Environmental Science & Technology LETTERS

Letter

pubs.acs.org/journal/estlcu

Improved Efficiency Reduces U.S. Industrial Water Withdrawals, 2005–2010

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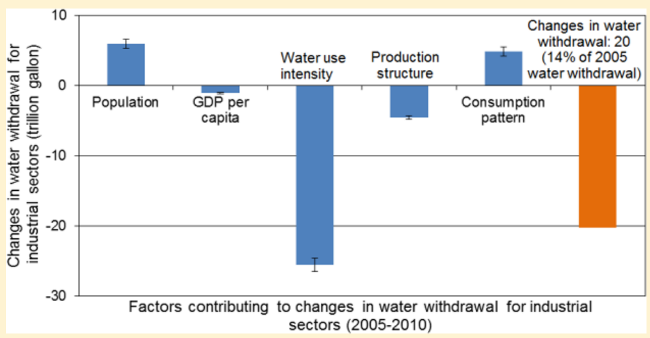
ABSTRACT: The total water withdrawal for U.S. industrial sectors decreased by ~20 trillion gallons for 2005–2010, representing a reduction of 14% compared to the 2005 water withdrawal. The contributions of five governing factors—population, GDP per capita, water use intensity, production structure, and consumption pattern—to changes in total water withdrawal for industrial sectors during the five years were investigated on the basis of the most recent U.S. economic input–output and U.S. Geological Survey water withdrawal data. Changes in population and consumption pattern caused increases in water withdrawal, while changes in GDP per capita, water use intensity, and production structure contributed to declines in water withdrawal between 2005 and 2010. The change in water use intensity was the greatest contributor to the overall reduction in total water withdrawal during 2005–2010.



■ INTRODUCTION

Increases in population, economy growth, and climate change drive increases in water demand.[1] Surprisingly, the U.S. total water withdrawals decreased by 17% during the period of 1980–2010, primarily from 2005 to 2010,[2] while population grew by 36%[3,4] and GDP per capita increased by ~70%[5] for the same period, suggesting that some other factors may offset the increased water demand.[6] Wang et al.[6] evaluated the factors contributing to a net increase in total water withdrawal of 4.2 trillion gallons for U.S. industrial sectors for 1997–2002. Increases in population, GDP per capita and changes in water use intensity contributed to increases in total water withdrawal, while changes in production structure and consumption pattern decreased total water withdrawal for the period, using structural decomposition analysis (SDA).[6,7]

According to the U.S. Geological Survey (USGS), the U.S. total water withdrawal that encompasses eight categories of water use—public supply, residential, mining, irrigation, livestock, aquaculture, thermoelectric, and industrial—decreased from 150 to 130 trillion gallons during 2005–2010.[2] This is the first time that U.S. total water withdrawal experienced a significant decrease since water withdrawal stabilized around 1985.[2] The contributions of five governing factors—population, GDP per capita, water use intensity, production structure, and consumption pattern—to the change in total water withdrawal for U.S. industrial sectors for 2005–2010 were investigated in this study. This analysis was done using the most recent economic input–output (EIO) data[8,9] and USGS water withdrawal data[2,10] for 2005 and 2010. Because no industrial sectors represent the final consumption, the total water withdrawal for industrial sectors in this research included seven categories of USGS water withdrawal, except for the residential water withdrawal.[6,11] Both freshwater and saline water were included in the total water withdrawal in this study. The specific objectives were (1) to estimate the total water withdrawal for U.S. industrial sectors for 2005 and 2010, using the economic input–output life cycle assessment (EIO–LCA) model, (2) to investigate the contributions of the five governing factors to changes in total water withdrawal for U.S. industrial sectors from 2005 to 2010, and (3) to compare the effects of the five factors on changes in total water withdrawal for industrial sectors for 2005–2010 to those previously determined for 1997–2002.

■ DATA SOURCES AND METHODS

The U.S. Census Bureau population data,[4] GDP per capita data provided by the World Bank,[5] USGS water withdrawal data excluding the residential water withdrawal,[6,11] and the EIO data from the U.S. Bureau of Economic Analysis (BEA) for 71 aggregated industrial sectors for both 2005 and 2010[8,9] were used in this study.

The total water withdrawal for industrial sectors can be computed considering both direct and supply chain water withdrawal based on the EIO–LCA model.[6,11,12]

$$\mathbf{W} = PY_g\mathbf{FLY_c} \quad (1)$$

In eq 1, the bold terms represent vectors or matrices and the unbold terms denote scalars. **W** is a vector representing total

Received: January 27, 2015
Revised: March 5, 2015
Accepted: March 9, 2015
Published: March 9, 2015

DOI: 10.1021/acs.estlett.5b00023
Environ. Sci. Technol. Lett. 2015, 2, 79–83

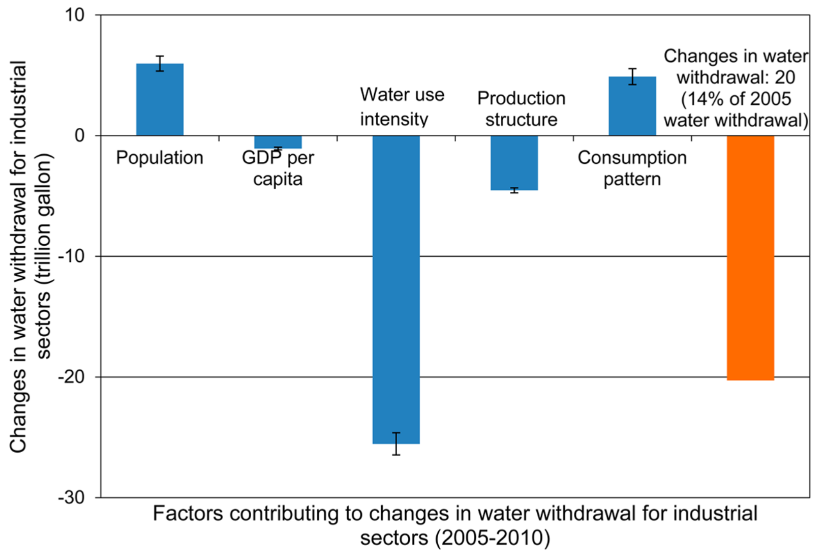


Figure 1. Changes in total water withdrawal for industrial sectors from 2005 to 2010 caused by five governing factors. The results indicate the mean across the 120 decomposition forms, and the bars represent the standard deviation of the 120 decompositions.

water withdrawal for each industrial sector in gallons. P is the population. Y_g is the GDP per capita in dollars. $\mathbf{F}$ is the water use intensity matrix in gallons per dollar (affected by the technology choices industries make to manage water), a diagonal matrix of the water withdrawn per dollar of industrial output. $\mathbf{L}$ is the production structure matrix in dollars (affected by the choices industries make in their supply chains that affect water), in which the entries represent the total intersectoral purchase per dollar of final consumption of goods and services. $\mathbf{Y_c}$ is the consumption pattern vector (nondimensional) (affected by the choices consumers make for more or less water-efficient products), representing the fraction of GDP produced by each industrial sector.

The water use intensity represents the ratio of water withdrawn to total dollar output for the sector. It was estimated on the basis of the allocated water withdrawal by seven categories of USGS water withdrawal to each industrial sector and the sector's industry output. The USGS water withdrawals for seven categories were allocated to the 71 aggregated industrial sectors based on the industry output, process data, economic activities, etc.[6,11] The water withdrawals for irrigation, livestock, and aquaculture were allocated to the sector *Farms(111CA)* directly;[2,6,8,9,11] the corresponding BEA code is presented in parentheses. The public supply water withdrawal was allocated to the sectors that have purchases from the detailed sector *Water, sewage and other systems (221300)*.[2,6,10,11,13] The detailed sector *Water, sewage and other systems (221300)* is included in the aggregated sector *Utilities (22)* in the 2005 and 2010 EIO accounts, and its economic activity data were not reported separately.[13] We assumed that the proportion of commodity purchase from *Water, sewage and other systems (221300)* in 2005 and 2010 was the same as in 2007, based upon the EIO data available at the more detailed level in 2007.[13] The USGS thermoelectric power generation water withdrawal was mapped to three detailed sectors, *Electric power generation, transmission, and distribution (221100)*, *Federal electric utilities (S00101)*, and *State and local government electric utilities (S00202)*, based on the proportion of their industry output.[2,6,10,11,13] We also assumed that the proportion of industry output for these three sectors in 2005 and 2010 was identical to that in 2007, because of the unreported industry output data for both 2005 and 2010. The USGS industrial water withdrawal was allocated to the manufacturing-associated sectors, including *Food and beverage and tobacco products (311FT)*, *Paper products (322)*, *Chemical products (325)*, etc.[2,6,10,11,13−18] The water withdrawals for three mining aggregated sectors [*Oil and gas extraction (211)*, *Mining except oil and gas (212)*, and *Support activities for mining (213)*] were estimated on the basis of the process data, production of mine ore, and USGS mining water withdrawal data.[2,6,10,11,19−28]

The effects of the five governing factors on the change in total water withdrawal for industrial sectors from 2005 to 2010 were quantified with the SDA method.[6,7,29,30] The SDA technique was used to decompose the change in total water withdrawal to changes in the five governing factors. With the five factors considered in this study, 5! = 120 decomposition forms exist.[6,7,29,30] The mean and standard deviation of the 120 decompositions are reported in Figure 1.

■ RESULTS AND DISCUSSION

Figure 1 shows the effects of the five governing factors on the change in total water withdrawal for U.S. industrial sectors for 2005−2010. The total water withdrawal for industrial sectors decreased from approximately 140 to 120 trillion gallons between 2005 and 2010, accounting for 14% of 2005 total water withdrawal for industrial sectors (the orange bar). However, increases in water withdrawal were associated with increased population and changed consumption pattern, each contributing an increase of ∼5 trillion gallons. GDP per capita (in 2005 constant USD) reduced 1 trillion gallons of water withdrawal (a small amount compared to the other changes). A reduction of 4.53 trillion gallons in water withdrawal was caused by production structure change. The changed water use intensity was the largest contributor to the decline in total water withdrawal in 2010 compared to 2005, yielding a decrease of more than 25 trillion gallons between these years.

Table 1 shows the change in total water withdrawal for U.S. industrial sectors due to changes in the five governing factors for 1997−2002 and 2005−2010. The effects of the five factors on the change in total water withdrawal vary based on the specific time period. The change in population increased total

DOI: 10.1021/acs.estlett.5b00023
Environ. Sci. Technol. Lett. 2015, 2, 79−83

Table 1. Comparison of Contributions of Governing Factors to Changes in Total Water Withdrawal for 1997−2002 and 2005−2010

factor	change in total water withdrawal for industrial sectors due to changes in five factors (trillion gallons)	
	1997−2002	2005−2010
population	10.0	5.97
GDP per capita	12.1	−1.07
water use intensity	14.3	−25.5
production structure	−10.6	−4.53
consumption pattern	−21.6	4.89
net water withdrawal change	4.2	−20.2

water withdrawal for both five-year periods, but its contribution is smaller during 2005−2010 than during 1997−2002. Reduction in water withdrawal was caused by production structure change during these two time periods, though the resulting reduction from 2005 to 2010 was only half of that which occurred from 1997 to 2002. Changes in GDP per capita and water use intensity exhibited effects that reversed from 1997−2002 to 2005−2010. The change in water use intensity caused a moderate increase in water withdrawal for 1997−2002, while it became the largest net contributor to the reduction in water withdrawal for 2005−2010. The change in consumption pattern reduced more than 20 trillion gallons of water withdrawal for 1997−2002 but caused 4.89 trillion gallons of additional water to be withdrawn in 2010 than in 2005.

An approximate 4% increase in water withdrawal is estimated to have resulted from the 4.6% increase in U.S. population during 2005−2010.[4] The U.S. experienced a severe economic recession from December 2007 to June 2009.[31] The national average unemployment rate increased from 5.1 to 9.6% during 2005−2010,[32] and GDP per capita (in constant 2005 USD) decreased by 0.8% between 2005 and 2010.[5] This implies that consumers had less consumption ability and fewer goods and services produced in 2010 than in 2005, leading to a decrease in water use for industrial sectors. Both the 7.5% increase in population and the 12.9% increase in GDP per capita for 1997−2002 caused increases in water withdrawal.[6]

The decrease in total water withdrawal due to changes in water use intensity mainly resulted from decreases in water use intensity for *Farms* and *Utilities*. The decline in water use intensity for *Farms* was caused by increases in its industry output[8,9] and a decrease in its water withdrawal between 2005 and 2010.[2,10] The decrease in water use intensity for *Farms* not only reduces water withdrawal for the sector itself but also reduces water withdrawals for other sectors through the supply chain.[6] The main contributor to *Farms* water withdrawal is agricultural irrigation. Climate conditions, irrigated acres, and application rate are the important drivers that determine the water demand for agricultural irrigation.[2,10] The U.S. national average precipitation in 2010 was 0.4% higher than in 2005, and the average temperature decreased from 53.64 to 52.98 °F during 2005−2010.[33] The more ample rainfall and lower temperature in 2010 are likely to have reduced the need for agricultural irrigation. In 2010, 3.6% more acres were irrigated with the sprinkler irrigation method and 1.5% fewer acres were irrigated with surface irrigation technology as compared with those in 2005.[2,10] Although irrigated acres increased from 61.5 to 62.4 million acres for 2005−2010, the shift in irrigation systems caused an estimated 11% decrease in the average application rate.[2,10] However, the drier and hotter climate in 2002 than in 1997 and the higher average irrigation rate in 2002 caused increased water use intensity for agriculture,[6] resulting in 14.3 trillion gallons of additional water withdrawn in 2002.

Utilities is the largest water withdrawal sector,[2,10] and changes in its water use intensity significantly impact total water withdrawal for industrial sectors. Although the industry output for thermoelectric power generation decreased by 5.8% from 2005 to 2010,[8,9] the 20% reduction in thermoelectric power water withdrawal resulted in a smaller water use intensity in 2010 than in 2005.[2,10] The *Utilities* water withdrawals are primarily for thermoelectric power generation. The water requirements for thermoelectric power generation mainly depend on fuel type, cooling system, and generation technology.[34] Nuclear power plants generally require more water for every unit of electricity generation than coal and natural gas facilities.[34] Recirculating cooling technology requires less water than once-through cooling technology for every unit of electricity generation.[2,10] An increase in the use of recirculating cooling technology continues to occur in many thermoelectric power plants, replacing once-through cooling technology.[35] By 2010, 53% of thermoelectric power was generated by power plants with recirculating cooling systems, only withdrawing 6.7% of the total thermoelectric power water.[2] The water withdrawal for thermoelectric power generation is also affected by regulations. The federal Clean Water Act regulations specify that cooling water withdrawals at power plants must follow the best available technology.[34]

The change in production structure reduced total water withdrawal for industrial sectors between 2005 and 2010, implying that intersectoral purchases of commodities from the intensive water use sectors decreased during this period. The shift in consumption pattern from 2005 to 2010 caused an increase in water withdrawal, reflecting consumption of more goods and services from the higher water demand sectors in 2010 than 2005. In particular, the personal consumption for the two largest water use sectors *Farms* and *Utilities* increased by 8.2 and 9.7% for 2005−2010, respectively,[8,9] mainly accounting for the increased total water withdrawal due to changes in consumption pattern for the five years.

Although changes in each of the five factors could yield decreases in future water withdrawal, long-term decreases in population and GDP per capita are unlikely. The U.S. population is projected to increase by 30% over the next 50 years,[36] and while reductions in GDP per capita are possible, positive growth is generally anticipated. The most likely opportunities for reduced water withdrawal are thus likely to arise from changes in consumption pattern favoring goods and services with lower water requirements, and further decreases in water use intensity through technology evolution and innovation, such as a shift in the cooling system for thermoelectric power generation from once-through cooling to recirculating cooling, or to renewable technologies with minimal water use.

Because of the impacts of water withdrawal changes in 2005−2010 on the effects of the five governing factors, the timely estimation of the contributions of governing factors is helpful for sustainable water use management planning. The water withdrawals can be projected under different scenarios for the governing factors, which can provide insight into the influence of the various factors governing water use in the future.

DOI: 10.1021/acs.estlett.5b00023
Environ. Sci. Technol. Lett. 2015, 2, 79−83

Uncertainties in the original USGS water data, the EIO data, and the assumptions introduced some uncertainties,[6] but most uncertainties are not easy to quantify.[6] This research was based on the USGS water data, but other data sources that employ different estimation methods exist.[37,38] For example, the USGS thermoelectric water withdrawal was estimated on the basis of a heat and water budget model, while the Energy Information Administration (EIA) thermoelectric water withdrawal was estimated on the basis of the fuel and net generation data.[37,38] The non-unique decomposition of SDA resulted in variability, and the standard deviation bars in Figure 1 present the quantification of this variability.

While this work focuses on the demand side of water withdrawals, changes in the supply side of the equation associated with source degradation or other factors affecting natural and engineered water systems could make the need to manage and limit our water withdrawals even more important in the future. The consumptive water coefficient representing the fraction of water consumption varies across industrial sectors, e.g., ~2% for the largest water withdrawal sector thermoelectric power generation and 40 to 100% for agriculture, the largest water consumption sector.[39−41]The same methodology can be used to investigate the contributions of changes in water consumption in future studies.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by a Steinbrenner Institute U.S. Environmental Sustainability Ph.D. Fellowship at Carnegie Mellon University. This fellowship program is supported by a grant from the Colcom Foundation. Mitchell J. Small was supported by the H. John Heinz III Professorship and David A. Dzombak by the Hamerschlag University Professorship. Thanks are extended to Prof. Chris T. Hendrickson from the Department of Civil and Environmental Engineering at Carnegie Mellon University and Dr. Christopher L. Weber from the World Resource Institute (Washington, DC) for their helpful comments.

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DOI: 10.1021/acs.estlett.5b00023
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