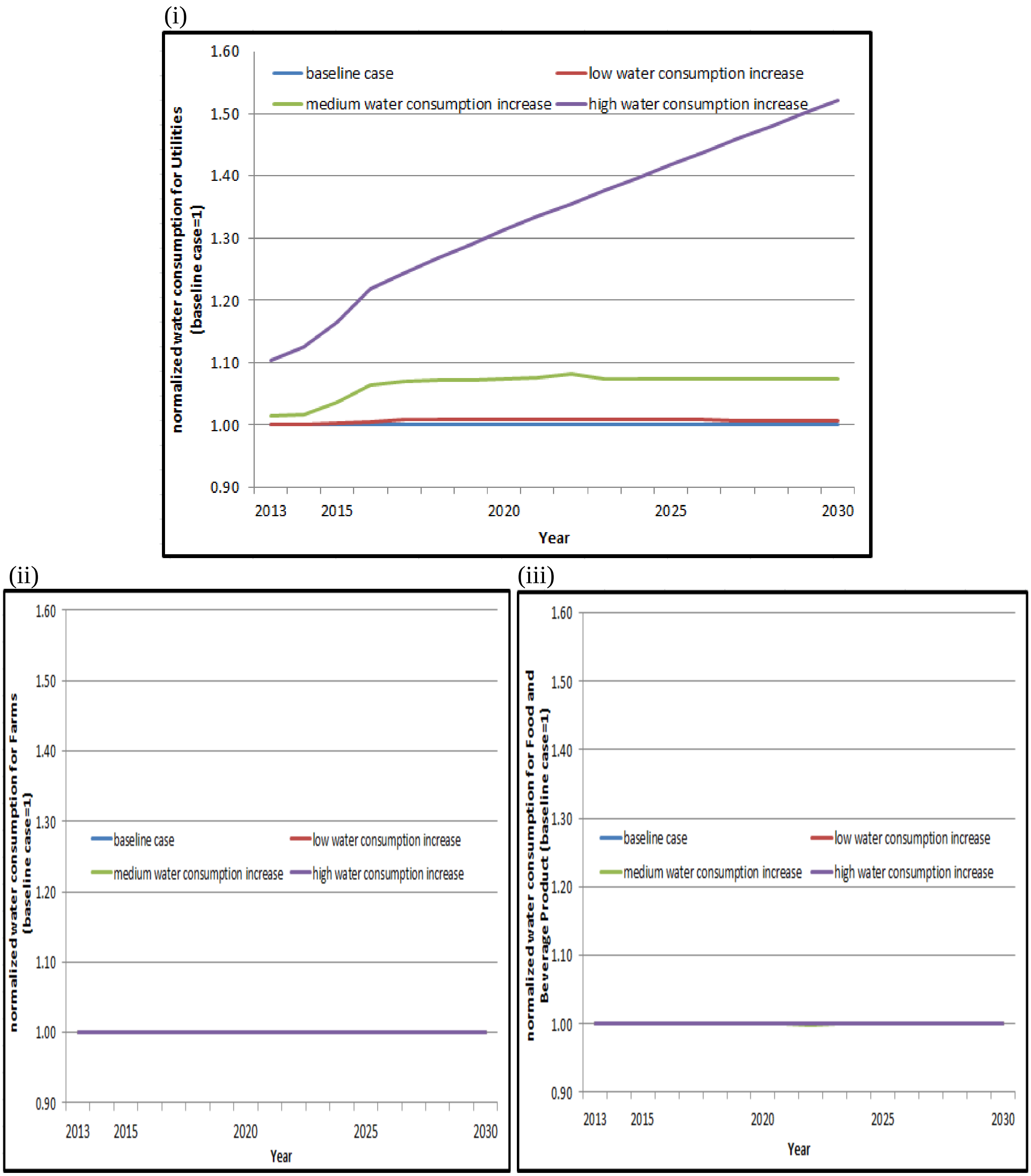

Figure 4-3a. Projected normalized consumptive water use for (i) *Utilities*, (ii) *Farms* and (iii) *Food and beverage products* under four scenarios for cooling technology and constant baseline scenario for industry output of *Utilities*. The consumptive water use under the baseline case for cooling technology is used for normalization.

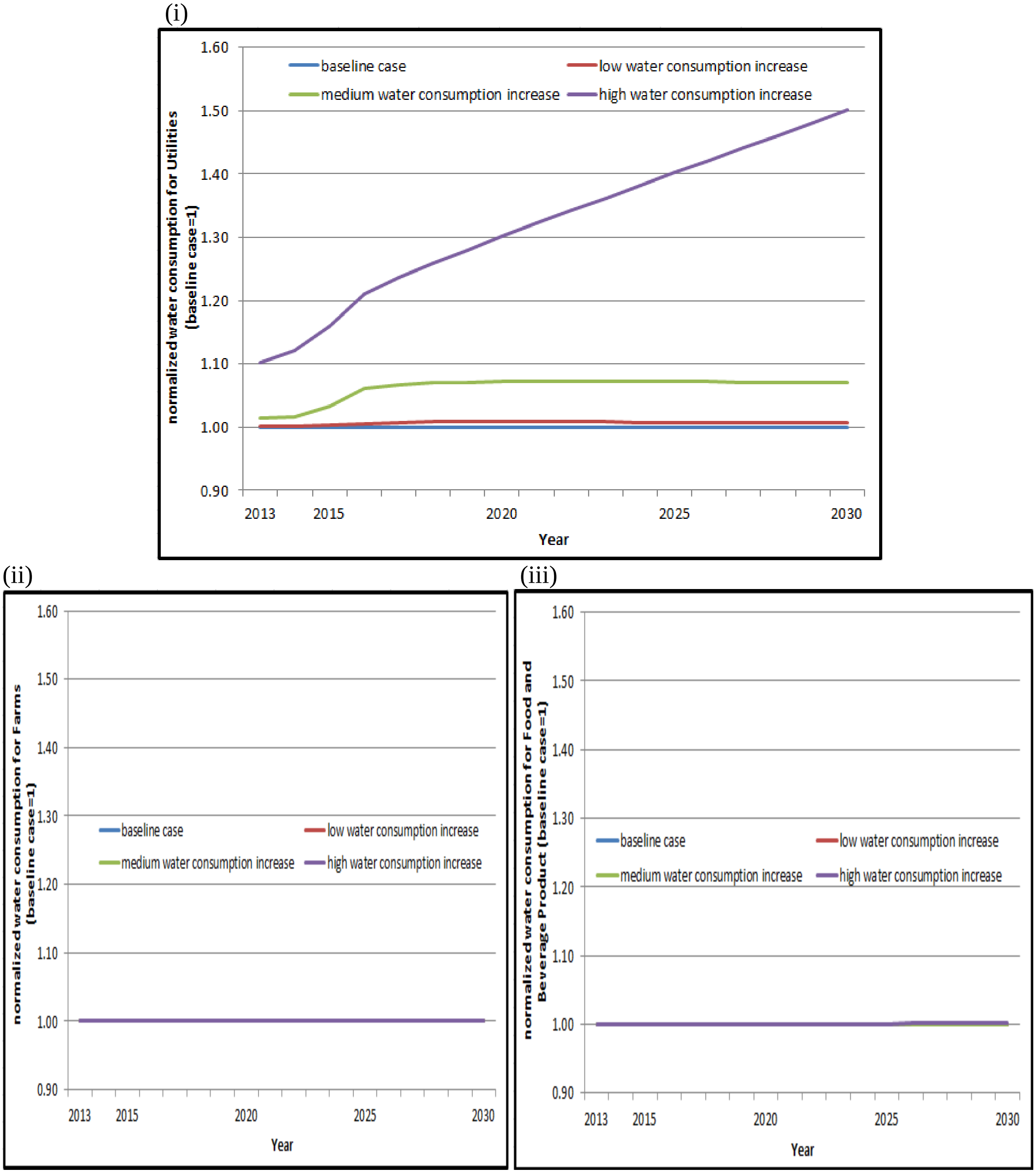

Figure 4-3b. Projected normalized consumptive water use for (i) *Utilities*, (ii) *Farms* and (iii) *Food and beverage products* under four scenarios for cooling technology and low economic growth scenario for industry output of *Utilities*. The consumptive water use under the baseline case for cooling technology is used for normalization.

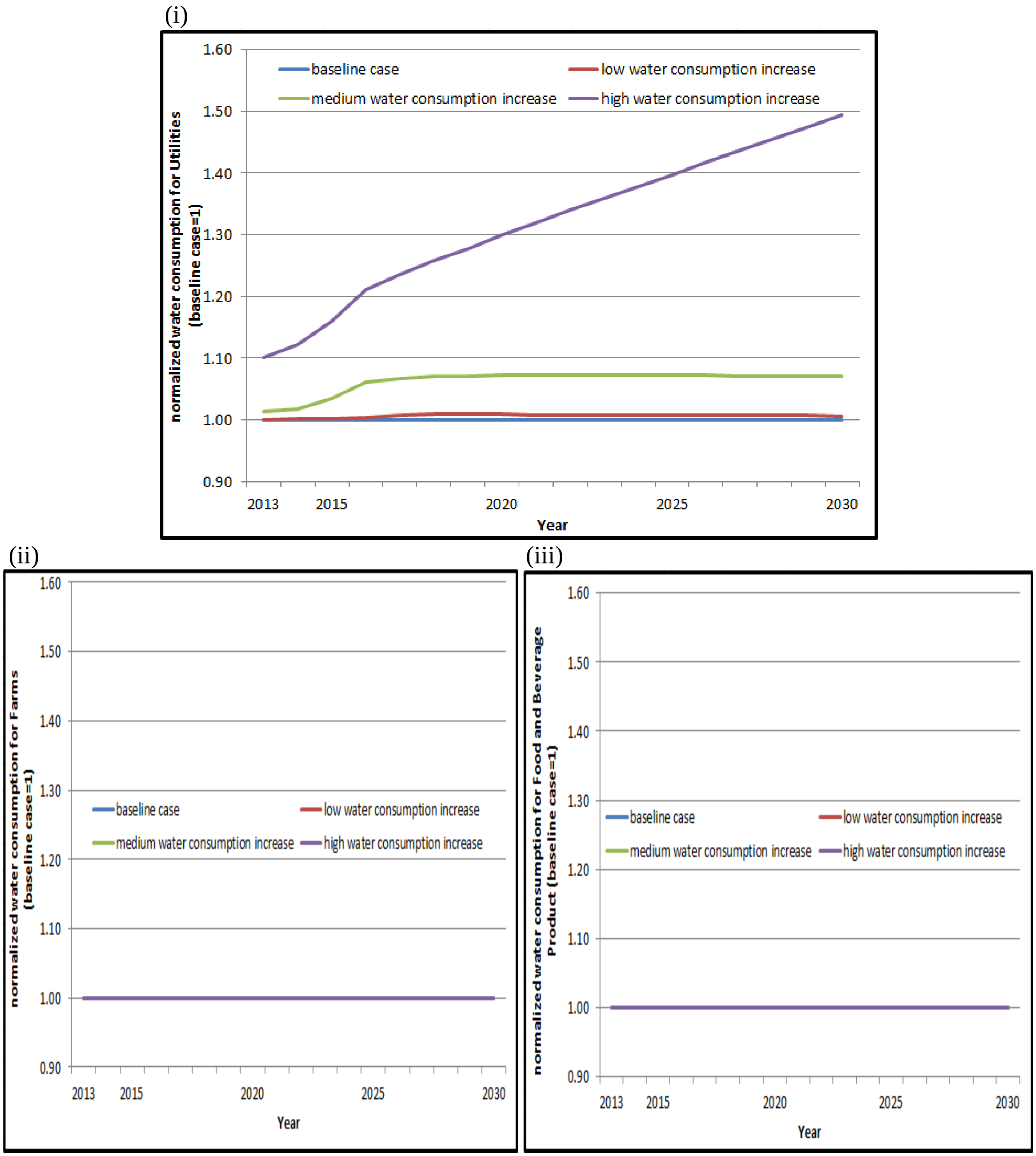

Figure 4-3c. Projected normalized consumptive water use for (i) *Utilities*, (ii) *Farms* and (iii) *Food and beverage product*s under four scenarios for cooling technology and medium economic growth scenario for industry output of *Utilities*. The consumptive water use under the baseline case for cooling technology is used for normalization.

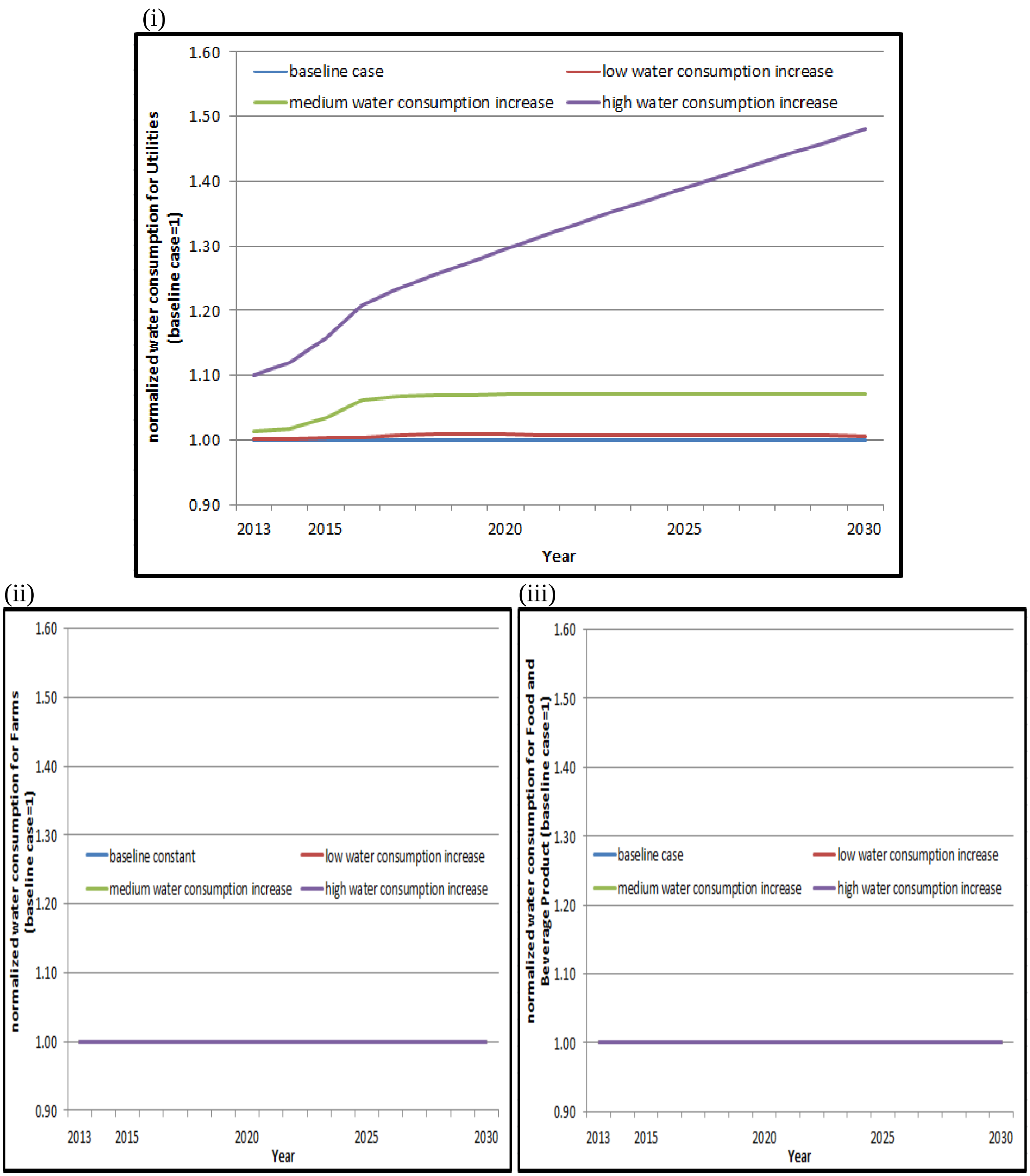

Figure 4-3d. Projected normalized consumptive water use for (i) *Utilities*, (ii) *Farms* and (iii) *Food and beverage products* under four scenarios for cooling technology and high economic growth scenario for industry output of *Utilities*. The consumptive water use under the baseline case for cooling technology is used for normalization.

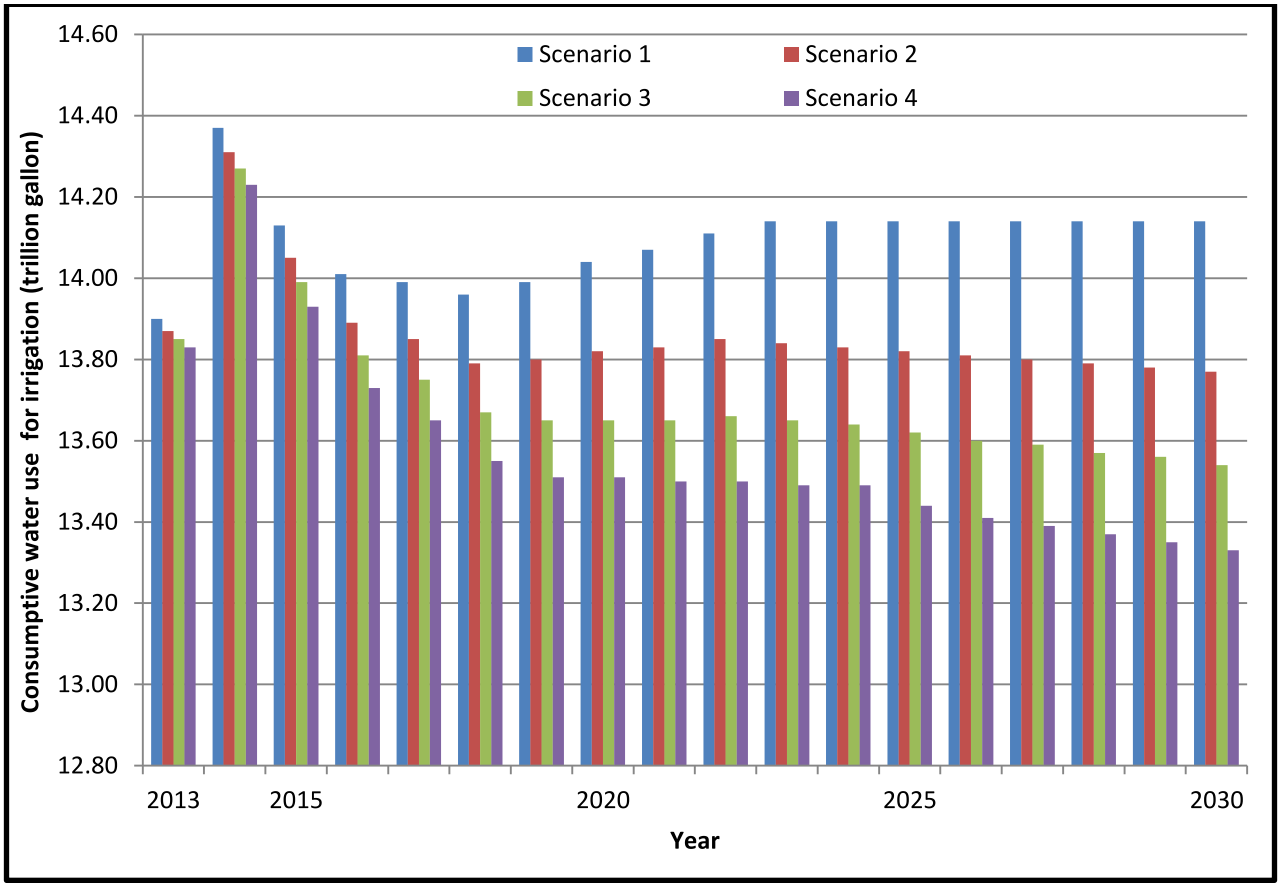

Figure 4-4. Projected consumptive water use for agricultural irrigation for 2013-2030 under four scenarios for irrigation technology

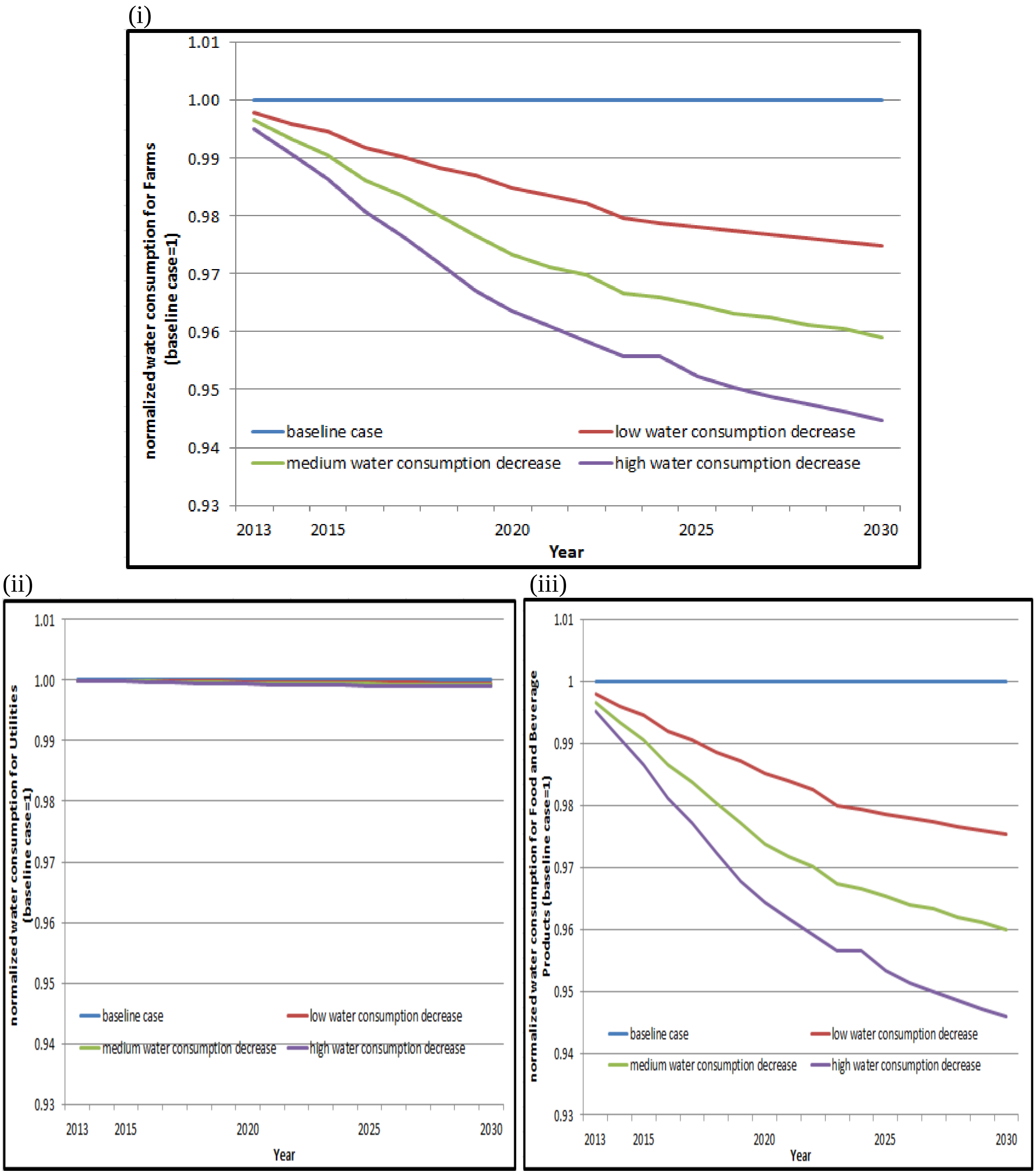

Figure 4-5a. Projected normalized consumptive water use for (i) *Farms*, (ii) *Utilities*, and (iii) *Food and beverage products* under four scenarios for irrigation technology and baseline constant scenario for industry output of *Farms*. The consumptive water use under the baseline case for irrigation technology is used for normalization.

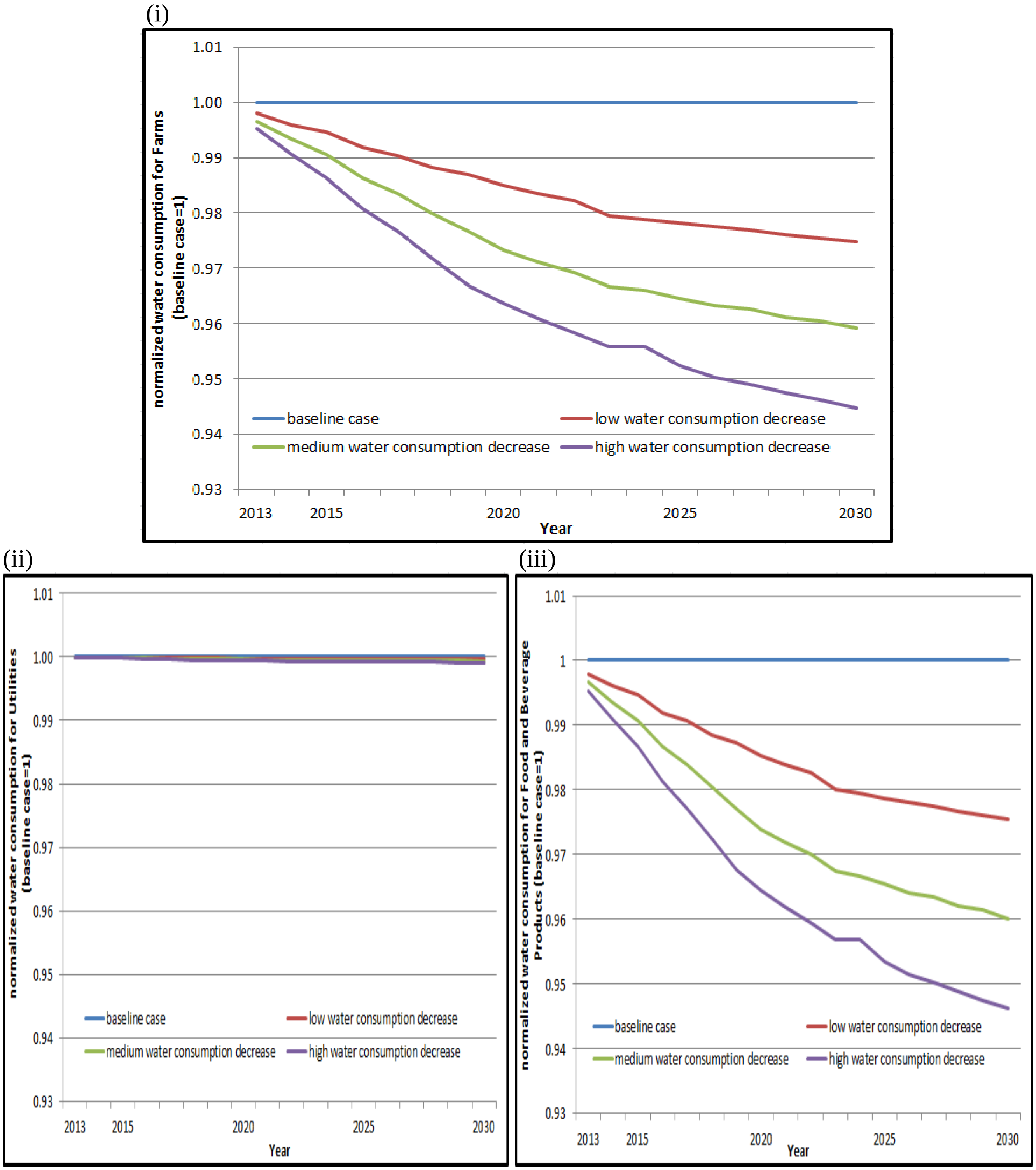

Figure 4-5b. Projected normalized consumptive water use for (i) *Farms*, (ii) *Utilities*, and (iii) *Food and beverage products* under four scenarios for irrigation technology and low economic growth scenario for industry output of *Farms*. The consumptive water use under the baseline case for irrigation technology is used for normalization.

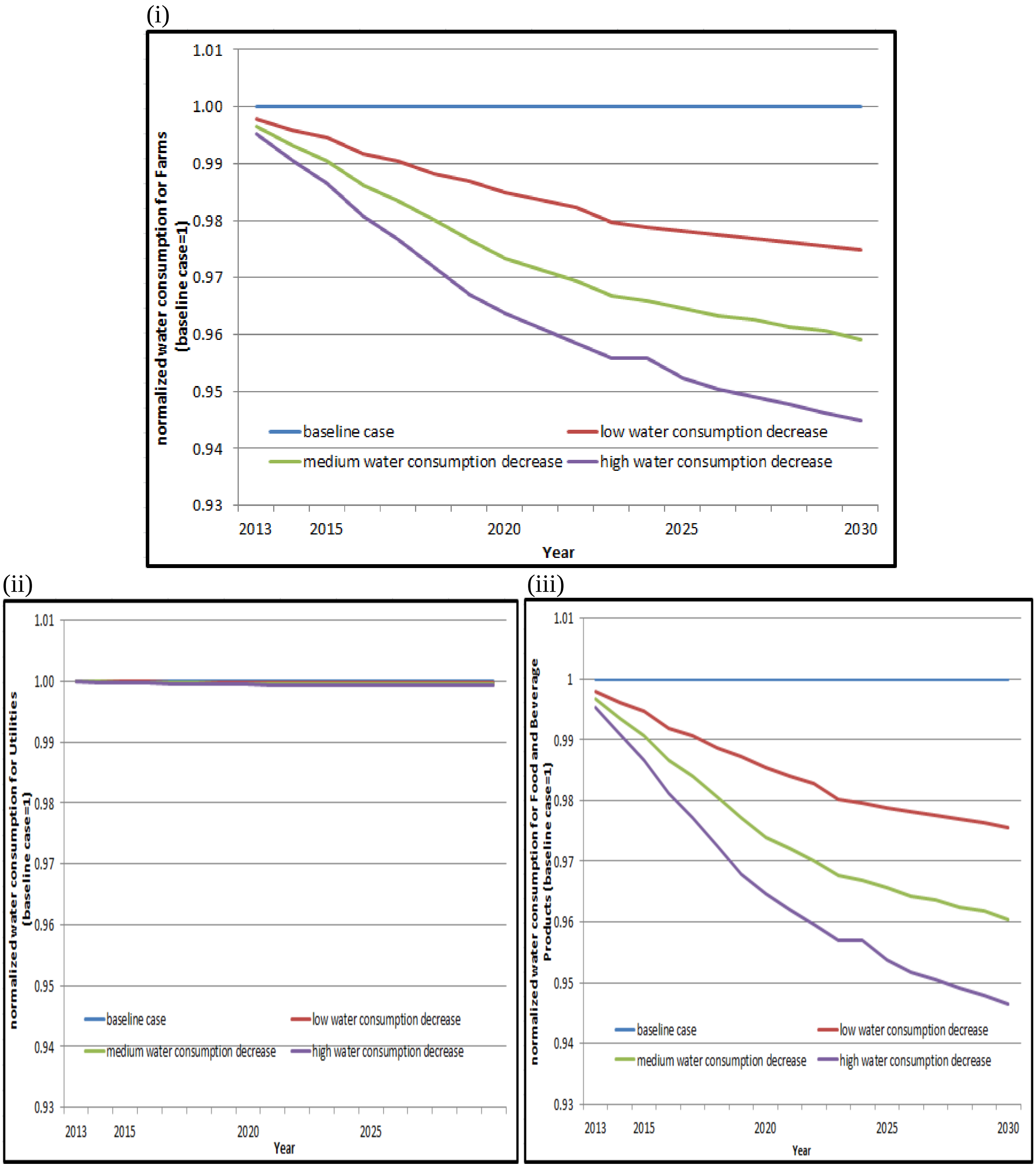

Figure 4-5c. Projected normalized consumptive water use for (i) *Farms*, (ii) *Utilities*, and (iii) *Food and beverage products* under four scenarios for irrigation technology and medium economic growth scenario for industry output of *Farms*. The consumptive water use under the baseline case for irrigation technology is used for normalization.

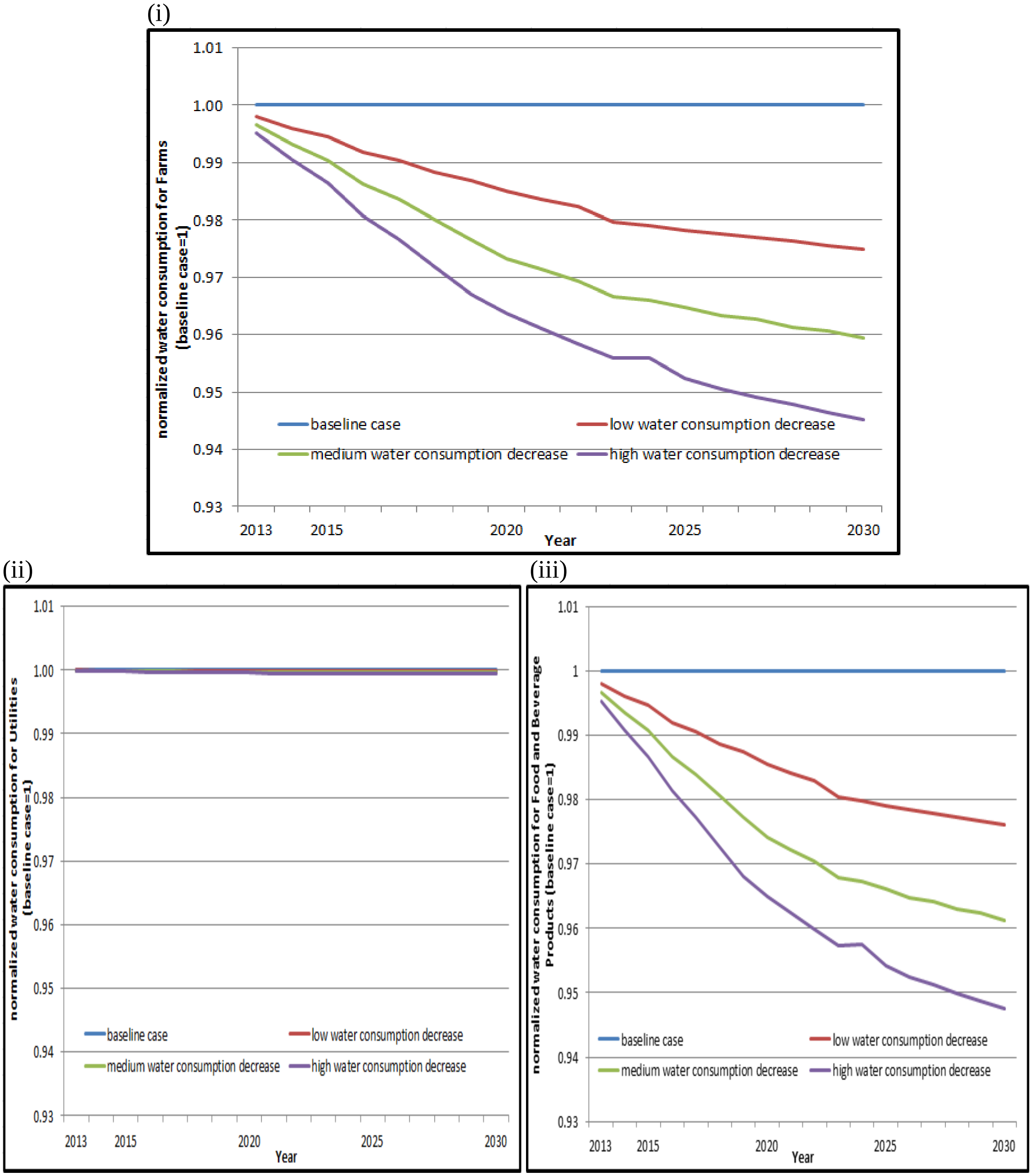

Figure 4-5d. Projected normalized consumptive water use for (i) *Farms*, (ii) *Utilities*, and (iii) *Food and beverage products* under four scenarios for irrigation technology and high economic growth scenario for industry output of *Farms*. The consumptive water use under the baseline case for irrigation technology is used for normalization.

Chapter 5: Conclusions and Future Work

5.1 Summary and Conclusions

The overall objectives of this study were to understand the contributions of the five factors — population, GDP per capita, water use intensity, production structure and consumption patterns — affecting the total water withdrawals including direct and supply chain water withdrawal for U.S. industrial sectors, to project total water withdrawals and consumptive water uses under different scenarios for the five governing factors, and investigate the impacts of shifts in cooling technology used for thermoelectric power generation and irrigation technology for agriculture. To achieve these goals, the structural decomposition analysis (SDA) method was applied for the quantification of the contributions of the five factors to changes in total water withdrawal across 135 summary industrial sector estimated by the EIO-LCA model during 1997-2002. The total water withdrawals for 66 aggregated U.S. industrial sectors from 2013-2030 were projected across the combinations of various scenarios for five governing factors using the EIO-LCA model with fixed and changing economic structure. In addition, the consumptive water uses for the 66 aggregated U.S. industrial sectors were projected for 64 combinations of four scenarios for each of population, GDP per capita and consumptive water use intensity for 2013-2030. The consumptive water uses across the 66 aggregated industrial sectors under various scenarios for cooling technology for thermoelectric power generation and irrigation technology for agriculture were estimated for 2013-2030 for agriculture to evaluate the effects of changes in cooling and irrigation technology on changes in consumptive water use for other industrial sectors.

Changes in total water withdrawal for U.S. industrial sectors are jointly influenced by population, GDP per capita, water use intensity, production structure and consumption pattern. Increases in population, GDP per capita and water use intensity all resulted in a net increase in water withdrawal across the U.S. economy, while changes in production structure and consumption patterns reduced the total water withdrawal for the U.S. economy during 1997-2002. The change in consumption pattern was the largest net contributor to changes in total water withdrawal, whereas the overall contributions of increases in population and GDP per capita to change in water withdrawal were modest for 1997-2002.

The total water withdrawal for U.S. industrial sectors was projected to range from 80-340 trillion gallons in 2030 using the EIO-LCA model with fixed economic structure. The total water withdrawal was projected to range from 80- 380 trillion gallons in 2030 with changing economic structure. The median water withdrawal projected by the EIO-LCA model with fixed economic structure increased from 161 trillion gallons in 2013 to 176 trillion gallons in 2030 with an annual average growth rate of 0.5%, while the median annual growth rate obtained from the fixed economic structure was 0.7% during the same period. The contribution of variations in population to variance in the total projected water withdrawal was the smallest among the five governing factors, while the effects of variations in the GDP per capita and water use intensity on the variations in projected total water withdrawals were significant for 2013-2030.

The consumptive water use for all industrial sectors projected by the EIO-LCA model with fixed economic structure ranged from 23-51 trillion gallons in 2030 across 64 scenarios, accounting for about 30% of total water withdrawal. The median total consumptive water use was projected to grow at an average annual rate of 0.5% during the period 2013-2030. Changes in cooling technology do not impact consumptive water use projections for most sectors, but do impact power generation-related sectors themselves. Shifts in irrigation technology do not only affect consumptive water use for agriculture, but also affect consumptive water use for sectors using agricultural products as important supply chain components.

The main contributions of this work are as follows: (1) the SDA method was applied to U.S. water use study which has not been done previously; (2) the total water withdrawals and consumptive water uses (including direct and indirect part) were projected for U.S. industrial sectors, going beyond past studies which have focused on the direct and fresh water uses; and (3) the database for consumptive water use coefficients by individual industrial sectors was developed.

5.2 Recommendation for Future Work

This study could be further developed by future work in several following ways. Future studies can take advantage of important data due to be released soon, and can consider other factors not addressed in the present work.

The original data used for estimating factors affecting changes in water withdrawal are fairly old. They include water withdrawal data for 1995, 2000 and 2005, and benchmark economic input-output data for 1997 and 2002. Benchmark economic input-output data for 2007 have been published at the beginning of 2014 by U.S. Bureau of Economic Analysis. The U.S. Geological Survey will release 2010 water withdrawal data at the end of 2014. The analysis is suggested to be extended based upon the updated database in the future.

The projections of future water withdrawals and consumptive water uses were based upon scenarios with constant annual change rate for the five governing factors, which resulted in very large water use for the maximum projections in the future decades. However, severe water shortages might also cause a contraction in the economy and population growth. The modeling approach employed could be modified by adjusting the scenarios to allow population growth, economic growth, and technological innovation rates to change during periods of water shortage (or surplus).

This work only focused on water withdrawals and consumptive water uses at the national level for industrial sectors excluding residential water use. In fact, the water withdrawal and water consumption vary widely across regions in the U.S. due to population density, climate conditions, industry pattern etc. If both regional water use data and regional economic production structure data become available, the analysis should be to the region level in future work, especially for the water-short regions. The estimation and projection of residential water use were not included in this study, since no industrial sectors are related to residential water use. In future studies, residential water use could be considered as an "industrial sector" and estimated through the EIO-LCA model.

This study provides various assumptions for projected water withdrawal and consumption based on the combinations of different scenarios for governing factors, which provides insights into relationships between future water withdrawal (consumption) and governing factors but has limitations with respects to accurate forecasting. The use of prior probabilities for each of the scenarios could be considered, allowing the observed, evolving state of the population, economic, technological, and water use outcomes to be incorporated in providing dynamic Bayesian updates to the forecasts. Such an approach would allow the identification of more likely scenarios for future water withdrawal and consumption and reduce uncertainty in forecasting.

The climate condition is an important factor affecting the water withdrawals and consumptive water use, especially for agricultural irrigation. However, climate variability and change were not considered in this study. The effects of climate change on changes in consumptive water use for industrial sectors should be examined in future studies.

Appendix A: Supporting Information for Chapter 2

A.1 Details of Methods of Allocation of USGS Water Withdrawal to U.S. Industrial Sectors

The following subsections show the detailed method of allocation of USGS category water withdrawal to 135 industrial summary sectors and the results of allocation. The methods of allocation for public supply water withdrawal, industrial water withdrawal and some mining water withdrawal are based upon the method developed by Blackhurst et al (Blackhurst et al., 2010). The methods for crop production, animal production and electric power generation were modified after those used by Blackhurst et al.(2010).

A.1.1 Public Supply Water Withdrawal

Public supply water withdrawal reported by USGS was mapped to the summary industrial sectors which have purchases from the sector "*Water, sewage and other systems (2213)*". USGS public supply water withdrawal was allocated to 115 sectors in 1997 EIO table and 126 sectors in 2002 EIO table. Equation A-1 shows the allocation of USGS public supply water withdrawal (Blackhurst et al., 2010).

$$Public\ Supply\ Water\ Withdrawal_i = \frac{Sector\ i\ Purchase\ from\ Sector\ 2213}{Total\ Commodity\ Output\ of\ Sector\ 2213} \times USGS\ Public\ Supply \qquad [A-1]$$

where $Public\ Supply\ Water\ Withdrawal_i$ is the allocated public supply water withdrawal for sector i; $Sector\ i\ Purchase\ from\ Sector\ 2213$ is the commodity purchased by sector i from Sector 2213 (*Water, sewage and other systems)*; $Total\ Commodity\ Output\ of\ Sector\ 2213$ is the total amount of commodity produced by *Water, sewage and other systems (2213)*; *USGS public supply* is the public supply water withdrawal reported by USGS.

A.1.2 Power Generation Water Withdrawal

USGS power generation water withdrawal was allocated to three detailed sectors associated with electricity generation and utilities (Blackhurst et al., 2010), *"Power generation and supply (221100)"*, *"Federal electric utilities (S00101)"* and *"State and local government electric utilities (S00202)"* based upon the proportion of industry output. The estimated power generation water withdrawals for all three detailed sectors also represent the power generation category water withdrawal for their corresponding summary sectors, *"Power generation and supply (2211)"*, *"Federal government enterprise (S001)"* and *"State and local government enterprise (S002)"*. The estimation of power generation water withdrawal for the industrial sectors is presented in Equation A-2.

$$Power\ Generation\ Water\ Withdrawal_i = \frac{Industry\ Output_i}{\sum_{i=1}^{3} Industry\ Output_i} \times USGS\ Power\ Generation \qquad [A-2]$$

$Power\ Generation\ Water\ Withdrawal_i$ is the estimated power generation water withdrawal for sector i, here sector i includes three detailed sectors 221100, S00101 and S00202; $Industry\ Output_i$ is the amount of output of industry i; $\sum_{i=1}^{3} Industry\ Output_i$ is the sum of industry output of these three detailed sectors associated with power generation; $USGS\ Power\ Generation$ is the power generation category water withdrawal reported by USGS.

A.1.3 Irrigation Water Withdrawal

USGS irrigation water withdrawal was directly allocated to the summary sector *"Crop production (1110)"* for both 1997 and 2002 which includes 10 detailed sectors representing grain, vegetable, fruit, etc. (Blackhurst et al., 2010).

A.1.4 Livestock and Aquaculture Water Withdrawal

USGS livestock and aquaculture water withdrawal was mapped to the summary sector *"Animal production (1120)"*. This summary sector consists of three detailed sectors in 1997 and four detailed sectors in 2002 regarding cattle ranching and farming, poultry and egg production, etc. (Blackhurst et al., 2010)

A.1.5 Industrial Water Withdrawal

The USGS industrial water withdrawal was allocated to 53 manufacturing sectors in the EIO table for 1997 and 2002. We assumed that U.S industrial water use pattern was similar to Canada (Blackhurst et al., 2010). We used the Canadian industrial water use per employee to derive the U.S. industrial water withdrawal estimates (Industry Canada, 2012; Statistics Canada, 2005; U.S. BLS, 2002; U.S. Census Bureau, 1997), and then the estimates were scaled to match the USGS industrial water withdrawal. One Canadian manufacturing industry represents one or more U.S. manufacturing sectors (Blackhurst et al., 2010). We assumed that all U.S. manufacturing sectors corresponding to the same Canadian manufacturing industry had a common Canadian water use per employee data. Because of the limited data source, the 2005 Canadian industrial water use and 2002 industrial employee data were used to derive Canadian industrial water use per employee for both 1997 and 2002. Equation A-3 indicates the allocation of industrial water withdrawal method.

$$Industrial\ Water\ Withdrawal_i = \frac{(\frac{CA\ WaterUse}{CA\ Employee})_i \times US\ Employee_i}{\sum_{i=1}^{53}(\frac{CA\ Water\ Use}{CA\ Employee})_i \times US\ Employee_i} \times USGS\ Indudtrial\ Water\ Withdrawal \quad [A-3]$$

$Industrial\ Water\ Withdrawal_i$ is the estimated industrial water withdrawal for sector i; $(\frac{CA\ WaterUse}{CA\ Employee})_i$ is the Canadian industrial water use per employee for sector i; $US\ Employee_i$ is the number of US employees working for sector i; $USGS\ Industrial\ Water\ Withdrawal$ is the reported USGS industrial water withdrawal data.

A.1.6 Mining Water Withdrawal

The water withdrawals for five summary mining sectors were obtained by summing water withdrawal for the detailed sectors belonging to each summary sector. Water withdrawals for the 11 detailed mining sectors in the EIO table for 1997 and 2002 were estimated based on process data, employee data, production of mine ore and USGS reported mining category water withdrawal data (Blackhurst et al., 2010).

A.1.6.1 Oil and gas extraction (2110)

The detailed sector *Oil and gas extraction (211000)* is the only sector under the summary sector *Oil and gas extraction (2110)*. Water withdrawal in the sector *Oil and gas extraction (211000)* was estimated by process data and total production for both 1997 and 2002 (Blackhurst et al., 2010). The off-shore extraction process data wasn't reported; we assumed that water withdrawals per energy content of product for offshore drilling were the same as for those reported for on shore.

(1) Oil extraction

Primary and secondary oil production accounts for 0.2% and 79.7% of total U.S. production respectively (Mielke et al., 2012). Water use intensity for secondary oil production, the energy content of crude oil, and the crude oil production in 1997 and 2002 were used to estimate the water withdrawal for oil extraction (Mielke et al., 2012; Silverman, 2012; U.S. EIA, 2012). We assumed that water use intensity of oil extraction was the same for 1997 and 2002.

(2) Gas extraction

For conventional natural gas extraction, the net water intensity is close to 0 (Mielke et al., 2012). The water withdrawal for gas extraction is negligible.

A.1.6.2 Coal mining (2121)

Only the detailed sector *Coal mining (212100)* is included in this summary sector. The amount of water taken in coal mining depends on whether the mine is an underground or a surface mining. The calculated weighted average water consumption per MBtu reported by U.S. Department of Energy (Mielke et al., 2012; U.S. DOE, 2012), and the annual coal production in 1997 and 2002 (U.S. EIA, 1997; U.S. EIA, 2002) were used to estimate water withdrawals for coal mining. We assumed that water use intensity for coal mining did not change from1997 to 2002.

A.1.6.3 Metal ores mining (2122)

This summary sector consists of three detailed sectors. The water withdrawal for the metal ores mining was estimated based on process data and commodity production.

(1) Iron ore mining (212210)

It was reported that 0.3KL of water was required per ton of production of iron ore in Australia in 2002 (Institute for Social Sustainability, 2012). We assumed that water use pattern of iron ore mining in U.S was similar to Australia, and the water use intensity for iron mining for1997 and 2002 was the same.

(2) Gold, silver and other metal ore mining (2111A0)

Water withdrawals in this sector were estimated based on process data (Lovel et al., 2004; Mudd et al., 2007) and total commodity production reported by USGS (Blackhurst et al., 2010; Kelly et al., 2005). Process data were reported only for gold, the water use intensity for gold was assumed to be similar to silver. Aluminum is the dominant metal among the remaining metals. The water use intensity of aluminum was also used for other metals. We assumed there was no change in water use intensity of gold, silver and other metal ore mining from 1997 to 2002.

(3) Copper, nickel, lead and zinc mining (212230)

Water withdrawals in this sector were estimated by process data and total commodity production (Gunson et al., 2012; Kelly et al., 2005). The water use intensity for copper was assumed to be similar to nickel, lead and zinc. We also assume that the water use intensity for copper, nickel, lead and zinc mining in 1997 and 2002 were the same.

A.1.6.4 Nonmetallic minerals mining and quarrying (2123)

Three detailed sectors *Stone mining and quarrying (*212310), Sand, gravel, clay, and refractory mining (212320), and *Other nonmetallic mineral mining and quarrying (212390)* are included in this summary sector.

(1) Stone mining and quarrying (212310)

We assumed *Stone mining and quarrying* (212310) had a similar water use pattern as sand, gravel, clay, and refractory mining. The water withdrawal for *Stone mining and quarrying* was estimated by scaling the water withdrawal for *Sand, gravel, clay, clay and refractory mining* (212320) by the number of employees (Blackhurst et al., 2010; U.S. BLS, 2002; U.S. Census Bureau, 1997). The estimation of water withdrawal for *Stone mining and quarrying* is summarized in Equation A-4.

$$Mining\ Water\ Withdrawal_{212310} = \frac{Mining\ Water\ Withdrawal_{212320}}{Employee_{212320}} \times Employee_{212310} \qquad [A-4]$$

$Mining\ Water\ Withdrawal_{212310}$ is the mining water withdrawn for sector 212310; $Mining\ Water\ Withdrawal_{212320}$ is the estimated mining water withdrawal for sector 212320; $Employee_{212320}$ is the number of employees in sector 212320; and $Employee_{212310}$ is the number of employees working for sector 212310.

(2) Sand, gravel, clay, and refractory mining (212320)

It was reported that 15 sand and gravel facilities operating in Tucson area, AZ used 5176 acre-feet ground water in 1995, and predicted to use 7000 acre-feet groundwater in 2025 (Gelt et al., 1999). The water used for these 15 facilities in 1997 and 2002 was estimated based on the reported water use in 1995 and predicted water use in 2025 using interpolation. The nation's water withdrawal for this sector in 1997 and 2002 was estimated by scaling the estimated water use for these 15 facilities in 1997 and 2002 (Blackhurst et al., 2010). We assumed that the water use pattern in the 15 sand and gravel facilities was representative of the entire U.S. (Blackhurst et al, 2010)

(3) Other nonmetallic mineral mining and quarrying (212390)

The water withdrawal for *Other nonmetallic mineral mining and quarrying* was estimated by allocating reported USGS mining water withdrawal by the fraction of all mining sectors employees (Blackhurst et al., 2010; U.S. BLS, 2002; U.S. Census Bureau, 1997).

A.1.6.5 Support activities for mining (2130)

The summary sector *Support activities for mining (2130)* includes three detailed sectors: *Drilling oil and gas wells (213111), Support activities for oil and gas operations (213112)* and *Support activities for other mining (21311A).*

(1) Drilling oil and gas wells (213111)

The water withdrawal for this sector was estimated by scaling the water withdrawal for *Oil and gas extraction* (211000) by employees (Blackhurst et al., 2010; U.S. BLS, 2002; U.S. Census Bureau, 1997).

(2) Support activities for oil and gas operations (213112)

The water withdrawal for *Support activities for oil and gas operations* was estimated by allocating reported USGS mining water withdrawal by the fraction of all mining sectors employees (Blackhurst et al., 2010; U.S. BLS, 2002; U.S. Census Bureau, 1997).

(3) Support activities for other mining (21311A)

The water withdrawal for *Support activities for other mining* was estimated by allocating reported USGS mining water withdrawal by the fraction of all mining sectors employees (Blackhurst et al., 2010; U.S. BLS, 2002; U.S. Census Bureau, 1997).

A.2 U.S. Industrial Sectors and Their Estimated Water Withdrawals in 1997 and 2002

Tables A-1and A-2 present the estimated water withdrawal and water use intensity for 1997 and 2002 summary industrial sectors, the description of sectors and their corresponding input-output codes in the EIO table, the detailed information about the industrial sectors at BEA is provided by Horowitz et al. and Yuskavage (Horowitz et al., 2009; Yuskavage, 2000).

A.3 Largest Changed Water Withdrawal Sectors due to Change in Importation

Table A-5 shows the five largest increased and decreased water withdrawal sectors due to changed imports during 1997-2002. The largest increased and decreased water withdrawal sectors were associated with foods. The change in importation for high water intensity sectors resulted in a significant amount of water withdrawal change (e.g. *Crop production* and *Food manufacturing*).

A.4 Percentage Change in per Capita Final Uses for the Largest Increased and Decreased Water Withdrawal Sectors during 1997- 2002

Figure A-3 shows the percentage change in final uses per capita for the five largest increased and decreased water withdrawal sectors from 1997 to 2002 (U.S BEA, 1997; U.S. BEA, 2002). During these five years, the U.S. inhabitants preferred more consumption on *Construction*, *Housing*, *Education*, *Health care* and *Government industry*, and reduced final use on the sectors related to food and energy. The switch of consumption patterns led to an increase in GDP per capita by about 10% from 1997 to 2002. These changes in consunption preferrence for the products and services translated to changes in their water withdrawals as well.

Table A-1. Allocated water withdrawal for 1997 U.S. industrial sectors and water use intensity

I-O Code	Sector Name	Allocated Water Withdrawal (billion gallon)	Water Use Intensity (billion gallon/$M)
1110	Crop production	4.98E+04	3.69E-01
1120	Animal production	2.09E+03	1.99E-02
1130	Forestry and logging	1.48E+00	5.36E-05
1140	Fishing, hunting and trapping	1.09E+00	1.80E-04
1150	Support activities for agriculture and forestry	0.00E+00	0.00E+00
2110	Oil and gas extraction	7.74E+02	8.47E-03
2121	Coal mining	6.56E+01	2.81E-03
2122	Metal ores mining	9.43E+00	8.40E-04
2123	Nonmetallic mineral mining and quarrying	6.42E+02	3.74E-02
2130	Support activities for mining	6.75E+02	2.71E-02
2211	Electric power generation, transmission, and distribution	6.14E+04	2.88E-01
2212	Natural gas distribution	6.67E+00	1.25E-04
2213	Water, sewage and other systems	0.00E+00	0.00E+00
2301	New residential construction	4.78E+01	1.83E-04
2302	New nonresidential construction	5.36E+01	1.45E-04
2303	Maintenance and repair construction	3.59E+01	2.93E-04
3110	Food manufacturing	3.37E+02	8.05E-04
3121	Beverage manufacturing	7.45E+01	1.13E-03
3122	Tobacco manufacturing	1.84E+01	4.41E-04
3130	Textile mills	3.21E+01	5.51E-04
3140	Textile product mills	1.15E+01	3.72E-04
3150	Apparel manufacturing	8.66E+00	1.31E-04
3160	leather and allied product manufacturing	1.10E+00	1.11E-04
3210	Wood product manufacturing	1.00E+02	1.14E-03
3221	Pulp, paper, and paperboard mills	1.00E+03	1.41E-02
3222	Converted paper product manufacturing	1.89E+03	2.47E-02
3230	Printing and related support activities	1.03E+01	1.07E-04
3240	Petroleum and coal products manufacturing	6.63E+02	3.82E-03

3251	Basic chemical manufacturing	4.69E+01	4.15E-04
3252	Resin, rubber, and artificial fibers manufacturing	1.23E+02	1.91E-03
3253	Agriculture chemical manufacturing	4.04E+01	1.70E-03
3254	Pharmaceutical and medicine manufacturing	2.13E+02	2.50E-03
3255	Paint, coating, and adhesive manufacturing	7.85E+01	3.12E-03
3256	Soap, cleaning compound, and toiletry manufacturing	1.33E+02	2.63E-03
3259	Other chemical product and preparation manufacturing	1.31E+02	3.48E-03
3260	Plastics and rubber products manufacturing	5.30E+01	3.39E-04
3270	Nonmetallic mineral product manufacturing	1.14E+02	1.34E-03
331A	Iron and steel mills and manufacturing from purchased steel	8.14E+02	1.06E-02
331B	Nonferrous metal production and processing	5.69E+02	9.16E-03
3315	Foundries	7.66E+02	2.68E-02
3321	Forging and stamping	5.37E+02	2.24E-02
3322	Cutlery and handtool manufacturing	2.90E+00	2.70E-04
3323	Architectural and structural metals manufacturing	1.42E+01	2.76E-04
3324	Boiler, tank, and shipping container manufacturing	3.81E+00	1.70E-04
332A	Ordnance and accessories manufacturing	1.40E+00	2.51E-04
332B	Other fabricated metal product manufacturing	3.71E+01	3.04E-04
3331	Agriculture, construction, and mining machinery manufacturing	1.72E+00	3.33E-05
3332	Industrial machinery manufacturing	1.44E+00	4.21E-05
3333	Commercial and service industry machinery manufacturing	1.27E+00	5.21E-05
3334	HVAC and commercial refrigeration equipment manufacturing	1.34E+00	4.56E-05

3335	Metalworking machinery manufacturing	1.94E+00	6.62E-05
3336	Engine, turbine, and power transmission equipment manufacturing	1.06E+00	3.66E-05
3339	Other general purpose machinery manufacturing	2.64E+00	4.49E-05
3341	Computer and peripheral equipment manufacturing	3.42E+00	3.46E-05
334A	Audio, video, and communications equipment manufacturing	3.90E+00	4.40E-05
3344	Semiconductor and electronic component manufacturing	7.27E+00	5.35E-05
3345	Electronic instrument manufacturing	5.87E+00	6.80E-05
3346	Magnetic media manufacturing and reproducing	6.60E-01	6.86E-05
3351	Electric lighting equipment manufacturing	9.80E-01	8.13E-05
3352	Household appliance manufacturing	1.17E+00	5.76E-05
3353	Electrical equipment manufacturing	2.61E+00	7.57E-05
3359	Other electrical equipment and component manufacturing	2.92E+00	7.16E-05
3361	Motor Vehicle manufacturing	6.33E+00	2.88E-05
336A	Motor Vehicle body, trailer, and parts manufacturing	2.39E+01	1.22E-04
3364	Aerospace product and parts manufacturing	1.39E+01	1.20E-04
336B	Other transportation equipment manufacturing	5.62E+00	1.71E-04
3370	Furniture and related product manufacturing	7.46E+00	1.19E-04
3391	Medical equipment and supplies manufacturing	2.58E+00	6.06E-05
3399	Other miscellaneous manufacturing	3.68E+00	6.22E-05
4200	Wholesale trade	1.25E+02	1.66E-04
4A00	Retail trade	2.14E+02	2.93E-04
4810	Air transportation	1.00E+01	8.40E-05
4820	Rail transportation	4.49E+00	1.18E-04
4830	Water transportation	4.45E+00	1.82E-04

4840	Truck transportation	1.56E+01	9.22E-05
4850	Transit and ground passenger transportation	8.33E+00	3.38E-04
4860	Pipeline transportation	0.00E+00	0.00E+00
48A0	Scenic and sightseeing transportation and support activities	1.32E+01	2.97E-04
4920	Couriers and messengers	3.80E+00	9.08E-05
4930	Warehousing and storage	1.43E+01	4.88E-04
5111	Newspaper, periodical, book, and directory publishers	7.24E+00	6.38E-05
5112	Software publishers	1.79E+00	2.91E-05
5120	Motion picture and sound recording industries	1.03E+01	1.69E-04
5131	Radio and television broadcasting	6.06E+00	1.47E-04
5132	Cable network and program distribution	1.65E+01	3.66E-04
	Internet publishing and broadcasting	0.00E+00	0.00E+00
5133	Telecommunications	1.10E+02	3.98E-04
5142	Internet service providers, web search portals	3.18E+00	8.89E-05
5141	Other information services	7.00E-01	5.96E-05
52A0	Monetary authorities, credit intermediation and related activities	1.12E+02	2.39E-04
5230	Securities, commodity, contracts, investments and related activities	3.22E+01	1.62E-04
5240	Insurance carries and related activities	1.80E+01	5.29E-05
5250	Funds, trusts, and other financial vehicles	9.00E-02	1.36E-06
5310	Real estate	5.62E+02	9.25E-04
S008	Owner-occupied dwelling	0.00E+00	0.00E+00
5321	Automotive equipment rental and leasing	3.97E+00	9.42E-05
532A	Consumer goods and general rental centers	6.98E+00	2.74E-04
5324	Commercial and industrial machinery and equipment rental and leasing	8.55E+00	2.08E-04
5330	Lessors of nonfinancial intangible assets	0.00E+00	0.00E+00

5411	Legal services	1.15E+01	7.57E-05
5412	Accounting, tax preparation, bookkeeping, and payroll services	5.85E+00	8.18E-05
5413	Architectural, engineering, and related services	1.53E+01	1.17E-04
5414	Specialized design services	5.10E+00	2.88E-04
5415	Computer systems design and related services	5.41E+00	3.88E-05
5416	Management, scientific, and technical consulting services	6.46E+00	7.59E-05
5417	Scientific research and development services	2.63E+01	4.15E-04
5418	Advertising and related services	4.19E+00	7.26E-05
5419	Other professional, scientific, and technical services	1.73E+01	2.85E-04
5500	Management of companies and enterprises	1.84E+02	5.83E-04
5613	Employment services	8.30E-01	9.35E-06
5613	Travel arrangement and reservation services	4.40E+01	1.75E-03
561A	All other administrative and support services	3.96E+01	2.09E-04
5620	Waste management and remediation services	8.43E+01	2.02E-03
6100	Educational services	1.75E+01	1.72E-04
6210	Ambulatory health care services	6.78E+01	1.78E-04
6220	Hospitals	1.48E+02	5.53E-04
6230	Nursing and residential care facilities	8.52E+01	9.11E-04
6240	Social assistance	4.00E+01	6.03E-04
71A0	Performing arts, spectator sports, museums, zoos, and parks	1.91E+01	3.54E-04
7130	Amusements, gambling, and recreation	7.68E+01	9.66E-04
7210	Accommodation	1.20E+02	1.52E-03
7220	Food services and drinking places	1.48E+02	4.30E-04
8111	Automotive repair and maintenance	5.55E+01	3.81E-04
811A	Electronic, commercial, and household goods repairs	1.34E+01	1.41E-04
8120	Personal and laundry services	6.19E+01	6.50E-04

813A	Religious, grantmaking, giving, and social advocacy organization	3.25E+01	5.98E-04
813B	Civic, social, professional and similar organizations	2.40E+01	5.33E-04
8140	Private households	0.00E+00	0.00E+00
S001	Federal government enterprise	2.47E+03	3.31E-02
S002	State and local government enterprise	7.01E+03	5.64E-02
S005	General government industry	0.00E+00	0.00E+00
S003	Noncomparable imports	0.00E+00	0.00E+00
S004	Scrap, used and secondhand goods	0.00E+00	0.00E+00
S006	Rest of the world adjustment	0.00E+00	0.00E+00
S007	Inventory valuation adjustment	0.00E+00	0.00E+00

Table A-2. Allocated water withdrawal for 2002 U.S. industrial sectors and water use intensity

I-O Code	Sector Name	Allocated Water Withdrawal (billion gallon)	Water Use Intensity (billion gallon/$M)
1110	Crop production	4.90E+04	4.10E-01
1120	Animal production	2.81E+03	2.79E-02
1130	Forestry and logging	2.17E+00	6.72E-05
1140	Fishing, hunting and trapping	8.80E-01	1.63E-04
1150	Support activities for agriculture and forestry	0.00E+00	0.00E+00
2110	Oil and gas extraction	7.35E+02	7.06E-03
2121	Coal mining	6.51E+01	3.19E-03
2122	Metal ores mining	7.56E+00	9.48E-04
2123	Nonmetallic mineral mining and quarrying	6.61E+02	3.35E-02
2130	Support activities for mining	6.45E+02	1.99E-02
2211	Electric power generation, transmission, and distribution	6.31E+04	2.81E-01
2212	Natural gas distribution	6.40E+00	7.68E-05
2213	Water, sewage and other systems	0.00E+00	0.00E+00
2302	New residential construction	5.34E+01	1.22E-04
2301	New nonresidential construction	7.61E+01	1.71E-04
2303	Maintenance and repair construction	1.97E+01	1.32E-04
3110	Food manufacturing	4.70E+02	1.04E-03
3121	Beverage manufacturing	1.08E+02	1.51E-03
3122	Tobacco manufacturing	1.90E+01	4.00E-04
2130	Textile mills	3.45E+01	7.71E-04
3140	Textile product mills	1.34E+01	4.48E-04
3150	Apparel manufacturing	7.65E+00	1.93E-04
3160	leather and allied product manufacturing	2.42E+00	4.18E-04
3210	Wood product manufacturing	1.12E+02	1.26E-03
3221	Pulp, paper, and paperboard mills	8.85E+02	1.27E-02
3222	Converted paper product manufacturing	1.98E+03	2.44E-02
3230	Printing and related support activities	1.91E+01	1.94E-04
3240	Petroleum and coal products manufacturing	7.77E+02	3.69E-03
3251	Basic chemical manufacturing	5.73E+01	5.45E-04

3252	Resin, rubber, and artificial fibers manufacturing	1.34E+02	2.25E-03
3253	Agriculture chemical manufacturing	5.04E+01	2.70E-03
3254	Pharmaceutical and medicine manufacturing	3.34E+02	2.46E-03
3255	Paint, coating, and adhesive manufacturing	9.75E+01	3.70E-03
3256	Soap, cleaning compound, and toiletry manufacturing	2.00E+01	3.31E-04
3259	Other chemical product and preparation manufacturing	1.31E+02	3.65E-03
3260	Plastics and rubber products manufacturing	8.49E+01	5.03E-04
3270	Nonmetallic mineral product manufacturing	1.39E+02	1.50E-03
331A	Iron and steel mills and manufacturing from purchased steel	6.19E+02	1.01E-02
331B	Nonferrous metal production and processing	5.67E+02	1.14E-02
3315	Foundries	6.38E+02	2.45E-02
3321	Forging and stamping	7.11E+00	3.38E-04
3322	Cutlery and handtool manufacturing	3.40E+00	3.38E-04
3323	Architectural and structural metals manufacturing	2.17E+01	3.73E-04
3324	Boiler, tank, and shipping container manufacturing	6.11E+00	2.66E-04
332A	Ordnance and accessories manufacturing	1.98E+00	3.85E-04
332B	Other fabricated metal product manufacturing	2.24E+01	1.82E-04
3331	Agriculture, construction, and mining machinery manufacturing	4.48E+00	1.00E-04
3332	Industrial machinery manufacturing	2.96E+00	1.05E-04
3333	Commercial and service industry machinery manufacturing	2.32E+00	1.17E-04
3334	HVAC and commercial refrigeration equipment manufacturing	3.49E+00	1.13E-04
3335	Metalworking machinery manufacturing	4.10E+00	1.69E-04

3336	Engine, turbine, and power transmission equipment manufacturing	3.24E+00	9.33E-05
3339	Other general purpose machinery manufacturing	6.78E+00	1.26E-04
3341	Computer and peripheral equipment manufacturing	4.58E+00	6.78E-05
334A	Audio, video, and communications equipment manufacturing	6.22E+00	8.79E-05
3344	Semiconductor and electronic component manufacturing	1.88E+01	1.74E-04
3345	Electronic instrument manufacturing	1.03E+01	1.15E-04
3346	Magnetic media manufacturing and reproducing	1.17E+00	1.59E-04
3351	Electric lighting equipment manufacturing	2.07E+00	1.76E-04
3352	Household appliance manufacturing	2.50E+00	1.18E-04
3353	Electrical equipment manufacturing	3.56E+00	1.22E-04
3359	Other electrical equipment and component manufacturing	4.93E+00	1.38E-04
3361	Motor Vehicle manufacturing	1.19E+01	5.01E-05
336A	Motor Vehicle body, trailer, and parts manufacturing	1.09E+02	4.91E-04
3364	Aerospace product and parts manufacturing	1.77E+01	1.46E-04
336B	Other transportation equipment manufacturing	9.66E+00	2.35E-04
3370	Furniture and related product manufacturing	2.80E+01	3.82E-04
3391	Medical equipment and supplies manufacturing	6.29E+00	1.07E-04
3399	Other miscellaneous manufacturing	1.29E+01	1.99E-04
4200	Wholesale trade	6.08E+01	6.98E-05
4A00	Retail trade	1.35E+02	1.50E-04
4810	Air transportation	1.32E+00	1.34E-05
4820	Rail transportation	2.65E+00	6.53E-05
4830	Water transportation	2.10E+01	7.97E-04
4840	Truck transportation	1.06E+01	5.20E-05

4850	Transit and ground passenger transportation	5.11E+01	1.62E-03
4860	Pipeline transportation	0.00E+00	0.00E+00
48A0	Scenic and sightseeing transportation and support activities	2.65E+01	4.16E-04
4920	Couriers and messengers	5.07E+00	8.24E-05
4930	Warehousing and storage	8.38E+00	1.97E-04
5111	Newspaper, periodical, book, and directory publishers	4.96E+00	3.55E-05
5112	Software publishers	1.18E+00	1.13E-05
5120	Motion picture and sound recording industries	3.75E+00	4.45E-05
5151	Radio and television broadcasting	2.06E+00	4.14E-05
5152	Cable network and program distribution	8.10E-01	3.15E-05
5161	Internet publishing and broadcasting	1.50E-01	1.74E-05
5170	Telecommunications	1.18E+02	2.71E-04
5180	Internet service providers, web search portals	3.46E+00	4.81E-05
5190	Other information services	4.80E-01	7.05E-05
52A0	Monetary authorities, credit intermediation and related activities	3.00E+01	4.41E-05
5230	Securities, commodity, contracts, investments and related activities	8.34E+00	2.93E-05
5240	Insurance carries and related activities	3.27E+00	7.23E-06
5250	Funds, trusts, and other financial vehicles	1.50E-01	1.67E-06
5310	Real estate	3.13E+02	3.83E-04
S008	Owner-occupied dwelling	0.00E+00	0.00E+00
5321	Automotive equipment rental and leasing	3.71E+00	9.57E-05
532A	Consumer goods and general rental centers	5.96E+00	1.83E-04
5324	Commercial and industrial machinery and equipment rental and leasing	3.68E+00	7.84E-05
5330	Lessors of nonfinancial intangible assets	2.22E+01	1.79E-04
5411	Legal services	5.66E+00	2.76E-05

5412	Accounting, tax preparation, bookkeeping, and payroll services	3.53E+00	3.46E-05
5413	Architectural, engineering, and related services	9.59E+00	5.43E-05
5414	Specialized design services	7.00E-01	3.23E-05
5415	Computer systems design and related services	2.76E+00	1.08E-05
5416	Management, scientific, and technical consulting services	3.31E+00	2.59E-05
5417	Scientific research and development services	9.78E+00	9.27E-05
5418	Advertising and related services	7.43E+00	9.22E-05
5419	Other professional, scientific, and technical services	5.04E+00	6.83E-05
5500	Management of companies and enterprises	5.18E+00	1.18E-05
5613	Employment services	1.10E+00	7.98E-06
5615	Travel arrangement and reservation services	5.50E-01	1.97E-05
561A	All other administrative and support services	4.10E+01	1.49E-04
5620	Waste management and remediation services	6.35E+01	1.19E-03
6100	Educational services	6.83E+02	4.82E-03
6210	Ambulatory health care services	5.67E+01	1.09E-04
6220	Hospitals	1.07E+02	2.82E-04
6230	Nursing and residential care facilities	5.65E+01	4.45E-04
6240	Social assistance	3.69E+01	3.62E-04
71A0	Performing arts, spectator sports, museums, zoos, and parks	9.82E+00	1.29E-04
7130	Amusements, gambling, and recreation	3.80E+01	4.11E-04
7210	Accommodation	1.09E+02	1.02E-03
7220	Food services and drinking places	1.98E+02	4.23E-04
8111	Automotive repair and maintenance	5.09E+01	2.89E-04
811A	Electronic, commercial, and household goods repairs	3.03E+01	3.17E-04
8120	Personal and laundry services	5.27E+01	4.14E-04
813A	Religious, grantmaking, giving, and social advocacy organization	2.24E+01	2.43E-04

813B	Civic, social, professional and similar organizations	5.32E+01	8.38E-04
8140	Private households	0.00E+00	0.00E+00
S001	Federal government enterprise	2.88E+03	3.45E-02
S002	State and local government enterprise	6.58E+03	4.08E-02
S005,S006, S007	General government industry	2.16E+03	1.18E-03
S003	Noncomparable imports	0.00E+00	0.00E+00
S004	Scrap, used and secondhand goods	0.00E+00	0.00E+00
S009	Rest of the world adjustment	0.00E+00	0.00E+00
NA	Inventory valuation adjustment	0.00E+00	0.00E+00

Table A-3. Detailed information for direct and indirect water withdrawal for the 10 largest sectors in 1997

Sector Name	Direct Water Withdrawal (trillion gallon)		Indirect Water Withdrawals (trillion gallon)	
Power generation and supply	Power generation and supply	28	State and local government enterprise	0.66
			Federal government enterprise	0.16
			Oil and gas extraction	0.085
			Crop production	0.049
			Other sectors	0.13
Food manufacturing	Food manufacturing	0.24	Crop production	18
			Power generation and supply	1.6
			Animal production	1.4
			Converted paper product manufacturing	0.23
			Other sectors	0.46
Crop production	Crop production	16	Power generation and supply	0.23
			State and local government enterprise	0.027
			Oil and gas extraction	0.012
			Nonmetallic mineral mining and quarrying	0.011
			Other sectors	0.057
Food services and drinking place	Food services and drinking place	0.12	Crop production	5.5
			Power generation and supply	1.9
			Animal production	0.34
			State and local government enterprise	0.14
			Other sectors	0.48
Retail trade	Retail trade	0.19	Power generation and supply	3.5
			State and local government enterprise	0.35

			Crop production	0.32
			Federal government enterprise	0.24
			Other sectors	0.48
Natural gas distribution	Natural gas distribution	0.0040	Power generation and supply	3.1
			State and local government enterprise	0.14
			Oil and gas extraction	0.14
			Crop production	0.015
			Other sectors	0.057
Real estate	Real estate	0.24	Power generation and supply	1.9
			State and local government enterprise	0.38
			Crop production	0.16
			Federal government enterprise	0.6
			Other sectors	0.11
New residential construction	New residential construction	0.047	Power generation and supply	1.1
			Crop production	0.51
			Nonmetallic mineral mining and quarrying	0.14
			State and local government enterprise	0.09
			Other sectors	0.55
New nonresidential construction	New nonresidential construction	0.052	Power generation and supply	1.3
			Crop production	0.31
			Nonmetallic mineral mining and quarrying	0.11
			State and local government enterprise	0.1
			Other sectors	0.6
Hospitals	Hospitals	0.14	Power generation and supply	1.1
			Crop production	0.56

			Federal government enterprise	0.14
			State and local government enterprise	0.11
			Other sectors	0.3
General government industry	General government industry	0	All sectors	0

Table A-4. Detailed information for direct and indirect water withdrawal for the 10 largest sectors in 2002

Sector Name	Direct Water Withdrawal (trillion gallon)		Indirect Water Withdrawal (trillion gallon)	
Power generation and supply	Power generation and supply	25	State and local government enterprise	0.39
			Federal government enterprise	0.15
			Oil and gas extraction	0.06
			Crop production	0.046
			Other sectors	0.073
Food manufacturing	Food manufacturing	0.34	Crop production	17
			Power generation and supply	2.1
			Animal production	1.9
			Converted paper product manufacturing	0.31
			Other sectors	0.43
Crop production	Crop production	17	Power generation and supply	0.35
			State and local government enterprise	0.023
			Animal production	0.015
			Oil and gas extraction	0.013
			Other sectors	0.054
Food services and drinking place	Food services and drinking place	0.16	Crop production	2.9
			Power generation and supply	2.5
			Animal production	0.27
			Federal government enterprise	0.23
			Other sectors	0.49
Retail trade	Retail trade	0.12	Power generation and supply	3.5
			Crop production	0.53
			Federal government enterprise	0.31
			State and local government enterprise	0.22
			Other sectors	0.32

Natural gas distribution	Natural gas distribution	0.0025	Power generation and supply	1.1
			Oil and gas extraction	0.11
			State and local government enterprise	0.10
			Crop production	0.014
			Other sectors	0.035
Real estate	Real estate	0.13	Power generation and supply	1.6
			State and local government enterprise	0.31
			Crop production	0.27
			Federal government enterprise	0.029
			Other sectors	0.069
New residential construction	New residential construction	0.052	Power generation and supply	1.6
			Crop production	1.2
			Nonmetallic mineral mining and quarrying	0.23
			Converted paper product manufacturing	0.08
			Other sectors	0.64
New nonresidential construction	New nonresidential construction	0.075	Power generation and supply	1.4
			Crop production	0.59
			Nonmetallic mineral mining and quarrying	0.099
			Oil and gas extraction	0.080
			Other sectors	0.54
Hospitals	Hospitals	0.10	Power generation and supply	1.9
			Crop production	0.78
			State and local government enterprise	0.12
			Federal government enterprise	0.12
			Other sectors	0.53
General government	General government industry	1.9	Power generation and supply	4.5

industry			Crop production	1.9
			State and local government enterprise	0.54
			Federal government enterprise	0.28
			Other sectors	1.42

Table A-5. Five largest increased and decreased water withdrawal sectors due to change in importation

Sector Name	Change in Water Withdrawal (trillion gallon)	% Change in Imports
Crop production	0.73	-13.30%
Semiconduct and electronic component manufacturing	0.13	-27.40%
Iron and steel mills and manufacturing from purchased steel	0.12	-20.42%
Nonferrous metal production and processing	0.05	-8.45%
Textile mills	0.04	-13.29%
Food manufacturing	-0.46	22.54%
Motor vehicle manufacturing	-0.36	39.76%
Oil and gas extraction	-0.35	31.76%
Pharmacetical and medicine manufacturing	-0.27	98.03%
Apparel manufacturing	-0.21	22.02%

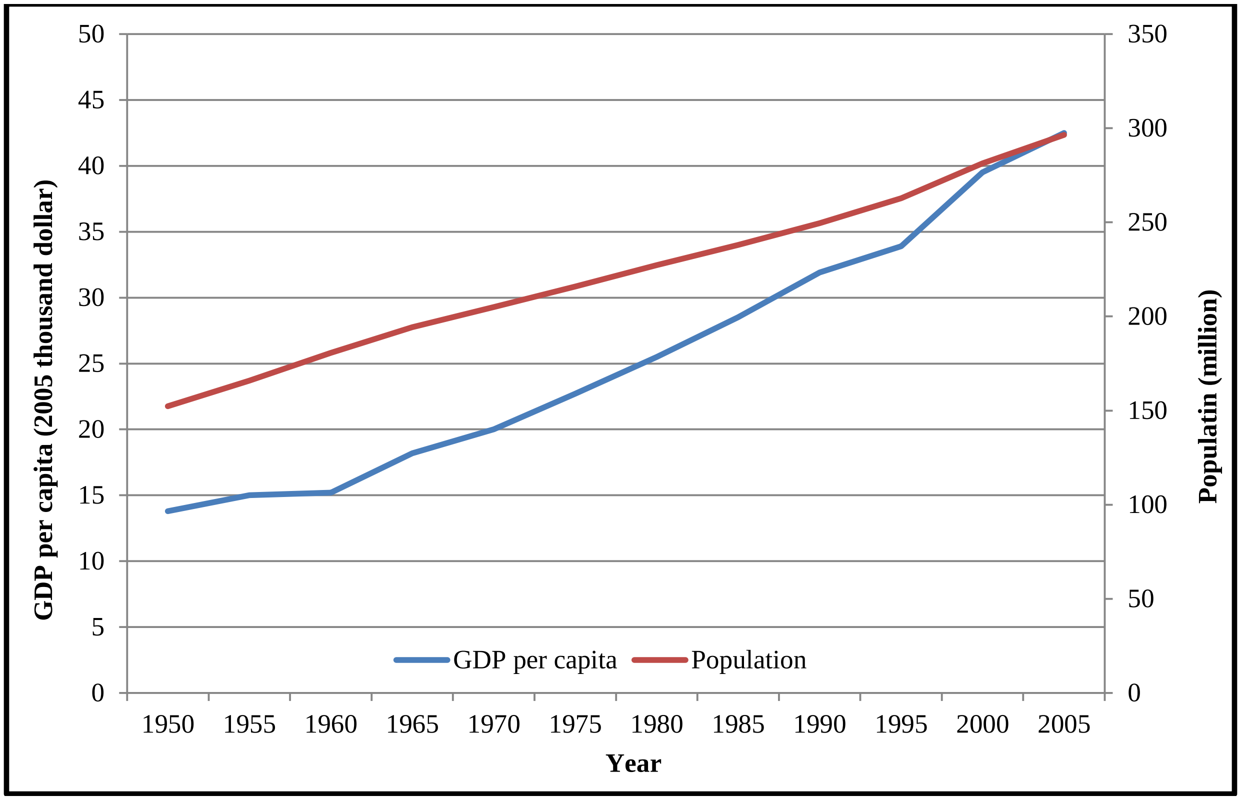

Figure A-1. Trends in U.S. population and GDP per capita 1950-2005

(*The World Bank, 2012; U.S. Census Bureau, 2012a; U.S. Census Bureau, 2012b)*

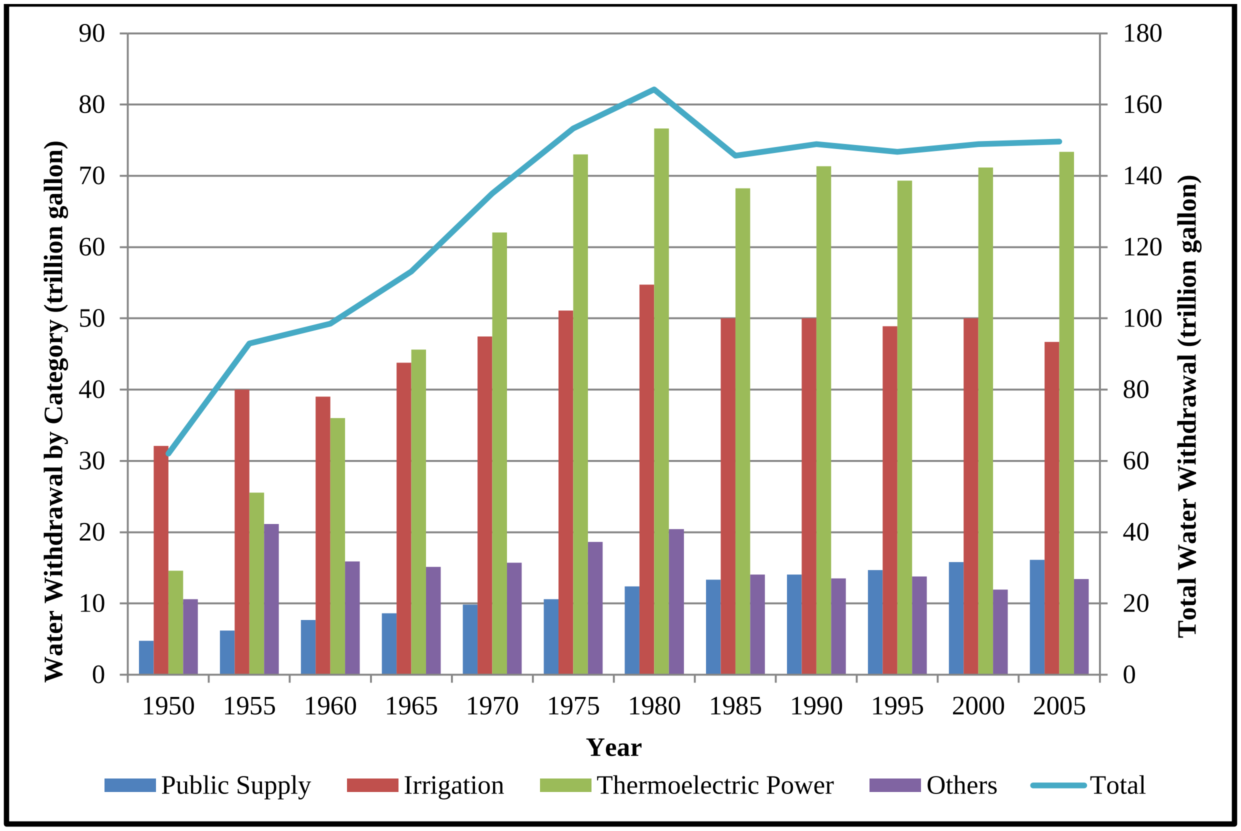

Figure A-2. Trends in U.S. water withdrawal reported by USGS 1950-2005

(Kenny et al., 2005; Hutson et al., 2000 ; Solley et al., 1995 ; Solley et al., 1990 ; Solley et al., 1985 ; Solley et al., 1980 ; Murray et al., 1975 ; Murray et al., 1970 ; Murray et al., 1965 ; MacKichan et al., 1960 ; MacKichan et al., 1955 ; MacKichan et al., 1950)

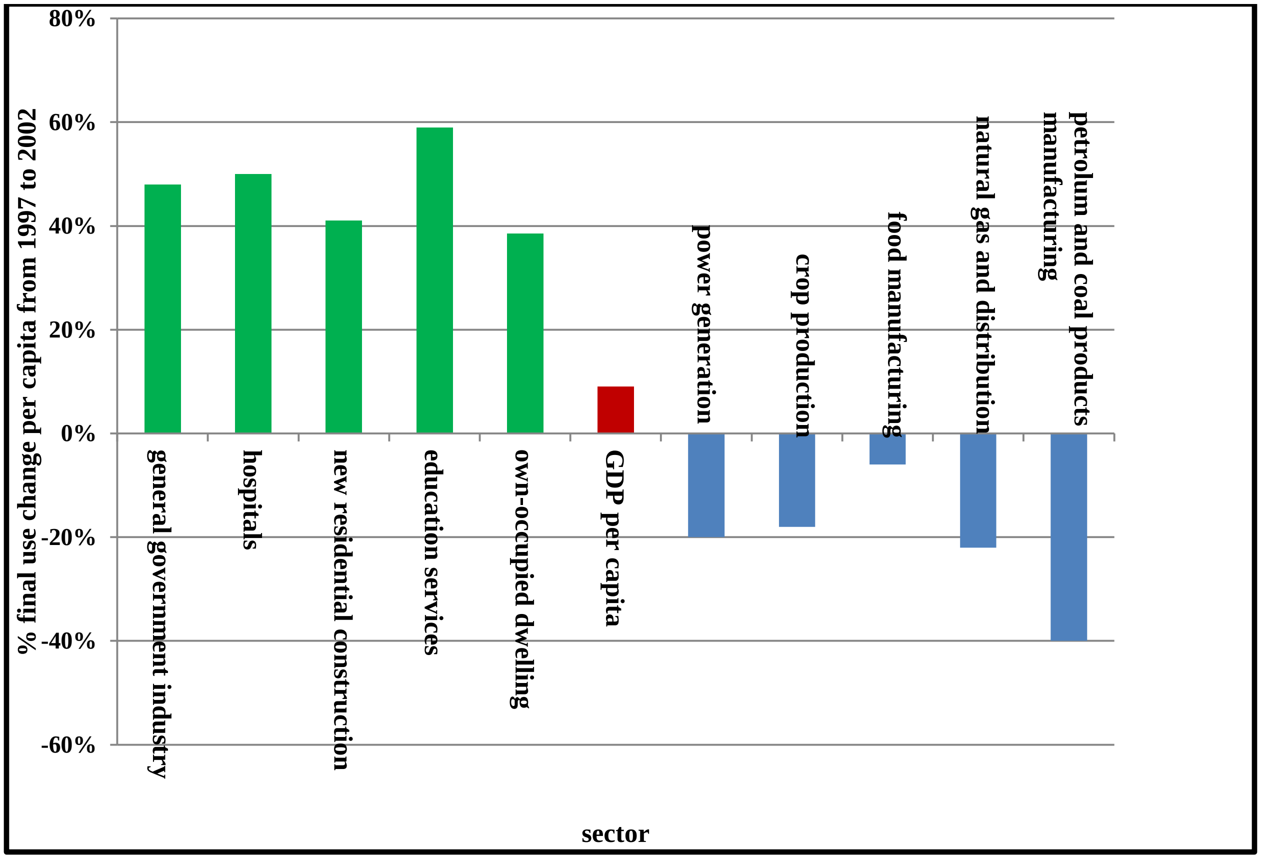

Figure A-3. Final use change per capita in percentage for the five largest increased and decreased water withdrawal sectors from 1997 to 2002

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Appendix B: Supporting Information for Chapter 3

B.1 Scenarios Design for Water Use Intensity during 2013-2030

The World Bank reported water productivity data every five years during 1992-2011(The World Bank, 2013). Table B-1 shows the average annual change rate of overall water use intensity (total water withdrawal per dollar of total industry output). During the 20 year period, the water use intensity experienced a continuous reduction, with the annual decrease rate showing an increasing trend ranging from -3% during 1992-1997 to -1% during 2007-2011 (The World Bank, 2013). The maximum and minimum decrease rate (-3% and -1%) were selected to be the average change rate for the scenario of the high and low reduction in water use intensity, respectively. The scenario of low increase in water use intensity with an annual increase rate of 0.5% was also considered in our study, as the change rate exhibited a continuous increasing trend.

B.2 Scenarios Design for Economic Production Structure during 2013-2030

B.2.1 Projection of Total Industry Output, Total Commodity Output, Intermediate Industry Output, and Intermediate Commodity Output

Three scenarios of GDP annual growth rate for 2013-2030 reported by U.S. EIA were used as the main constrains to design the scenarios of total industry outputs and intermediate industry outputs (U.S. EIA, 2013). GDP is linked with industry output and industry intermediate output via Equation. [B-1].

$$GDP = \sum_{i=1}^{66} industry\ output_i - \sum_{i=1}^{66} industry\ \mathrm{int}ermediate\ output_i \qquad [B-1]$$

The annual make tables and use tables for 68 commodities and 66 industries from 1997 to 2012 were reported by U.S. BEA (U.S. BEA, 2011). The make table shows the production of commodities by industries. The row totals of make table represent the outputs of 66 industries, and the column totals display the outputs of 68 commodities (U.S. BEA, 2011). The use table shows the uses of commodities by intermediate industries and final users, the row totals of intermediate portion of the use table represent the intermediate outputs of 68 commodities and the column totals of intermediate portion of the use table show the intermediate outputs of 66 industries (U.S. BEA, 2011).

We assumed that all the total outputs and intermediate outputs of 66 industries, and all the total outputs and intermediate outputs of 68 commodities follow the natural logarithm linear relationship versus time during 1997-2012. The 66 total and intermediate industry outputs and 68 total and intermediate commodity outputs during 2013-2030 were estimated based on the assumed logarithm linear relationship. The total commodity outputs were adjusted to satisfy Equation [B-2] by multiplying the ratio of sum of total industry outputs to sum of total commodity outputs, and the intermediate commodity outputs were adjusted by multiplying the ratio of sum of industry intermediate outputs to sum of commodity intermediate outputs to satisfy Equation [B-3].

$$\sum_{i=1}^{66} total\ industry\ output_i = \sum_{j=1}^{68} total\ commodity\ output_j \qquad [B-2]$$

$$\sum_{i=1}^{66} intermediate\ industry\ output_i = \sum_{j=1}^{68} intermediate\ commodity\ output_j \qquad [B-3]$$

The GDP estimated from the total industry outputs and intermediate industry outputs represent 2.3% average annual growth rate of GDP, which is close to the growth rate (2.5%) for medium economic growth scenario proposed by U.S. EIA. The estimated total industry outputs, intermediate industry outputs, total commodity outputs, and intermediate commodity outputs based upon the natural logarithm linear relationship were treated as the estimations under the medium economic growth scenario.

It has been found that GDPs estimated for 2013-2030 well match the low (2%) and high economic growth (3%) proposed by U.S. EIA respectively. The two estimates for GDP were obtained as follows: (1) GDPs obtained from 0.75 times of annual growth rate of estimated industry outputs and industry intermediate outputs based on the natural logarithm relationship. (2) GDPs obtained from 1.5 times of annual growth rate of estimated industry outputs and industry intermediate outputs based on the natural logarithm relationship. The corresponding commodity outputs and commodity intermediate outputs were adjusted to satisfy Equation [B-2] and [B-3] using the methods previously described.

B.2.2 Projection of Make Tables and Use Tables

The 2012 make table was updated to produce 2013-2030 make tables using the three scenarios of estimated total industry outputs and commodity outputs for 2013-2030 as the row totals constrain and column totals constrain, respectively, using the RAS method (Lahr et al., 2004).

The use tables for 2013-2030 were produced using the RAS method and the 2012 use table as the base table, with the estimated intermediate commodity outputs as the row totals constraint and the estimated intermediate industry outputs as the column totals constraint (Lahr et al., 2004).

B.3 Impact Population Affluence Technology (IPAT) Model

The IPAT model developed by Ehrlich and Holdren in 1970s describes the relationship between human activities and environmental impacts at an aggregated level (Chertow, 2001). The IPAT equation presents the environmental impacts (I) as the product of three driving factors population (P), affluence (A) and technology (T). The IPAT equation is shown in Equation [B-4].

$$I=P*A*T \qquad [B - 4]$$

where I is the environmental impacts, expressed by U.S. total water withdrawal in this study [gallons]; P refers to the U.S. resident population size; A refers to the consumption of goods and services by people, and the gross domestic product (GDP) per capita is used to measure this factors [dollars]; T refers to the environmental impacts per unit of people's consumption of goods and services, described by total water withdrawal per dollar of GDP here [gallons/dollar].

B.3.1 Scenarios Design for Technology

The technology factor was represented as total water withdrawal per dollar of GDP. The total water productivity represents the dollars of gross domestic product (GDP) produced with every gallon of freshwater withdrawal, its inverse describing freshwater withdrawal per dollar of GDP produced during 1992-2011 was used to generate the scenarios of technology (The World Bank, 2013). As the total freshwater withdrawal accounted for approximately 85% of total water withdrawal during 1990-2005 (Huston et al., 2000; Kenny et al., 2005; Solley et al., 1995), we assumed the percentage of freshwater withdrawal to total water withdrawal remained constant during 2013-2030. Under this assumption, the change rate of the inverse of water productivity is identical to the change rate of technology. The freshwater withdrawal per dollar of GDP experienced a continuous reduction during the period of 1992-2011. The average annual decrease rate exhibited an increasing trend ranging from -3% during 1992-1997 to -1% during 2007-2011 (The World Bank, 2013). The maximum and minimum decrease rate (-3% and -1%) were selected to be the annual change rate of technology for the scenarios of high and low reduction for 2013-2030, respectively. The scenario of low increase in technology with an annual increase rate of 0.5% was considered in our study as well, as the change rate exhibited a continuous increasing trend. These three scenarios of technology for 2013-2030 were projected based on 2012 technology and the design annual growth rate (-3%, -1%, and 0.5%).

B.3.2 Projected U.S. Total Water Withdrawal by IPAT Model for 2013-2030

Figure B-1 shows the U.S. total water withdrawal projected for 2013-2030 by the IPAT model via a boxplot. The IPAT model projected the U.S. total water withdrawal based upon four scenarios each for population, GDP per capita, and overall water withdrawn per dollar of GDP produced in the U.S., which generated 64 scenarios of total water withdrawal for each year during 2013-2030. Considering the design scenarios over time, the projected total water withdrawal range expounded across the 18 years. The maximum projected water withdrawal was 1.1 times of minimum value in 2013, ranging from 150 to 161 trillion gallons in 2013; and the ratio of two extreme projected water withdrawals in 2030 increased to 4.3. The minimum projected water withdrawal across 64 scenarios each year occurred under the conditions that population remains at the 2012 level, GDP per capita decreases about 0.95% every year and water withdrawal per dollar of GDP produced decreases by 3% every year. The largest water withdrawal for each year is projected under the scenario that population and economy grow fast, but water withdrawal increases by 0.5% to produce one dollar of GDP per year.

The projection of total U.S. water withdrawal was extended to 2100 using the IPAT model based on the same scenarios generated for the projections for 2013-2030, as indicated in Figure B-3. The maximum water withdrawal was projected to occur in 2100, considering population, GDP per capita and technology with a high growth rate. The maximum water withdrawal in 2100 is about 7000 trillion gallon, which is about 50 times of U.S. water withdrawal in 2005 (Kenny et al., 2005).

B.4 Simplified IPAT Model

In this model, the future projection of water withdrawal was made based upon population and water withdrawal rate (water withdrawal per capita) by water use category. The water withdrawal was projected under the "business-as-usual" scenario (Brown, 2000; Roy et al., 2005; Roy et al., 2012), assuming that the future rate of water withdrawal remains at the current level. Water withdrawals for residential, industrial, mining, irrigation, livestock, aquaculture and thermoelectric for 2013-2030 were projected based on future population and water withdrawal rate for each category in 2012, as shown in Equation [B-5]. The total water withdrawal is the sum of projected water withdrawal for all water use categories, as indicated in Equation [B-6]

$$W_{i,t} = P_t * R_{i,2012} \quad \text{[B - 5]}$$

$$W_t = \sum_i W_{i,t} \quad \text{[B - 6]}$$

where $W_{i,t}$ is the projected water withdrawal for category i in the year t; P_t is the projected population of year t; $R_{i,\ 2012}$ is the water withdrawal per capita for category i in 2012; W_t is the projected total water withdrawal in the year t. The water withdrawal per capita in 2012 for each category was estimated based on the estimated water withdrawal by category in 2012 and population in 2012. The 2012 water withdrawal for each water use category was estimated based on 2000 and 2005 water withdrawals reported by USGS using extrapolation (Hutson et al., 2000; Kenny et al., 2005).

B.4.1 Projected U.S. total water withdrawal by simplified IPAT model for 2013-2030

The total water withdrawal during 2013-2030 projected by the simplified IPAT model under the business-as-usual scenario with three scenarios of population growth (low, medium and high growth series), is shown in Figure B-2. The projection of water withdrawal in this model only relies on the growth of population. The projected total water withdrawal under the low growth scenario of population is 149 trillion gallons in 2013, which is 0.03 trillion gallons less than under the medium scenario of population growth and 0.06 trillion gallons less than under the high scenario of population growth. The total water withdrawal is projected to increase by 11.8%, 13.3% and 14.8% under the low, medium and high scenario of population growth from 2013 to 2030, which results in the projected total water withdrawal under the high scenario of population growth of more than 170 trillion gallons.

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Table B-1. Description for aggregated industrial sectors

Sector	Industry Sector
1	Farms
2	Forestry, fishing, and related activities
3	Oil and gas extraction
4	Mining, except oil and gas
5	Support activities for mining
6	Utilities
7	Construction
8	Wood products
9	Nonmetallic mineral products
10	Primary metals
11	Fabricated metal products
12	Machinery
13	Computer and electronic products
14	Electrical equipment, appliances, and components
15	Motor vehicles, bodies and trailers, and parts
16	Other transportation equipment
17	Furniture and related products
18	Miscellaneous manufacturing
19	Food and beverage and tobacco products
20	Textile mills and textile product mills
21	Apparel and leather and allied products
22	Paper products
23	Printing and related support activities
24	Petroleum and coal products
25	Chemical products
26	Plastics and rubber products
27	Wholesale trade
28	Retail trade
29	Air transportation
30	Rail transportation
31	Water transportation
32	Truck transportation
33	Transit and ground passenger transportation
34	Pipeline transportation
35	Other transportation and support activities
36	Warehousing and storage

37	Publishing industries, except internet (includes software)
38	Motion picture and sound recording industries
39	Broadcasting and telecommunications
40	Data processing, internet publishing, and other information services
41	Federal Reserve banks, credit intermediation, and related activities
42	Securities, commodity contracts, and investments
43	Insurance carriers and related activities
44	Funds, trusts, and other financial vehicles
45	Real estate
46	Rental and leasing services and lessors of intangible assets
47	Legal services
48	Computer systems design and related services
49	Miscellaneous professional, scientific, and technical services
50	Management of companies and enterprises
51	Administrative and support services
52	Waste management and remediation services
53	Educational services
54	Ambulatory health care services
55	Hospitals
56	Nursing and residential care facilities
57	Social assistance
58	Performing arts, spectator sports, museums, and related activities
59	Amusements, gambling, and recreation industries
60	Accommodation
61	Food services and drinking places
62	Other services, except government
63	Federal general government
64	Federal government enterprises
65	State and local general government
66	State and local government enterprises

Table B-2. Overall water use intensity average annual change rate for 1992-2011 (The World Bank, 2013)

Time Period	**Average annual change rate**
1992-1997	-3.04%
1997-2002	-2.64%
2002-2007	-2.33%
2007-2011	-0.91%

Table B-3. Description of scenarios for projected make table and use table

Scenario	Make Table	Use Table	Production Structure
Current	M_1: 2012 make table	U_1: 2012 use table	L_1: 2012 production structure
0.75*baseline trend	M_2: Project using 0.75 times of annual growth rate of estimated industry output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity output as the constraint	U_2: Project using 0.75 times of annual growth rate of estimated industry intermediate output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity intermediate output as constraint	L_2: Estimate using M_2 and U_2
Baseline trend	M_3: Project using estimated industry output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity output as the constraint	U_3: Project using estimated industry intermediate output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity intermediate output as constraint	L_3: Estimate using M_3 and U_3
1.5* baseline trend	M_4: Project using 1.5 times of annual growth rate of estimated industry output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity output as the constraint	U_4: Project using 1.5 times of annual growth rate of estimated industry intermediate output based on natural logarithm relationship versus time during 1997-2012 and corresponding adjusted commodity intermediate output as constraint	L_4: Estimate using M_4 and U_4

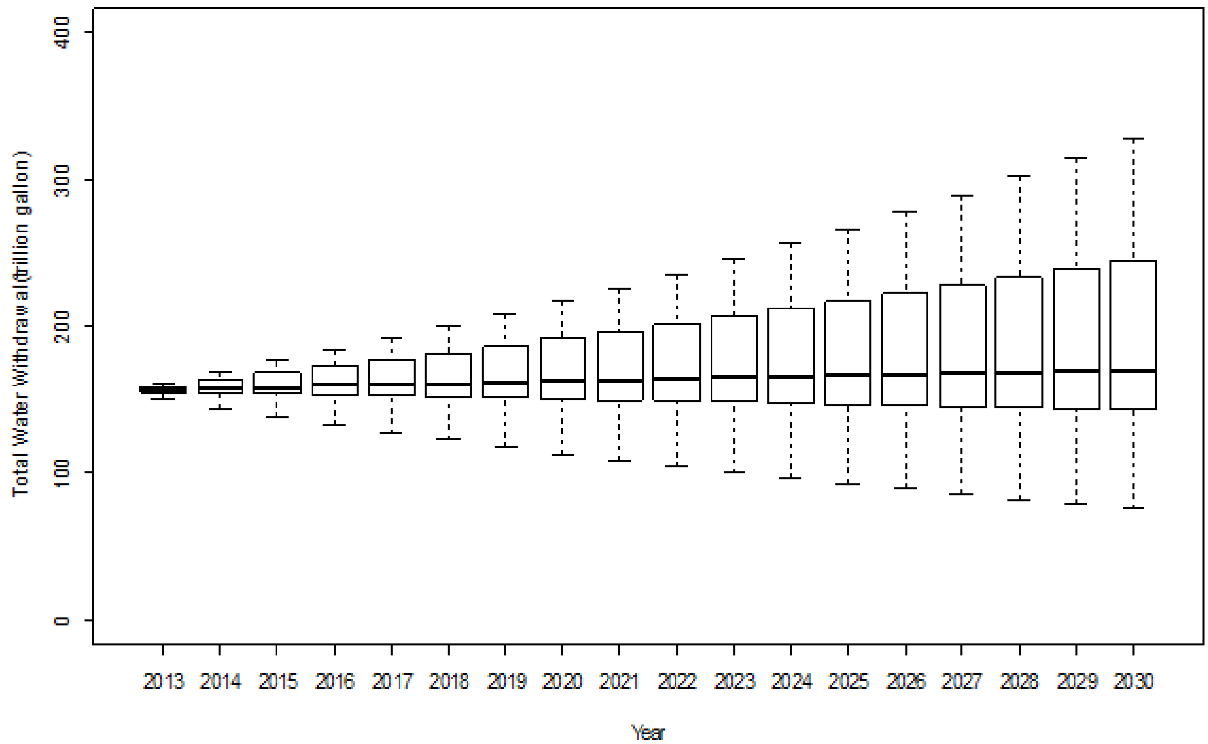

Figure B-1. Projected U.S. total water withdrawals for 2013-2030 by the IPAT model. The solid line in the box represents the median of various scenarios of projected water withdrawals across 64 scenarios for each year. The upper and lower edge of the box indicate the 75th percentile and 25th of the 64 scenarios of projected total water withdrawal.

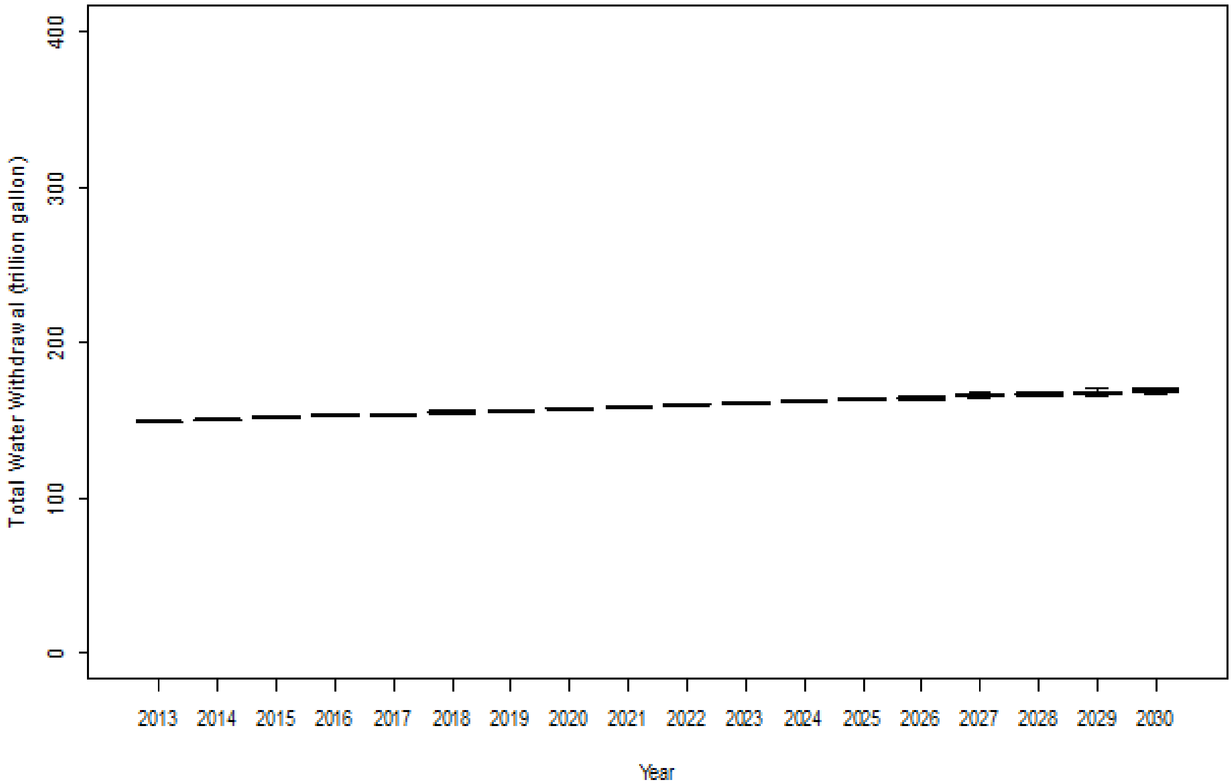

Figure B-2. Projected U.S. total water withdrawals for 2013-2030 by the simplified IPAT model. The solid line in the box represents the median of various scenarios of projected water withdrawals across three scenarios for each year. The upper and lower edge of the box indicate the 75th percentile and 25th of the three scenarios of projected total water withdrawal.

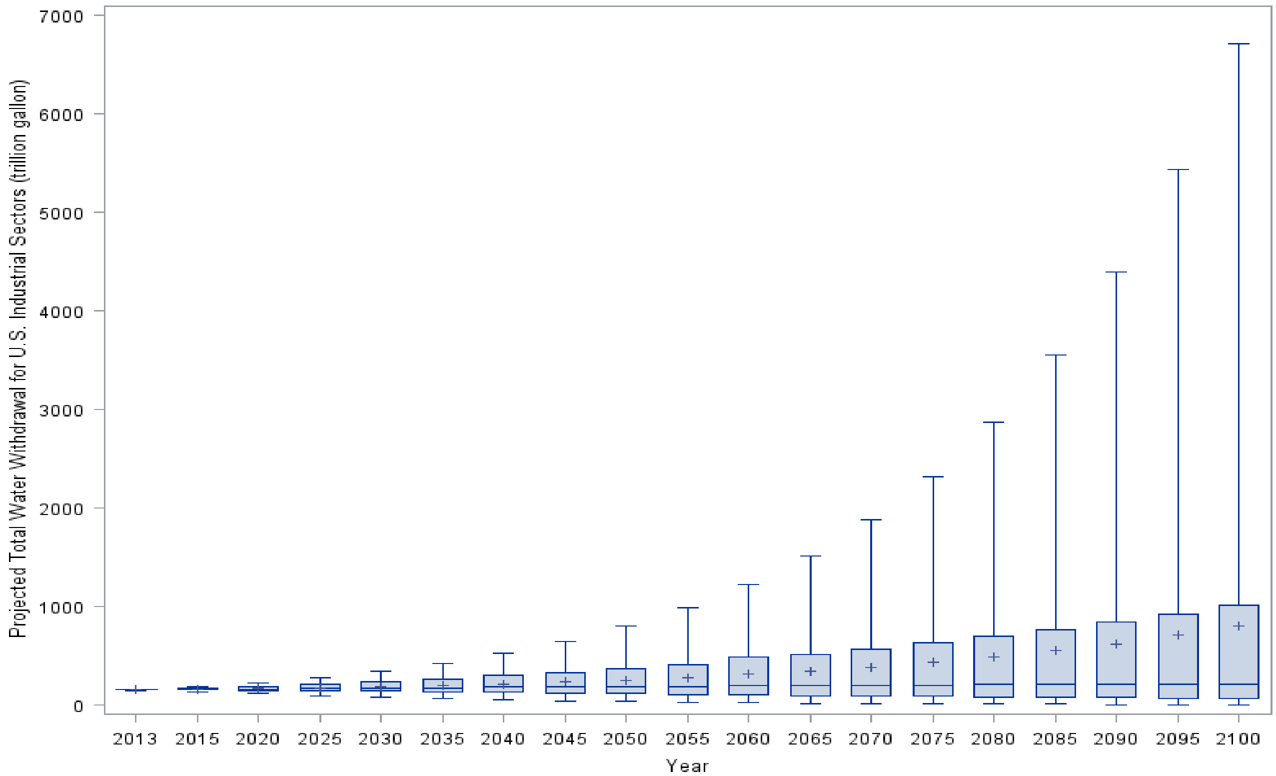

Figure B-3. Projected U.S. total water withdrawals for 2013-2100 by the IPAT model. The solid line in the box represents the median of various scenarios of projected water withdrawals across the combinations of four scenarios for three factors in the IPAT model for each year. The plus sign in the box represents the mean of various scenarios of projected water withdrawals for each year. The upper and lower edges of the box indicate the maximum and minimum of projected total water withdrawal across 64 scenarios.

Appendix C: Supporting Information for Chapter 4

C.1 Estimation of Consumptive Water Use Coefficients for Industrial Sectors

The consumptive water use coefficient represents the percentage of water consumed from the total water withdrawal. The consumptive water use coefficients for 66 aggregated U.S. industrial sectors (shown in Table C-1) were estimated based on both water withdrawal by industrial sector (Wang et al., 2014b) and consumptive water use by industrial sector projected by the EIO-LCA model with fixed economic structure for 2013-2030. The consumptive water use coefficients for industrial sectors were computed under the same scenarios for both water withdrawal and water consumption, resulting in 64 scenarios for consumptive water use coefficients for industrial sectors. Since very similar methods and data were applied to generate the five factors for projection of both water withdrawal and water consumption for 2013-2030 and the average consumptive water use coefficient for 1985-1995 from USGS was used to project water consumption across time (Solley et al., 1985; Solley et al., 1990; Solley et al., 1995), the consumptive water use coefficients for industrial sectors are almost constant across scenarios and time. The consumptive water use coefficients for all 66 aggregated industrial sectors were listed in Table C-2.

Table C-1. Description for aggregated industrial sectors

Sector	Industry Sector
1	Farms
2	Forestry, fishing, and related activities
3	Oil and gas extraction
4	Mining, except oil and gas
5	Support activities for mining
6	Utilities
7	Construction
8	Wood products
9	Nonmetallic mineral products
10	Primary metals
11	Fabricated metal products
12	Machinery
13	Computer and electronic products
14	Electrical equipment, appliances, and components
15	Motor vehicles, bodies and trailers, and parts
16	Other transportation equipment
17	Furniture and related products
18	Miscellaneous manufacturing
19	Food and beverage and tobacco products
20	Textile mills and textile product mills
21	Apparel and leather and allied products
22	Paper products
23	Printing and related support activities
24	Petroleum and coal products
25	Chemical products
26	Plastics and rubber products
27	Wholesale trade
28	Retail trade
29	Air transportation
30	Rail transportation
31	Water transportation
32	Truck transportation
33	Transit and ground passenger transportation
34	Pipeline transportation
35	Other transportation and support activities
36	Warehousing and storage

37	Publishing industries, except internet (includes software)
38	Motion picture and sound recording industries
39	Broadcasting and telecommunications
40	Data processing, internet publishing, and other information services
41	Federal Reserve banks, credit intermediation, and related activities
42	Securities, commodity contracts, and investments
43	Insurance carriers and related activities
44	Funds, trusts, and other financial vehicles
45	Real estate
46	Rental and leasing services and lessors of intangible assets
47	Legal services
48	Computer systems design and related services
49	Miscellaneous professional, scientific, and technical services
50	Management of companies and enterprises
51	Administrative and support services
52	Waste management and remediation services
53	Educational services
54	Ambulatory health care services
55	Hospitals
56	Nursing and residential care facilities
57	Social assistance
58	Performing arts, spectator sports, museums, and related activities
59	Amusements, gambling, and recreation industries
60	Accommodation
61	Food services and drinking places
62	Other services, except government
63	Federal general government
64	Federal government enterprises
65	State and local general government
66	State and local government enterprises

Table C-2. Range of estimated consumptive water use coefficients for aggregated industrial sectors

Sector	Industry Sector	Consumptive Water Use Coefficient
1	Farms	0.56
2	Forestry, fishing, and related activities	0.54~0.56
3	Oil and gas extraction	0.25~0.26
4	Mining, except oil and gas	0.24~0.26
5	Support activities for mining	0.28~0.29
6	Utilities	0.02~0.03
7	Construction	0.19~0.23
8	Wood products	0.30~0.34
9	Nonmetallic mineral products	0.13~0.16
10	Primary metals	0.11~0.14
11	Fabricated metal products	0.13~0.14
12	Machinery	0.11~0.15
13	Computer and electronic products	0.11~0.15
14	Electrical equipment, appliances, and components	0.07~0.13
15	Motor vehicles, bodies and trailers, and parts	0.14~0.20
16	Other transportation equipment	0.11~0.15
17	Furniture and related products	0.16~0.23
18	Miscellaneous manufacturing	0.18~0.22
19	Food and beverage and tobacco products	0.54
20	Textile mills and textile product mills	0.32~0.36
21	Apparel and leather and allied products	0.40~0.42
22	Paper products	0.17~0.23
23	Printing and related support activities	0.17~0.23
24	Petroleum and coal products	0.16~0.23
25	Chemical products	0.25~0.31
26	Plastics and rubber products	0.18~0.24
27	Wholesale trade	0.12~0.18
28	Retail trade	0.10~0.15
29	Air transportation	0.17~0.20
30	Rail transportation	0.15~0.18
31	Water transportation	0.11~0.14
32	Truck transportation	0.15~0.21
33	Transit and ground passenger transportation	0.14~0.18
34	Pipeline transportation	0.14~0.18
35	Other transportation and support activities	0.14~0.20

36	Warehousing and storage	0.05~0.07
37	Publishing industries, except internet (includes software)	0.16~0.20
38	Motion picture and sound recording industries	0.16~0.21
39	Broadcasting and telecommunications	0.14~0.18
40	Data processing, internet publishing, and other information services	0.14~0.18
41	Federal Reserve banks, credit intermediation, and related activities	0.18~0.23
42	Securities, commodity contracts, and investments	0.14~0.19
43	Insurance carriers and related activities	0.18~0.23
44	Funds, trusts, and other financial vehicles	0.15~0.20
45	Real estate	0.08~0,11
46	Rental and leasing services and lessors of intangible assets	0.15~0.20
47	Legal services	0.16~0.23
48	Computer systems design and related services	0.16~0.23
49	Miscellaneous professional, scientific, and technical services	0.17~0.22
50	Management of companies and enterprises	0.12~0.16
51	Administrative and support services	0.21~0.26
52	Waste management and remediation services	0.13~0.17
53	Educational services	0.17~0.21
54	Ambulatory health care services	0.16~0.21
55	Hospitals	0.17~0.24
56	Nursing and residential care facilities	0.27~0.31
57	Social assistance	0.29~0.33
58	Performing arts, spectator sports, museums, and related activities	0.22~0.26
59	Amusements, gambling, and recreation industries	0.36~0.40
60	Accommodation	0.18~0.23
61	Food services and drinking places	0.39~0.43
62	Other services, except government	0.11~0.17
63	Federal general government	0.17~0.26
64	Federal government enterprises	0.10~0.13
65	State and local general government	0.10~0.14
66	State and local government enterprises	0.12~0.19

References

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Solley, W.B., Pierce R.R.; Perlman, H.A., 1990. Estimated use of water in the United States in 1990. U.S. Geological Survey. U.S. Department of the Interior, Washington, D.C.

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Appendix D: R Code for Estimation and Projection of Water Withdrawal and Consumption for U.S. Industrial Sectors

The programming language R was used for estimation of water withdrawals for U.S. industrial sectors for 1997 and 2002 and projection of water withdrawals and consumptive water uses for industrial sectors for 2013-2030 using the EIO-LCA model. The R code used in this study is shown as follows.

D.1 R Code for Estimation of Water Withdrawal for Industrial Sectors for 1997 Using the EIO-LCA Model

```
import.csv <- function(filename) {
   return(read.csv(filename, sep = ",", header = FALSE))
}
write.csv <- function(ob, filename) {
   write.table(ob, filename, quote = FALSE, sep = ",", row.names = FALSE)
}
P1997<-import.csv('P1997.cvs')
F1997<-import.csv('F1997.csv')
Yg1997 <-import.csv('Yg1997.csv')
Yc1997<-import.csv('Yc1997.csv')
L1997<-import.csv('L1997.csv')
WT1997=P1997*Yg1997*as.matrix(diag(F1997))%*%as.matrix(L1997)%*%as.matrix(diag(Yc1997))
write.csv(WT1997,'WT1997.csv')
```

D.2 R Code for Estimation of Water Withdrawal for Industrial Sectors for 2002 Using the EIO-LCA Model

```
import.csv <- function(filename) {

   return(read.csv(filename, sep = ",", header = FALSE))

}

write.csv <- function(ob, filename) {

   write.table(ob, filename, quote = FALSE, sep = ",", row.names = FALSE)

}

P2002<-import.csv('P2002.cvs')

F2002<-import.csv('F2002.csv')

Yg2002 <-import.csv('Yg2002.csv')

Yc2002<-import.csv('Yc2002.csv')

L2002<-import.csv('L2002.csv')

WT2002=P2002*Yg2002*as.matrix(diag(F2002))%*%as.matrix(L2002)%*%as.matrix(diag(Yc2002))

write.csv(WT2002,'WT2002.csv')
```

D.3 R Code for Projection of Water Withdrawal for Industrial Sectors for 2013-2030 Using the EIO-LCA Model with Fixed Economic Structure

```
import.csv <- function(filename) {

   return(read.csv(filename, sep = ",", header = FALSE))

}

write.csv <- function(ob, filename) {

   write.table(ob, filename, quote = FALSE, sep = ",", row.names = FALSE)

}

P<-import.csv('P.cvs')
```

```
F<-import.csv('F.csv')

Yg <-import.csv('Yg.csv')

Yc<-import.csv('Yc2012.csv')

L<-import.csv('L2012.csv')

W<-c()

M<-c()

index=c()

cors=c()

t=0

n=4*4*4

for (i in 1:4) {

     for (j in 1:4){

       for (k in 1:4){

       W=P[i]*Yg[j]*as.matrix(diag(F[,k]))%*%as.matrix(L)%*%as.matrix(diag(Yc[,1]))

   t=t+1

   cors=cbind(t,i,j,k)

   index=rbind(index,cors)

   M=rbind(M,W)

         }

       }

    }

write.csv(M,'WT.csv')

write.csv(index,'index.csv')

nn<-nrow(M)

ng<-nn/68
```

```
water<-c()

sum.total<-c()

sum.direct<-c()

total.water<-c()

direct.water<-c()

for (ii in 1:ng){

  water[[ii]]<-M[((ii-1)*68+1):(68*ii),]

  total.water[[ii]]<-colSums(water[[ii]])

  sum.total[ii]<-sum(total.water[[ii]])

  direct.water[[ii]]<-diag(water[[ii]])

  sum.direct[ii]<-sum(direct.water[[ii]])

}

total.combine<-cbind(sum.total[1:ng])

direct.combine<-cbind(sum.direct[1:ng])

total.combine<-total.combine/1000

direct.combine<-direct.combine/1000

ratio=direct.combine/total.combine

write.csv(total.combine,'total.csv')

write.csv(direct.combine,'direct.csv')
```

D.4 R Code for Projection of Water Withdrawal for Industrial Sectors for 2013-2030 Using the EIO-LCA Model with Changing Economic Structure

```
import.csv <- function(filename) {

   return(read.csv(filename, sep = ",", header = FALSE))

}
```

```
write.csv <- function(ob, filename) {
   write.table(ob, filename, quote = FALSE, sep = ",", row.names = FALSE)
}
P<-import.csv('P.cvs')
F<-import.csv('F.csv')
Yg <-import.csv('Yg.csv')
Yc<-import.csv('Yc.csv')
L<-import.csv('L.csv')
W<-c()
M<-c()
index=c()
cors=c()
t=0
n=4*4*4*4*4
for (i in 1:4) {
     for (j in 1:4){
       for (k in 1:4){
         for (l in 1:4){
           for (n in 1:4){
       W=P[i]*Yg[j]*as.matrix(diag(F[,k]))%*%as.matrix(L[[((l-1)*68+1):(l*68),]%*%as.matrix(diag(Yc[,n]))
   t=t+1
   cors=cbind(t,i,j,k)
   index=rbind(index,cors)
   M=rbind(M,W)
```

```
      }
    }
  }
write.csv(M,'WT.csv')
write.csv(index,'index.csv')
nn<-nrow(M)
ng<-nn/68
water<-c()
sum.total<-c()
sum.direct<-c()
total.water<-c()
direct.water<-c()
for (ii in 1:ng){
  water[[ii]]<-M[((ii-1)*68+1):(68*ii),]
  total.water[[ii]]<-colSums(water[[ii]])
  sum.total[ii]<-sum(total.water[[ii]])
  direct.water[[ii]]<-diag(water[[ii]])
  sum.direct[ii]<-sum(direct.water[[ii]])
}
total.combine<-cbind(sum.total[1:ng])
direct.combine<-cbind(sum.direct[1:ng])
total.combine<-total.combine/1000
direct.combine<-direct.combine/1000
ratio=direct.combine/total.combine
write.csv(total.combine,'total.csv')
```

```
write.csv (direct.combine,'direct.csv')
```

D.5 R Code for Projection of Water Consumption for Industrial Sectors for 2013-2030 Using the EIO-LCA Model with Fixed Economic Structure

```
import.csv <- function(filename) {
   return(read.csv(filename, sep = ",", header = FALSE))
}
write.csv <- function(ob, filename) {
   write.table(ob, filename, quote = FALSE, sep = ",", row.names = FALSE)
}
P<-import.csv('P.cvs')
CF<-import.csv('CF.csv')
Yg <-import.csv('Yg.csv')
Yc<-import.csv('Yc2012.csv')
L<-import.csv('L2012.csv')
W<-c()
M<-c()
index=c()
cors=c()
t=0
n=4*4*4
for (i in 1:4) {
     for (j in 1:4){
       for (k in 1:4){
       W=P[i]*Yg[j]*as.matrix(diag(CF[,k]))%*%as.matrix(L)%*%as.matrix(diag(Yc[,1]))
```

```
   t=t+1
   cors=cbind(t,i,j,k)
   index=rbind(index,cors)
   M=rbind(M,W)
        }
      }
   }

write.csv(M,'WT.csv')
write.csv(index,'index.csv')
nn<-nrow(M)
ng<-nn/68
water<-c()
sum.total<-c()
sum.direct<-c()
total.water<-c()
direct.water<-c()
for (ii in 1:ng){
 water[[ii]]<-M[((ii-1)*68+1):(68*ii),]
 total.water[[ii]]<-colSums(water[[ii]])
 sum.total[ii]<-sum(total.water[[ii]])
 direct.water[[ii]]<-diag(water[[ii]])
 sum.direct[ii]<-sum(direct.water[[ii]])
}
total.combine<-cbind(sum.total[1:ng])
```

```
direct.combine<-cbind(sum.direct[1:ng])

total.combine<-total.combine/1000

direct.combine<-direct.combine/1000

ratio=direct.combine/total.combine

write.csv(total.combine,'total.consumption.csv')

write.csv(direct.combine,'direct.consumption.csv')
```