Decomposing U.S. Water Use Since 1950. Is the U.S. Experience Replicable Internationally?[1]

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Abstract

U.S. water use has been remarkable since 1950, not mimicking uninterrupted U.S. population increase, steady real GDP growth, and rising per capita GDP. After doubling between 1950 and 1980, water withdrawals have stabilized and even decreased. Our decomposition reveals 35-50 % of the productivity gains that let the U.S. produce each dollar of its GDP with less water stems from long-term structural changes (growing service economy). The remaining 50-65 % comes from improved production techniques, and esp. productivity improvements in electricity-generation. While globalization reduced U.S. water use, imports of more water-intensive goods are not the reason U.S. water use plateaued.

1. Introduction

Water use in the U.S. has followed a remarkable pattern since 1950. After doubling between 1950 and 1980, the total volume of water withdrawn has virtually remained unchanged. Moreover, the newly released U.S. Geological Survey (USGS) data for 2010 reveal that water use has even slightly decreased in the last few years.[2] The decreasing water use is especially striking in light of discussions about "green growth" as it documents that natural resource use can be decoupled from the relatively steady increase in U.S. population, GDP, and per capita GDP over the last sixty years.[3] As a matter of fact, population has more than doubled, GDP has increased more than sixfold and income per capita has tripled since 1950. It is important to note that population growth, economic growth, and rising standards of living and the lifestyle changes they entail are very often

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[2] Maupin et al. (2014) Estimated Use of Water in the United States in 2010, USGS Circular 1405.

[3] OECD, 2011. The OECD defines green growth as growth that ensures that "natural assets continue to provide the resources and environmental services on which our well-being relies"

expected to increase the demand for water and to further strain the available water resources.[4] Against the background of the California water crisis and the mounting global fears of freshwater scarcity, the leveling off and slight decrease in U.S. water use is a fascinating development.[5] Today, half of the world's cities lie in water-stressed river basins and one-fifth of the world population suffers from water scarcity.[6] To face the challenge of managing water effectively in the 21st century will require a solid understanding of the *exact* drivers of water use and of the determinants of countries' overall water efficiency.[7] While the focus in the literature is often on technology improvements, in this paper we show how long-term structural changes of the U.S. economy *next to* technological progress have allowed the United States to produce each dollar of its GDP with increasingly less water. [8] The latter has enabled the United States to call to a halt the increase of its overall water use in spite of continued population and GDP growth. In addition, our analysis should prove relevant beyond the U.S. context. In the absence of long-run, high-quality data of water use on a global scale, our analysis reveals, to some extent, whether the U.S. experience is replicable in other parts of the world, and also what such replication would require.[9]

In this paper we explain U.S. water use in economic terms.[10] We start by tying water use to the dramatic long-term structural changes of the U.S. economy. At the heart of this structural change is the rise of the United States as a service economy, and the accelerated demand for services since the mid-1970s to early 1980s. As a matter of fact, at the beginning of the 21st century, about 75

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[4] UN (2012), Rosegrant et al. (2002), Alcamo et al. (2003), and Vörösmarty (2000) also consider the role of climate change for future water stress.

[5] Pilita Clark, A world without water, Financial Times, July 14, 2014; The Economist, For Want of Drink, Special Report on Water, May 22nd 2010. National Geographic, Water Crisis News, http://news.nationalgeographic.com/news/archives/water-crisis/, Fang, Kenny, The Global Water Crisis: The Innovations to Watch For, Wall Street Journal, 2007, http://www.wsj.com/articles/SB119042333799235895.

[6] Richter et al. (2013) and UN Word Water Assessment Programme (2009).

[7] See Gleick (2003a, 2003b).

[8] See Gleick (2003a, 2003b) for discussion of technology improvements.

[9] A major challenge is the international comparability of water data, see also Gleick (2003a, 2003b). Shiklomanov (1998), for example, compiled aggregate, international water use data from country-specific statistics with varying methodologies. Flörke et al. (2013) reconstructed historical international water use relying on assumptions about human behavior and extrapolating trends in water productivity growth, some of which we investigate.

[10] In this paper, water use refers to surface and ground water withdrawal and not to water consumption. Water withdrawal equals both consumptive use and non-consumptive use that flows back to the environment. Consistent with USGS, we do not include hydropower withdrawals since this water is returned virtually directly to the environment. Our focus on blue water withdrawal is informed by data limitations (no consumptive data are available for 1950-1955 or 2000-2010, nor are disaggregate data available) and by our economic perspective: you pay, if at all, for water withdrawal, not consumptive use. Note, however, that the limited USGS data on water consumption between 1960 and 1995 mimic the longer pattern of water withdrawal.

percent of GDP is spent by consumers, local and federal governments and investors on services. This is more than 25 percentage points higher than in 1950; see Figure 1.[11] Related to the shift towards services, we also consider the drastic decrease of the U.S. manufacturing sector, the secular decline of agriculture, and the role of globalization that has made the U.S. an increasingly more open economy.[12] Note that the rise of the U.S. service sector and its implications for water use is directly relevant for assessing water use beyond the United States since the *World Development Indicators* reveal that a steadily increasing share of services in world GDP in the last couple decades.[13] The same is true for the U.S.' worsening trade balance since the late 1970s. It raises the question as to whether the United States was able to reduce its water use by importing more water-intensive goods, which would question the ability of the rest of the world to follow the U.S. example.

Our study builds on Leontief's seminal (1970) input-output analysis that has deep roots in economics.[14] We consider *total* water use of all final goods that are produced in the United States and sold to U.S. consumers, investors, governments, and foreigners – these final goods by definition make up all of U.S. GDP. We study both the water that is *directly* withdrawn during the production process of those goods as well as the water that is *indirectly* contained in the intermediates that are employed. While increasingly popular in environmental studies, input-output analyses are not prominent in water studies and have not been systematically applied to explaining the dynamics of water use.[15]

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[11] The reported shares are in current prices. After correcting for changing relative prices, growth in the share of services persists, and so does the slight acceleration since 1980. Final services demand is the relevant measure for our approach, see below. Value added or employment numbers also reveal a shift towards services, see Buera and Kaboski (2012).

[12] The extensive literature on the environmental Kuznets curve documents the inverted-U-shaped relationship between environmental degradation and countries' increasing per capita GDP. Jia et al. (2006) confirms a Kuznets curve for water use among industrialized countries. We explain overall (not per capita) water use in the United States (with positive population growth a Kuznets curve can imply either more or less water use) allowing for scale, changes in composition (of inputs and final demand) as well as changing technology, and globalization.

[13] World Development Indicators, http://databank.worldbank.org/data/. See also Timmer et al. (2014), and Uy,Yi, and Zhang (2013).

[14] See especially Miller and Blair (2009), the standard reference on input-output analysis.

[15] Our study complements innovative research on virtual water by Hoekstra and co-authors. Chapagain and Hoekstra (2008), Hoekstra and Chapagain (2008), Hoekstra and Mekonnen (2012), and Mekonnen and Hoekstra (2011) calculate virtual water use in agriculture in great detail. Without input-output tables, the interaction between agriculture and other sectors of the economy lacks detail. Hoekstra and co-authors study water consumption (not withdrawal), which explains their singular focus on agriculture. Blackhurst et al. (2010) is one of few who use U.S. input-output tables to calculate the direct and indirect water content of the sectors of the U.S. economy for 2002, as do Di Cosmo et al. (2012) who study direct and indirect water content of EU countries for 2005. Like us, Blackhurst et al. (2010) and Di Cosmo et al. (2012) focus on water withdrawal (not consumption).

An input-output analysis of direct and indirect water use holds great promise for investigating water use. So far, the standard presentation of water use data by the USGS shows *direct* water use for a few key sectors, with direct water use in the large services sector barely registering at five percent. The singular focus on direct water use limits our economic understanding because water is a very important resource for intermediate goods that are also used in services. Electricity generation and agriculture, for example, are responsible for over 70 percent of direct water withdrawals. While agriculture and electricity generation together account for a mere three percent of U.S. GDP in recent years, their output is widely used as an intermediate in other sectors. An input-output framework helps tie the majority of direct water use to the rest of the economy, and reveals that the service sector is in fact the largest total (direct and indirect) water user of the economy. Linking intermediate and final goods is all the more important since the open economy that the United States has become remains very dependent on *domestic* electricity generation and agriculture production.[16] Indeed, electricity generation is to a very large extent for the United States a non-traded good that could only be sourced from abroad at considerable cost, which is why increases in final demand will put additional stress on U.S. water resources. Similarly, the United States has a revealed comparative advantage in agricultural production, and substituting foreign agricultural inputs for domestic ones is prone to drive up production costs significantly.

Our empirical analysis decomposes U.S. water use in terms of its key drivers, and links the improving water productivity of the U.S. economy to the structural change and technological improvements. We modify in two ways the conventional decomposition that is perhaps best exemplified by Levinson (2009).[17] Following Levinson (2009), we relate water use to 1) the changing 'scale' of the economy, 2) the changing water productivity of water use at the sectoral level or the changing 'technique or technology improvements' and 3) the changing composition of the economy. Our focus on final demand and GDP lets us identify changes in scale with GDP growth, as well as break down the composition effect into a) the changing domestic and international demand for U.S. final products ('demand composition'), and b) the changing composition of the inputs that are used in the production process ('input composition').[18] Our

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[16] If electricity were traded internationally at comparable cost, for example, there would be less of a need to tie final goods demand to electricity use in an analysis to understand U.S. water use.

[17] See also Brock and Taylor (2005).

[18] See Section 2 for details. Levinson's (2009) study of air pollution by manufacturing since 1972 illustrates the standard decomposition well. Our study is different in a number of ways: 1) Unlike pollution, most water is used in a

second innovation follows from combining an aggregate and disaggregate analysis. Initially, we consciously work with aggregate sectors such as services, manufacturing, and agriculture that cover all sectors of the economy. Because of this fairly aggregate level, our decomposition displays the *between*-sector shifts of demand and inputs used since 1950. In other words, we can directly link our decomposition to the long-run structural changes of the U.S. economy whose drivers (human capital accumulation, the skill premium, and globalization) are relatively well understood.[19] The latter, at least to some extent, addresses a perceived shortcoming of decomposition analyses as failing to establish a causal link between the phenomenon that is studied (e.g. pollution or in our case water use) and the evolution of GDP, see Levinson (2008) and Levinson and O'Brien (2015).[20] Indeed, few will argue that the larger structural shift that has fueled the emergence of the service sector is driven by water scarcity, or by changing water prices for that matter. Finally, tying total water use to a growing service sector and a declining manufacturing and agricultural sector makes intuitive sense, since services is by far the least water-intensive sector.

We find that the changing composition of the U.S. economy is responsible for between 35 and 50 percent of the increased water productivity in the United States. The larger part of the changing composition comes from the shifting final demand by consumers, investors, governments, and foreign customers away from manufacturing and agricultural products towards services. By default, the overall water productivity gain that is not explained by the shifts between the key sectors, between 50 and 65 percent, is booked as technique improvement in the initial analysis. This sizable share is good news if one considers technique improvements opportunities for replication abroad. Transferring technology can be a more actionable way of bringing about less water use, especially when compared to the slow-moving process of structural shifts towards a less water-intensive service economy. In addition, we document that more than 60 percent of these

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few intermediate goods producers, which warrants our focus on the *total* water content of *final* demand. Levinson (except when considering pollution content of international trade) studies the direct pollution content of sectors' gross output. 2) Focusing on final demand lets us also break down the composition effect into a demand *and* input component, as well as link the scale effect to changing GDP – after all, final demand across the economy sums to total value added or GDP. Levinson and others investigate changing gross output (not value added) of individual sectors or the entire economy.

[19] See Section 3, and Buena and Kaboski (2012).

[20] In Levinson (2015)'s words, extending his critique to Environmental Kuznets curves (EKCs):"But EKCs are simply conditional correlations, without meaningful interpretations other than that pollution does not necessarily increase with economic growth." Because of this critique, Levinson (2015) turns to examining Environmental Engel Curves.

technical water savings are driven by lower water needs per kilowatt-hour in the electricity-generating sector. This finding underscores the role that public infrastructure and regulation can potentially play in constraining water use.

To make sure the fairly aggregate analysis does not bias our findings, we complement our *between*-sector calculations with a more common, granular decomposition that includes the shifts in demand *within* the key sectors. For this exercise we rely on 81 disaggregate sectors based on Blackhurst et al. (2010) who provide very disaggregate sectoral water use data for 2000. Our analysis confirms a shift over time towards less water-intensive products. What stands out, however, is that the shift toward less water-intensive products is only slightly more pronounced with disaggregate data than with the aggregate analysis. The aggregate between-sector shifts capture 75 percent of the shift toward less water-intensive (disaggregate) products since 1950, which underscores the explanatory power of the broad structural changes to understand water use in the United States. Note also that the slightly more pronounced shift at the disaggregate level suggests that our estimate of the contribution of technology should be interpreted as an upper bound. At the same time, our more disaggregate analysis documents the uneven pattern of technological progress that took off especially since the 1970s.

Our analysis finally considers the role of globalization and whether the recent stabilization and decrease in overall water use is due to imports of more water-intensive products. We study the hypothetical scenario where the United States would have to produce all the goods it consumes itself (with its own technology). In that case, we find that water use would have peaked in 2005, instead of in 1980. This result is driven by the increase in (U.S.) water content of net imports since the 1980s and especially by the worsening international trade deficit of the United States. It is important to note, however, that the magnitude of these water savings is a relatively limited: 17 percent of overall savings that can be attributed to the changing composition (both demand and input composition) and a mere one percent of overall water use. This finding is important for the international replicability of the U.S. experience. Running a trade deficit or shifting imports towards more water-intensive imports could not be a recipe for increasing worldwide water conservation.

The article is structured as follows. First, we lay out the analytical framework that guides the analysis, and which will be the basis for our description and decomposition of total U.S. water use.

In the next section we summarize direct water use data, before we specify sectors' total water use and its link to international trade. The third-to-last section then presents the results of our decomposition exercise. We finally conclude after we have corroborated and interpreted our findings in light of more detailed disaggregation.

2. The analytical framework

To gain a deeper understanding of the drivers of water use in the United States, we break down water use by its key sources. We propose a modification of the conventional decomposition into scale, composition, and technology effects that accommodates the specifics of water use and how water is reported in the water use statistics. At the same time, however, our approach should be applicable more broadly: 1) We look at the 'scale' of the U.S. economy and in particular how the changing overall size of the U.S. economy as measured by its GDP affects its water use. 2) We investigate how the 'composition' or how the changing sectoral structure of the economy affects water use. We propose to break up the traditional composition effect into two segments. One part reflects how output of final goods or, alternatively, the demand for final U.S. products changes. Final products are the products that are produced in the United States and bought by its consumers, investors, governments, and also by foreigners for their own use and not to be employed as intermediates in further production. This part of the composition effect reflects most clearly the changing demand that is driven by changing incomes as well as shifting preferences for U.S. products domestically and abroad. The second element of the composition effect is determined by the changing links between the sectors in the economy as mapped by the input-output table. The input-output table lays out how intermediate goods from one sector are used in another. This second composition effect captures changes in how intermediate goods are being combined into final goods. It is not so much associated with changing demand, but rather with the changing production process of final goods as such. 3) We finally investigate how 'technique' or the changing technologies yield water efficiency gains.[21]

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[21] This breakdown into scale, composition, and technique follows an emerging convention in environmental economics; see Grossman and Krueger (1993), Copeland and Taylor (2005), and Levinson (2009).

Equation (1) is a good starting point to introduce the equation that guides our decomposition of total water use in the United States, or of W. We define W as the following multiplication of vectors and a scalar,

$$W = \underline{\boldsymbol{w}}' \boldsymbol{\theta} Y \tag{1}$$

The $n \times 1$ vector $\underline{\boldsymbol{w}}$ captures for each sector i the total domestic water that is needed to produce one dollar of its final output in the United States. The vector $\underline{\boldsymbol{w}}$ encompasses both direct and indirect water use. This includes both the water used directly in a sector's output as well as the water contained in the intermediate products that are employed in the sector. Since the sum of domestic and foreign demand for sectors' final products totals a country's GDP, the U.S. total water use, W, is obtained by simply multiplying $\underline{\boldsymbol{w}}$ by the value of final demand in each sector, which is identical to the product of $\boldsymbol{\theta}$, an $n \times 1$ vector of the shares of sectors' final output/demand in U.S. GDP, and by Y, a scalar that measures U.S. GDP.

We borrow from Leontief's (1970) input-output analysis to calculate the total (direct and indirect) water use vector $\underline{\boldsymbol{w}}$. Equation (2) characterizes the well-known relationship between sectors' gross output (or, the total value of shipments) as the sum of the intermediate and the final products that sectors sell.

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \tag{2}$$

The $n \times 1$ vector $\boldsymbol{x}$ contains sectors' gross output. $\boldsymbol{A}\boldsymbol{x}$ is the product of the gross output vector and an $n \times n$ matrix $\boldsymbol{A}$ of input coefficients that characterizes sectors' intermediate goods use. To be precise, the elements a_{ij} of $\boldsymbol{A}$ indicate how much of sector i's intermediates are used in another sector j (as a fraction of gross output in sector j). The input coefficients are directly derived from the U.S. input-output table. The $n \times 1$ vector $\boldsymbol{y}$ reports sectors' final output. Sectors produce these final products for domestic and foreign customers. With some matrix manipulation we can rewrite equation (2) and directly relate sectors' gross output to their final demand as in equation (3).

$$\boldsymbol{x} = (\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{L}\,\boldsymbol{y} \tag{3}$$

To be clear, $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ is the famous Leontief matrix $\boldsymbol{L}$; $\boldsymbol{I}$ is the $n \times n$ identity matrix. The elements of the Leontief matrix l_{ij} report the total amount of sector i's intermediate output required to generate one dollar of final output in industry j, which includes whatever amount of sector i is used in all other industries whose intermediates are employed in *j*, as well as the amount of *i* used in the inputs to those industries.

We obtain total U.S. water use or *W* in equation (4a) when we pre-multiply equation (3) with the *n x 1* vector ***w*** of sectors' direct water use per unit of gross output in the United States. Using the notation of equation (1) we can rewrite expression (4a) as equation (4b). To be clear, the vector of total water use $\underline{\boldsymbol{w}}$ equals ***w'L***.

$$W = \boldsymbol{w}'\boldsymbol{x} = \boldsymbol{w}'\,\boldsymbol{L}\,\boldsymbol{y} \text{ or} \tag{4a}$$

$$W = \boldsymbol{w}'\,\boldsymbol{L}\,\boldsymbol{\Theta}\,Y \tag{4b}$$

The last expression (4b) is the equation that we will use in our decomposition to study the water use over time. To isolate the scale effect, we want to study what water use *W* would be if only the scale *Y* changed, all else equal. To be clear: as *Y* changes, we will assume there is no change in the technology ***w***, nor in the distribution of input use as found in ***L*** or in the distribution of final demand that is characterized by $\boldsymbol{\Theta}$. Similarly, to isolate the two composition effects and the effect of technology, we will respectively let ***L***, $\boldsymbol{\Theta}$ or ***w*** change over time while keeping all other factors the same.

Note that expressions (4a) and (4b) are particularly well fit for a decomposition of U.S. water use, in light of how the water data are reported and of how water use is distributed. As will be especially clear when we describe U.S. water data in the next section, the heaviest reported water users that are responsible for over 60 percent of overall water use are electricity generation, agriculture, and water utilities. Together these sectors are relatively small, accounting for less than three percent of GDP. Moreover, they are largely providing intermediate inputs to other sectors that comprise 97 percent of GDP. To understand changes in water use, therefore, it is instrumental to figure out what is driving this intermediate good demand, which warrants our focus on changing final demand, the engine for demand for intermediates. To be explicit, understanding that water use increases because water utilities deliver more water, or because more electricity is generated is one thing. It is especially informative to understand why more water is used, and which sectors use the electricity and for what. Therefore, once we focus on sectors' final demand and consider their total water use, we are explicitly accounting for the water contained in their intermediates and we link final and intermediate demand. Note also that our focus on final demand allows us to explicitly link water use to GDP, since the sum of sectoral final demand is total GDP.[22]

A second reason that our decomposition based on (4a) and (4b) will be informative relates to the non-tradable nature of a major water user such as electricity generation. For a large country such as the United States, most electricity is generated domestically. Because of this, any increase in production of all sectors that use electricity will put additional pressure on U.S. water resources. Our total (direct and indirect) water use measures reflect this. A similar argument could be made with respect to agriculture. Since the U.S. has a comparative advantage in agricultural production, increases in domestic manufacturing through its use of domestic agricultural inputs will pose additional pressure on domestic water resources.[23]

We will proceed with the implementation of the input-output analysis in two steps. First we will conduct the investigation at a relatively aggregate level, allowing us to directly link water use to the broad structural shifts *between* the major sectors in the economy. Next, we will rely on a more granular approach with more disaggregate data that allows us to study water use *within* the major sectors. Comparing between and within results will, on the one hand, reveal any biases involved and, more importantly, underscore the significant contribution of the large structural changes for understanding U.S. water use.

3. Data

Figure 2 shows how water withdrawals have evolved in the United States between 1950 and 2010 based on data from the USGS. The graph shows the cumulative water use of eight sectors of the economy – the data representation closely relates to how the USGS presents the water data. The USGS provides blue water withdrawal (not consumption) data since 1950 at five year intervals for the following eight aggregate sectors: industrial (manufacturing), mining, water utilities, electric utilities, livestock, agriculture, commercial use (services), and residential use. From an economic point of view, withdrawal data (rather than consumption data of water that is not returned to the environment) are more relevant, since you tend to pay for withdrawal, not consumption. In

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[22] If one focuses on the direct water content, one would have to interpret scale as total gross output (which is different from GDP). For reference, Levinson (2009) calculates the direct pollution content of gross output for manufacturing. Only when considering exports and imports does he focus on the total (direct and indirect) pollution.

[23] See Debaere (2014).

addition, water withdrawal data are preferred for our analysis since the consumption data are of lower quality, and only available for a limited period of time (1960-1995).[24] We also do not have for water consumption a comparable source to Blackhurst et al. (2010) that provides very disaggregate water withdrawal data (see discussion in Section 6). Moreover, our choice of water withdrawal as the focus of the analysis relates well to the point made by Gleick (2003) that over-emphasizing water consumption rather than withdrawal sometimes tends to underestimate the real *local* water savings associated with water withdrawal reductions, even when such withdrawal reductions were to have no impact on the water availability downstream.[25] Note also that the USGS data for electricity generation traditionally do not include hydropower, and we follow that convention.

In some years, the USGS does not break down industrial water use into water use by mining and manufacturing, nor does it identify residential demand. We rely on secondary data sources (often the input-output tables) to attribute water use to these sectors.[26] Note that sectoral water use as reported by USGS typically refers to self-supplied water, i.e., water supplied to wells – a notable exception is residential demand. For our decomposition of water use across the major, aggregate sectors of the economy, as well as in Figure 2, we have supplemented the provided self-supplied water data of the major sectors with the water that these sectors draw from water utilities. To distribute water from utilities across sectors we rely on estimates by the USGS, complemented by information from the input-output tables that specifies the payments of other sectors to the water utilities.[27] Note that we have to interpolate the data from the input-output tables to match the five-year intervals of the USGS water data.[28]

After we have redistributed the water use by the water utilities to all its customers, the water that remains is that which water utilities use in their process. As should be clear from Figure 2, agriculture and electric utilities are by far the heaviest (direct) water users, which over the entire

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[24] The consumption data between 1960 and 1995 do show the same pattern as the withdrawal data.

[25] Indeed, local reductions in withdrawal, for example, make it not necessary to tap into additional resources that could have downstream consequences.

[26] See Appendix.

[27] See Appendix.

[28] The available data from the input-output tables are 1947, 1958, 1963, 1967, 1972, 1977, 1982, 1987, 1992, 1997, 2002, and 2007. We interpolate to match the water data that are available every five years from 1950 to 2010.

period are responsible for 70 percent or more of all water withdrawn in the United States. Direct water use by services, on the other hand, is relatively minor at less than five percent in 2010.

As noted, to implement our decomposition of water use across the eight aggregate sectors, we match the USGS data with the sectoral information of the input-output data. We take the input-output data from the *Bureau of Economic Analysis*. Given the level of aggregation of our structural analysis, it is relatively straightforward to match gross output data and water use data in order to construct the direct water use vectors $\boldsymbol{w}$, and to link the gross output $\boldsymbol{x}$ and final output data $\boldsymbol{y}$. We also draw on the export and import data as provided in the input-output tables.[29,30]

The input-output data are reported in nominal values. To deflate the nominal values we take two different approaches, with our preference going to the double deflation method because it allows deflation by sector-specific price indexes. In the double deflation method, the output of a particular industry is first deflated by that industry's price index. The value added price index is then derived so that the fundamental identity that the total value of output equals the total value of input holds. See Miller and Blair (2009) for a detailed description of the double deflation procedure. The price indexes for our aggregate categories are chain-type price indexes for gross output by sector from the *Bureau of Economic Analysis*.[31,32] In the second deflation method, we simply deflate all values in the input-output table by the price index for value added, also from the BEA.

4. Total Water Use Across Sectors and International Trade

Figure 3 presents U.S. water data in a different way. We depict the total (direct and indirect) water that is contained in the final demand for the eight sectors mentioned above. When compared to the standard categorization of water use in Figure 2, Figure 3 tells a very different story that more

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[29] In some years, the utilities sector is not divided into electric and water utilities, and net exports are not divided into exports and imports. See Appendix for the methods we use to impute these values.

[30] In some sectors and years, the gross output numbers going across the rows of the input-output table do not match the gross output going down the columns. Even though the maximum difference is less than one percent, we need the gross output numbers to match for the decompositions, so that total water use matches the sum of water use across sectors. To maintain the equality of gross output by rows and columns, we adjust final demand.

[31] Prior to 1977, real gross output is not available to construct the price indexes, so we use appropriately scaled price indexes for corresponding sectors from the U.S. Bureau of Labor Statistics.

[32] We use the BEA price indexes for all sectors except the electricity-generating sector, for which we use the real total price of electricity (supplied to residential and industrial consumers) from the Energy Information Administration. This price index better captures price movement in the electricity-generating sector than the price index for utilities, which is the most closely related price index provided by the BEA.

clearly reflects the dramatic changes in the U.S. economy since 1950. As the United States became a service economy, the relative importance of its manufacturing sector diminished and agriculture experienced a secular decline as a fraction of GDP. As noted, since no sector in the U.S. economy can produce without electricity, the heaviest direct user of water, the total (direct and indirect) water content calculations of final demand show how much the final demand for products in various sectors puts pressure on the U.S. water resources. The same is true to some extent for the intermediate use of agricultural products. Since the United States has a comparative advantage in agriculture, increased input demand due to final demand for manufacturing goods will also strain U.S. water resources. As Figure 3 illustrates, manufacturing and the service sector's total (direct and indirect) water use comprise 60 percent or more of water use, and the role of the service sector as far as total water demand goes is ever increasing.[33] As a matter of fact, in 1950 services total water use was a mere 18 percent of all water use in the U.S, and grew by just three percent over the next three decades. After 1980, water use accelerated markedly, and by 2010 it stood at 35 percent of total water use. Manufacturing, on the other hand, initially accounted for 54 percent of U.S. water use, a number that dropped to 39 percent in 1980 and finally 23 percent in 2010.

To fully assess U.S. water, we also want to study how globalization has altered U.S. water use. We ask the question whether the United States would use more or less water in the hypothetical situation that it had to produce the goods it consumes (as in a closed economy).[34] To determine whether U.S. water saving is due to its exchange with the rest of the world economy, we calculate the total water content of net imports in Figure 4 *using U.S. technology*.[35] The exercise is particularly relevant if one is interested in assessing to what extent the U.S. experience can be replicated abroad.

Before assessing our findings, we should clarify two complications that come with calculating the water content of net imports. First, in order to produce goods, the U.S. economy uses imported intermediate inputs. There is no perfect way to account for the imported intermediates, which are typically not fully specified in an input-output table. The most common way to "scrub" the imports

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[33] The line for electricity utilities reflects the direct electricity used by residents and the water use it implies.

[34] Needless to say, this exercise is just a thought experiment – we assume that prices, production and consumption patterns are not altered by becoming a closed economy.

[35] There is a long tradition in the international trade literature to calculate the total factor content of net trade, see Baldwin (2008), as opposed to just comparing the direct factor content of exports and imports which ignores the factors used in the production of the intermediate goods used.

from intermediate inputs is to use a proportionality assumption. In this case one assumes that each sector uses imported intermediates to the same extent (i.e., the use of imported intermediates does not vary across the various sectors that one sector produces for). To that effect we multiply the input-output coefficients a_{ij} in the input coefficient matrix $\boldsymbol{A}$ by the adjustment factor for sector $\boldsymbol{i}$. We follow Levinson (2009) and Miller and Blair (2009) and use for each sector the ratio of *imports/(domestic production + imports – exports)* as the adjustment factor.[36] Note that because we are interested in evaluating what it would cost the United States in terms of water to produce the imported products itself, we evaluate imports by U.S. technology.[37]

We also want to address a second concern that relates to the level of aggregation as we assess the water content of net imports – aggregation will also play a role in how we interpret our decomposition results below. We can easily calculate the water content of net imports with our relatively aggregate data as $W_T = \underline{\boldsymbol{w}}'\,\boldsymbol{T} = \boldsymbol{w}'\boldsymbol{L}\;\boldsymbol{T}$, where $\boldsymbol{T}$ is the vector of imports minus exports and $\underline{\boldsymbol{w}}$ and $\boldsymbol{w}$ respectively the vector of total and direct water use for our major sectors in the United States. One might be concerned, however, about systematic differences in the mix of water-intensive products *within* the major sectors that we consider between imports, exports, and what the U.S. produces. In such a case, applying the aggregate $\underline{\boldsymbol{w}}$ and in particular the $\boldsymbol{w}$ measures that are based on the water use of the mix of goods of U.S. production sectors to the aggregate trade data $\boldsymbol{T}$ should bias the water content calculations.[38] We therefore propose to adjust our water content of net trade measures W_T by using more disaggregate data, while at the same time working around the constraint that we only have disaggregate water use data for one year – Blackhurst et al. (2010) disaggregate the USGS water data for 2000 and assign them to the 428 NAICS categories of the input-output table.

Here is how we proceed. For each year t in our sample, 1) we calculate the water content of exports and imports with our aggregate data that are readily available, $W_t^E = \boldsymbol{w}_t'\boldsymbol{L}_t\boldsymbol{E}_t$ and $W_t^{IM} = \boldsymbol{w}_t'\boldsymbol{L}_t\boldsymbol{IM}_t$, where $\boldsymbol{E}_t$ and $\boldsymbol{IM}_t$ are respectively the export and import vector; 2) we construct the water content

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[36] This adjustment factor is implied by the proportionality assumption, as described in Antràs et al. (2012), who use the assumption to construct an open-economy adjustment to their measure of the upstreamness of production.

[37] We are able to relax the proportionality assumption with import shares computed from the Asian Input-Output tables, which distinguish U.S. imports by use. We apply the distribution of import shares across use within an industry for the year 2000 to the import shares computed using the BEA input-output tables. The decomposition results are unchanged.

[38] This concern does not arise when dealing with domestic final demand, as by construction $\underline{\boldsymbol{w}}'\,\boldsymbol{\Theta}\,Y = \underline{\boldsymbol{w}_d}'\,\boldsymbol{\Theta_d}\,Y$.

of exports and imports for that year with the aggregate water use vector for the year 2000, $\boldsymbol{w}_{(2000)}$, and obtain $W^E_{t(2000)} = \boldsymbol{w}_{(2000)}'\boldsymbol{L}_t\boldsymbol{E}_t$ and $W^{IM}_{t(2000)} = \boldsymbol{w}_{(2000)}'\boldsymbol{L}_t\boldsymbol{IM}_t$ and, 3) we calculate the water content of the 81 disaggregate export and import sectors using the vectors E_{dt} and IM_{dt}, the disaggregate water use vector for 2000, $w_{d(2000)}$, and the disaggregate Leontief matrix, L_d, to obtain $W^E_{dt(2000)} = \boldsymbol{w}_{d(2000)}'\boldsymbol{L}_{dt}\boldsymbol{E}_{dt}$ and $W^{IM}_{dt(2000)}=\boldsymbol{w}_{d(2000)}'\boldsymbol{L}_{dt}\boldsymbol{IM}_{dt}$. Because of differences in product mix between exports, imports, and production within more aggregate sectors, it is possible that the total water content of, say, exports, $W^E_{t(2000)}$ differs from the disaggregate calculation $W^E_{dt(2000)}$. If we find that $W^E_{dt(2000)}$ differs from $W^E_{t(2000)}$ by a factor α_t in a particular year, we propose to pre-multiply our aggregate W^E_t measures by α_t to correct for a potential bias. Needless to say, α_t will vary over time. We do the same for the factor content of imports. For reference, we find that both the product mix of exports and imports tends to be somewhat less water-intensive than that of production, and on balance, especially for the later years, the water content of net trade that takes into account the variation in product mix is less water-intensive than the more aggregate net water content of trade, see Appendix.

Note that to make the disaggregation work, we have to address the changing classifications of the input-output tables, which is a challenge. In particular, before 1997 the sectors in the input-output tables were classified using SIC codes within 81 broad categories that we can easily follow through time. In later years, however, NAICS classification codes are used. We have to reconcile the 428 input-output sectors in NAICS codes with the 81 categories of the input-output table that we were following before. We build a concordance between 1997 and later years that largely follows Cicas et al. (2006).[39]

The lowest line in Figure 4 that captures the water content of U.S. net imports documents that there has been a significant change in the U.S. water exchange with the rest of the world over time. From 1950 to the 1980s the water content of net imports was negative as the water content of its exports was higher than the water it would take the United States to produce the imports itself. Since the 1990s, the total water use of net imports has turned positive, however. By 2010 the United States imported on net 3.8 billion gallons of water per day through its trade. This evidence suggests that some of the water savings achieved in the United States are due to its changing exchange with the rest of the world. Of particular interest here is the top curve in Figure 4. We have added the water

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[39] See Appendix for further details about the concordance.

contained in net imports (bottom line) to U.S. domestic water use (middle line), which is tantamount to assuming hypothetically that the United States would be producing all the goods it consumes (just like a closed economy).[40] As Figure 4 makes clear, under such hypothetical scenario the peak of U.S. water use would be in 2005 instead of 1980, suggesting indeed that overall water use has not leveled off but increased virtually continuously. While Figure 4 is qualitatively of interest, it should be noted that on balance the water content of net imports is only one percent of total water use, and as we will show unlikely an impediment for the replicability of water saving abroad.

5. Decomposing U.S. Water Use

Figure 5 presents our key findings for the decomposition of U.S. water use since 1950 that uses double deflation with industry-specific price deflators.[41] The decomposition compares U.S. water use under four hypothetical scenarios relative to what it was in 1950. Before emphasizing some of our key findings, let's make sure we understand the meaning of the various curves in Figure 5. For ease of interpretation we have scaled all curves by total 1950 water use. or by 180 billion gallons a day. In this way, it is fairly straightforward to assess changes in water use.

The lowest curve shows the increase of actual total water use as observed in the USGS data since 1950. Following equation 4b, observed water use, W_t, equals at every moment in time $\boldsymbol{w}_t' \boldsymbol{L}_t \boldsymbol{\Theta}_t Y_t$, which involves changes in all of its components (sectoral water productivity, the changing input-output matrix, the share of sectoral final demand in GDP, and GDP)**.** The top line singles out what happens to water use (relative to water use in 1950) once the scale of the economy changes, all else equal. In other words, it depicts what water use would have been if the economy had grown at its actual rate, while the water productivity (technology), the input-output relationships, and the distribution of final demand did not change from their 1950 levels. We calculate the water use that is implied by the changing scale of the economy as $\boldsymbol{w}_{1950}' \boldsymbol{L}_{1950} \boldsymbol{\Theta}_{1950} Y_t$ and divide it by 1950 water use. For ease of interpretation we introduce the subsequent changes (composition and technology)

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[40] It should be emphasized that this is nothing but a hypothetical scenario since prices are assumed not to change.

[41] We have also performed the decomposition uniformly applying the GDP deflator across all sectors, see Figure A1. Such an analysis increases the contribution of the changing composition to the water efficiency gains relative to the one we obtain with double deflation, and decreases the contribution of technological progress. Closer analysis reveals that deflating especially electricity generation with the GDP deflator fails to correct for the particular pattern of electricity pricing, understating technological progress.

in a cumulative fashion. The second and third curves from the top are labeled respectively scale *plus* demand composition, and scale *plus* demand *and* input composition. They are calculated as $\boldsymbol{w}_{1950}' \boldsymbol{L}_t \boldsymbol{\Theta}_{1950} Y_t$ and $\boldsymbol{w}_{1950}' \boldsymbol{L}_t \boldsymbol{\Theta}_t Y_t$ and compared to 1950 water use. The second and third curves allow the distribution of final demand, $\boldsymbol{\Theta}_t$, and the input-output structure of production, $\boldsymbol{L}_t$, to change over time in addition to the change in GDP.

With these definitions in mind, it is relatively straightforward to interpret the curves and the vertical differences between them.

- Since all curves are normalized by 1950 water use, they indicate how strong the changing scale or the changing scale *plus* (input and demand) composition would have pushed water use up compared to 1950, as well as how much actual water use did rise since 1950.

- Of even greater interest is the vertical difference between the lowest curve (the actual water use through time) and the highest curve (the scale effect) at every moment in time, which measures all realized water savings relative to 1950. As a matter of fact, at every moment in time the ratio of scale to actual water use is a measure of how water productivity has evolved since 1950, and how much less water it takes to produce one dollar's worth of GDP since 1950. The vertical distance between the first and second curve, the second and third curve, etc. – all the way down to the lowest (actual water use) curve – shows how the overall water productivity gains for the United States as a whole can be broken down.

- The difference between the first and the second curve (relative to the difference between the first and the lowest curve) reveals how important the changing composition due to the changing structure of final demand is for the improving water productivity in the United States.

- The difference between the second and the third curve informs us about water-productivity gains due to the evolving composition associated with the changing input-output matrix. This difference gets at the varying ways in which various intermediates are being combined to produce a final good. This reflects a changing production process.

- The difference between the third curve and the lowest curve that marks the actual water use attributes all of the remaining water productivity gains to improvements at the sectoral level that are summarized under the label technique or technology.

When looking more closely at the data, a few observations stand out. First and foremost, the United States has experienced substantial gains in overall water productivity between 1950 and 2010. While water use in 2010 was 1.95 times what it was in 1950, the upper, scale curve indicates that water use would have been 6.71 times the 1950 level if technology as well as the structure of demand and of input use had not changed since then. What can account for this overall increase in water productivity of almost 250 percent (6.71/1.95 = 3.44) since 1950? The most drastic water savings have occurred since the mid 1970s/early 1980s around which time water use was increasingly disconnected from GDP growth. Before water use was increasing virtually in step with the growing economy: real GDP grew 2.8 times between 1950 and 1980, and actual water use rose 2.4 times. Since 1980 the picture has been very different. Actual water use has decreased slightly (by 19 percent) since 1980, whereas GDP for 2010 has increased 2.4 times its 1980 level. In sum, while overall water productivity has increased a mere 1.2 times (1.2= 2.8/2.4) between 1950 and 1980, it has grown 2.7 times (2.7=2.4/0.89) since 1980.

Tracking for 2010 the vertical difference between the top curve and the second curve from the top, we notice that the changing composition associated with the changing final demand can account for 35 percent of the water productivity gains since 1950. The difference between the second and the third curve from the top assigns another 15 percent of the productivity gains to the changing input-output structure. We thus find a total composition effect of 50 percent, which underscores how crucial the structural shifts in the economy have been for slowing down water use in the United States.

In our analysis we study the impact of the structural changes of the U.S. economy on water use. We can draw on an important literature to explain what is behind the dramatic increase in the size of the service sector and the associated decrease of manufacturing and agriculture. A recent contribution, Buera and Kaboski (2012) provides a succinct summary of the key papers in the literature, from the early observers of the growth of the employment share of the service sector to the more recent theoretical contributions that also address increased final demand in services. A key factor in the emergence of the service sector is the very distinct human capital accumulation in the United States that is associated with the higher returns of skill acquisition in spite of an increase in supply of high-skilled labor.[42] According to Buera and Kaboski, increased specialization in skills gives way to an increasingly important role for the market to provide services that used to be provided in-house or in-family. Buera and Kaboski's data show that for much of U.S. history, the size of the service sector stayed relatively stable. By 1950 it began to increase, and since 1980 we even saw an acceleration of that share. Being able to link our decomposition to the structural change literature is of particular importance since it brings in an element of causation to one of the key drivers of water use: few will argue that the larger structural shift that has driven the emergence of the service sector is driven by water scarcity. [43]

The increasing relative size of the service sector, however, implies a decline in the relative size of the other sectors. Over the period that we study the decline of manufacturing is most pronounced since the 1980s. There is also a significant literature on the impact of globalization on the size of the manufacturing sector. A most recent article by Autor et al. (2014) in particular shows how increased competition due to the emerging Chinese economy as a major exporter of manufacturing products has hastened the decline in U.S. manufacturing.[44] Note that the structural change that we study makes sense in the context of our attempt to explain the stabilization of water use in the United States. Indeed, the rising service sector is one of the least water-intensive sectors, whereas the declining sectors, manufacturing and especially agriculture, are the more water-intensive ones. For reference, Table 1 reveals significant differences in water productivity at the sectoral level by multiple measures. For comparison, we also include total water use per final demand in a sector. Note that while the very stark differences in water productivity remain, counting total water use relative to final demand does reduce the extent of the sectoral water productivity differences by a factor of ten.

The remaining difference between the third curve and the lowest one in Figure 5 indicates that about 50 percent of the water productivity gains can be attributed to productivity gains in the water use within the various sectors. For those eager to replicate the successful reduction in U.S. water

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[42] The 20 percent increase in the service sector as a share of value added is entirely explained by the rise of high-skill services, see Buera and Kaboski (2012).

[43] This, at least for one of the key drivers that mitigated the fast increase in water use, addresses a criticism that is sometimes leveled at such decompositions, see Levinson (2008) and Levinson and O'Brien (2015).

[44] For related literature see Autor et al. (2014).

use, this is good news, as technological improvements (especially when compared to the slow-moving shift in a country's sectoral structure) are more likely to be influenced by policy and are also potentially faster to implement. We will come back to this finding as we compare our results with a more disaggregate analysis. Before doing so, however, we intend to refine the technology result, assess the impact of globalization, and vary the ranking of the decomposition.

5.1 A Closer Look at Technology

In this section, we take a closer look at the technology improvements. We impute the actual water savings (improvements in water per kilowatt-hour (kWh)) within the thermic electricity-generating sector, which is a good proxy for technical/technological advancements.[45] The imputation yields the fourth curve (the one right above the actual water use curve). What is striking is that the fourth curve lies not too far above the actual water use curve. This underscores the key nexus between energy generation and water use, and between technological improvements and water-productivity gains. There are non-negligible returns to water saving technology in the electricity-generating sector. As a matter of fact, the technological improvements by the electricity-generating sector are responsible for the vast majority (64 percent) of the water-productivity gains due to technique or technology.

While we do not formally investigate what is driving the move towards more water saving technology in electricity generation, a few facts have to be brought in. As Kenny et al. (2009) points out the *Clean Water Act* that amended the 1972 *Federal Water Pollution Control Act* most likely played a key role. The *Clean Water Act* regulated not only the technology of cooling water intake that should minimize the environmental effect, but also the cooling system thermal discharges. Increasingly since the 1970s power plants reduced their water use significantly by recycling water, or by using air-cooled systems instead of once-through cooling systems. This phenomenon has had a significant hand in accounting for the improvement in the water productivity. Corroborating this analysis is the fact that water use/gross output for electricity generation (relative to its 1980s value) shows the strongest decline of all sectors that we consider,

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[45] We formally do this by calculating (and drawing) $W_t = \boldsymbol{w}^{*\prime} \boldsymbol{L}_t \boldsymbol{\Theta}_t Y_t$, where the sectoral water productivity measures in $\boldsymbol{w}^*$ are identical to those of $\boldsymbol{w}_{1950}$, except for water use/gross output in electricity generation. Water productivity in electricity generation is allowed to change with the improvements in water/kWh in the data (U.S. Energy Information Administration), while kWh/gross output is held constant at its 1950 level. In particular w_t^* for electricity generation $= (w/kWh)_t*(kWh/gross\ output)_t$.

see Figure 10. We found that finding the proper deflator (we use the nominal electricity price for residential and industrial use) is also important.[46]

5.2. International Trade and the Decomposition

In this section, we get back to the impact of international trade. As noted, the changing composition of the U.S. economy plays an important role in accounting for its water savings. The question is whether and to what extent this aspect of water saving is to be attributed to the import of more water-intensive goods versus the export of less water-intensive products. Figure 6 is similar to Figure 5. For simplicity, we have lumped both composition effects together. In addition, we include two new curves. One curve is similar to the top curve of Figure 4 and adds the water content of net imports to domestic water use (while not allowing technique to change) in order to assess how much water saving that is associated with the changing composition of the U.S. economy comes from net imports. The other curve, then, corrects for the size of the U.S. current account. Notably, there has been a relatively dramatic change in the external position of the United States. In 1950 U.S. exports were larger than imports with a trade surplus was about 3.2 percent of GDP. In 2010, on the other hand, U.S. imports far outstripped exports, and the trade deficit was 3.3 percent of GDP.

As one can see from Figure 6, trade contributes a relatively small portion of the overall composition effect. If the United States had to produce all of its imports (the no-trade scenario) it would be saving 17 percent less water. If the United States were forced, on the other hand to run a level trade balance compared to 1950, it would reduce its savings by 16 percent. In other words, the trade deficit accounts for over 94 percent (16/17) of the water saving, and less than 6 percent (1/17) is to be attributed to a shift towards more water-intensive products. The relatively moderate role of imports in water savings is good news for the international replicability of U.S. water savings: running a current account deficit or shifting imports towards more water-intensive products is not a recipe for water saving that can be implemented by all countries of the world.

5.3. *Varying the Order of the Decomposition*

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[46] Using the price index for gross output of the utilities sector overstates the technological improvements after 1980 and understates the improvements before 1980. Using the GDP deflator does not capture the industry-specific price movements and understates the role of technological progress, see Figure 1A.

An attractive feature of our decomposition is that it explains the total change in water use and water productivity and breaks it down into the salient components, considering the various drivers of water use in the entire economy (scale, composition, and technology) cumulatively. A disadvantage is that the decomposition ignores any interactions between the various components, which is why we investigate the robustness of the decomposition with variations in the sequencing of the changes.[47] While we did investigate all possible orderings, only a few of them are meaningful. The decomposition that we presented so far is the most intuitive one that is directly in line with Leontief's input-output analysis in which change is driven by the changing final demand. There is one change of sequencing that we did want to report. We reversed the order of the technological component versus the input and demand composition component. For the entire period we find a stronger role for technology (65 percent instead of 50 percent) and a smaller role for the sectoral composition (35 percent instead of 50 percent). Reporting this decomposition lets us describe the range of the technology and composition effects. Note that other orderings are really not meaningful. Since our focus is on explaining changing water productivity (GDP/actual water use), the scale effect has to remain the first change to consider in the decomposition, and the actual water use by default the last one. We break down the overall composition into a demand and an input component. It is hard to rationalize inserting the technology component in between both composition effects.[48]

5.4 Aggregating Up

In this section and in Figure 7, we aggregate all the USGS sectors that we have been using in the decomposition up to two, services and the rest of the economy. The objective is to illustrate the robustness of the key role that services plays in the increased water productivity. We want to convince ourselves that what we have done so far, classifying the (in terms of water use) quite sizeable residential water and electricity demand as separate entities, did not distort the role of services in the decomposition of U.S. water saving. Lumping both water and electricity together with other goods is in line with much of the literature that classifies water and electricity use as a good, not a service, see Reshef (2013). Figure 7 is quite similar to Figure 5. The latter should not

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[47] Note that many decomposition studies cannot investigate the robustness as they do not have proper measures for all components, often attributing the residual of scale and composition to technology.

[48] If one would, one would not find any meaningful difference in the overall decomposition.

surprise. For one, residential water and electricity use are very small in terms of GDP and have not been growing at the rate that services has. In addition, both residential water and electricity use are far more water intensive than services. As such, they add to the water intensity of the slower-growing rest of the economy, which can only emphasize the water saving through the emergence and fast expansion of less water-intensive services.

6. Disaggregation

So far, we have shown how switches *between* the major sectors of the economy in terms of final demand and inputs used have played a non-negligible role next to technological progress in driving the pattern of water use in the United States. Using the more disaggregate water data by Blackhurst et al. (2010) we want to double check this observation and investigate whether and to what extent our finding is a consequence of ignoring action *within* our larger sectors. The between-sector analysis attributes improvements that cannot be explained by composition changes in final demand or input use between our major sectors to changes in technique/technology. Moreover, it treats the major sectors as relatively homogenous units. If it were the case that there were *within* agriculture, *within* manufacturing, or *within* services a shift towards the production of more water-intensive goods, our attribution of 50 (65) percent of the water productivity gains to technology would underestimate the total contribution of technology. The technological improvements within the respective sectors would simply have been offset by the consumption (and production) of more water-intensive final goods in those sectors. Alternatively, with a shift towards more consumption and production of less water-intensive goods within sectors, we would have overstated the technique/technology contribution.

In Figure 8a, we first confirm the important role of an overall composition shift over time towards less water-intensive goods also at the more disaggregate level – to simplify we lump together demand and input composition. Note that since disaggregate sectoral water use data are only for 2000, $\boldsymbol{w}_{2000}$, our analysis is more constrained than the between-sector analysis that drew on aggregate sectoral water use data for all the years of the period that we study. To tease out the composition effect, we compare total water use in 2000, which equals $\boldsymbol{w}_{d2000}' \boldsymbol{L}_{d2000} \boldsymbol{\Theta}_{d2000} Y_{2000}$, with what water use would have been if the United States had to generate its 2000 GDP with its 2000 water technology, but with the composition (final demand and input combinations) of the other periods, or with $\boldsymbol{w}_{d2000}' \boldsymbol{L}_{dt} \boldsymbol{\Theta}_{dt} Y_{2000}$. We find indeed that the composition of the earlier years would have given way to significantly more water use – on the order of 1.8 times as much water as in 2000 if the 1950 composition were used. Because of this shift towards less water-intensive goods over time within our broader sectors, the more aggregate between-analysis that we presented before by construction underestimates the extent of the composition effect, and hence overestimates the role of technology. What is striking, however, is that the big structural between-sector shifts (in particular the emergence of the service sector) that we have focused on and that are hard to be rationalize in terms of water scarcity or rising water prices in recent years account for a very important fraction of the composition effect. Calculating $\boldsymbol{w}_{2000}'\,\boldsymbol{L}_t\,\boldsymbol{\Theta}_t\,Y_{2000}$ with aggregate data for 1950, we capture 75 percent of the composition effect as calculated by disaggregate data $\boldsymbol{w}_{d2000}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{dt}\,Y_{2000}$: the 1950 hypothetical water use is 1.4 times as high as that of 2000.[49]

To tease out the impact of technology, in Figure 8b we compare with disaggregate data, total actual water use in United States or, $\boldsymbol{w}_{dt}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{dt}\,Y_t$, with what it would have been had 2000 technology been used, or with $\boldsymbol{w}_{d2000}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{dt}\,Y_t$. We also draw the same hypothetical water use with aggregate data, or $\boldsymbol{w}_{2000}'\,\boldsymbol{L}_t\,\boldsymbol{\Theta}_t\,Y_t$. As one can see, there is less of an improvement in technology with disaggregate data than what our aggregate analysis suggested. As noticed before, technological improvement is unevenly distributed over the time frame, and improvement picks up after 1975. Since we have only disaggregate water use data for one year to work with, we are constrained in how we can measure technological progress for individual sectors. We, for example, cannot compare $\boldsymbol{w}_{dt}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{idt}\,Y_{it}$ with $\boldsymbol{w}_{d2000}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{idt}\,Y_{it}$, for agriculture, manufacturing and services, which would let us directly tease out the role of technology.[50] In Figure 9 we plot the aggregate ***w***'s for the various sectors – to make the ratios comparable we divide each water intensity by its 1980 value. What stands out in the aggregate data is the change in the water to gross output ratio comes from agriculture and especially from the electricity- generating sector. Since 1960 there is a

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[49] For reference, in Figure 8a, we only let the composition change over time. If one wanted to get a sense of what the comparable impact of technology as the only changing factor would be, one could compare water use of 2000 ($\boldsymbol{w}_{2000}'\,\boldsymbol{L}_{2000}\,\boldsymbol{\Theta}_{2000}\,\boldsymbol{Y}_{2000}$) with what water use would have been if one were to produce the 2000 GDP with the composition of 2000, yet with technology that evolves over time (i.e., $\boldsymbol{w}_t'\,\boldsymbol{L}_{2000}\,\boldsymbol{\Theta}_{2000}\,\boldsymbol{Y}_{2000}$). One would find that water use in 1950 would have been 1.9 times that of 2000. Note that this comparison should be with aggregate data since we have no disaggregate ***w*** vector that changes over time.

[50] To be explicit, $\boldsymbol{w}_{dt}'\,\boldsymbol{L}_{dt}\,\boldsymbol{\Theta}_{idt}\,\boldsymbol{Y}_{it}$ does not correspond to the water use within agriculture, manufacturing or services as reported by the USGS, as it refers to the water contained in final goods demand/production, not water contained in gross output.

continuous improvement in electricity generation, whereas for agriculture we have to wait till 1980.

7. Conclusion

Adequate water management is one of the major challenges the world faces today, and will surely continue to face in the decades to come. With increased regularity, the media points our attention towards water crises, not only in California, but also in Australia, Spain, Brazil and many other places. Reports of water scarcity inevitably raise the question of how we can more efficiently and equitably use water. Contrary to discussions about climate change, and no doubt related to the tangible, local impact of water crises, the public (especially in the United States) has a more willing ear for the often alarming news about this precious resource that is essential for life. To properly guide how water is allocated, however, it is key that the drivers of water use are understood, as well as the mechanism that make water saving and increased water productivity possible.

In this paper we have decomposed the long-term, blue water use for the United States that in spite of significant GDP growth has stabilized and even decreased since 1980. To shed light on the significant overall water productivity growth that made this stabilization in water use possible, we have explicitly linked the main sectors of the U.S. economy to water through their direct and indirect water use. The literature tends to favor technological/behavioral explanations of water productivity improvements; we have documented that the changing structure of final demand and production of the U.S. economy (the evolving service economy, the decline in manufacturing, and the secular decline of agriculture) has played a critical role in slowing down water use. It is not the case that water savings are solely driven by improvements in technology. Thirty-five to 50 percent comes from the changing composition of the U.S. economy. Moreover, as far as technological improvements go, the lion’s share comes from efficiency gains in the electricity-generating sector.

Our conclusions for the United States are directly relevant for the global economy, especially since long-term, detailed and internationally comparable water data are not available on a global scale. We do not find that the majority of the productivity gains in the United States are at the expense of the rest of the world. The U.S. current account deficit and imports of water-intensive goods have an only limited impact on the overall outcome. More importantly, our finding that structural change that moves an economy towards services slows down water withdrawals is relevant for a world economy that is increasingly oriented towards services. And finally, the major role of electricity generation that we uncover in driving technological improvements in water productivity is directly relevant from a policy perspective.

There is another way in which our findings matter. Our analysis shows a decoupling of water use from GDP growth. This is important in light of discussions of green growth that favor restricting natural resource use to avoid further resource depletion or pollution. The most prominent example of explicit restrictions on water use has been Australia. In the wake of the decade-long severe drought it imposed a cap on overall water use in its economic heartland, the Murray Darling basin to ensure enough water availability for rivers, lakes and wetlands. Our evidence of stable and decreasing water use in the United States suggest that, at least for water, a hard cap on resource use should be reconcilable with sustained growth. At the same time, however, the water stress in California indicates that the slight reduction in overall water use and the impressive water productivity gains may not be enough. The sustainable level of water use for the United States may well be lower than its current level.

Our analysis also calls for studying water demand and supply at a more disaggregate level to retrieve some underlying reasons for why water productivity gains are achieved. We have a fairly good understanding of how skill accumulation, globalization and service markets drive long-term, structural changes, and how they thus are related to water productivity gains as induced by *between*-sector shifts. Our analysis, however, takes *within*-sector shifts towards less water-intensive products as well as technological improvements that increase water productivity as given. It is an open, empirical question whether a causal connection can be established between the extent of the water scarcity in a region in a particular time period, and technological progress. Whether and how scarcity and drought trigger innovation and efficiency gains is an important question that needs more empirical research with micro-level data.

Finally, our findings should also matter for ongoing discussions about societal water redistribution in the wake of water crises. Legitimate concerns arise about water use in agriculture, a sector that uses a very large amount of water but that has a ratio of value added created per gallon of water that is an order of magnitude smaller than that of services, which is suggestive of a significantly lower marginal product of water. One may wonder whether we should not opt for a more equitable distribution of water across sectors that is also more economical. In particular, we should strive for a distribution that allows more water to go to where it is most productively used and question policies that have subsidized agriculture and provided it with water at highly subsidized prices. Our analysis confirms that water is on average more productively used in services and manufacturing compared to agriculture. However, we argue there is a need to consider the indirect water use of the key sectors caught in the debate (services, manufacturing and agriculture) especially since much of the intermediate water use (such as the water linked to electricity generation) is non-tradable. Including the indirect water use of sectors indicates that the water productivity differences across sectors are still significant but not as stark as initially assumed.

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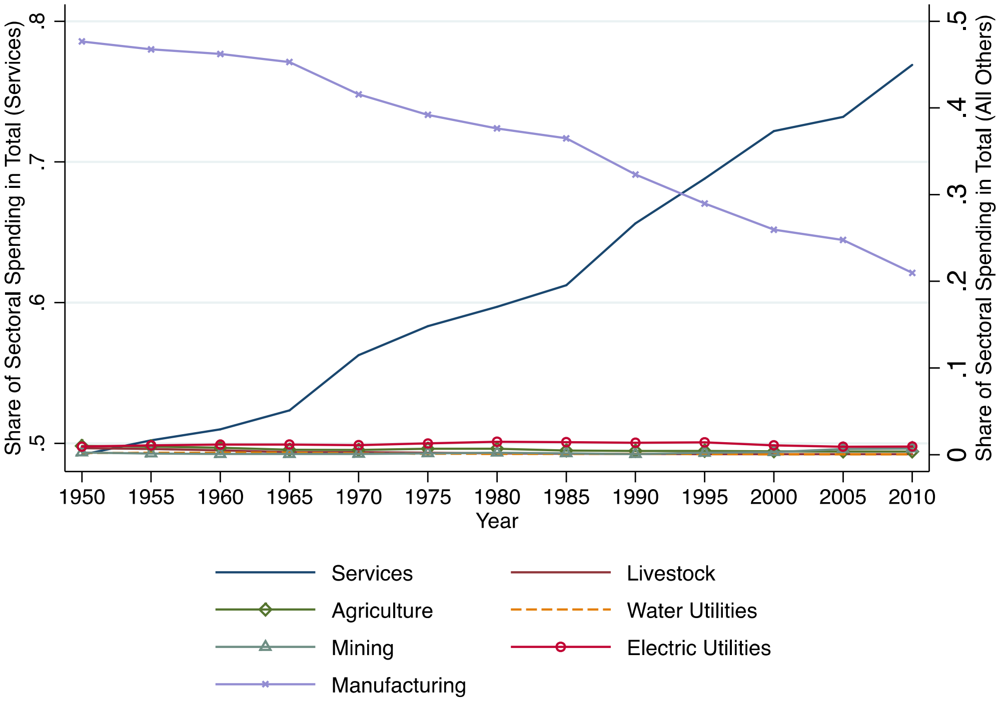
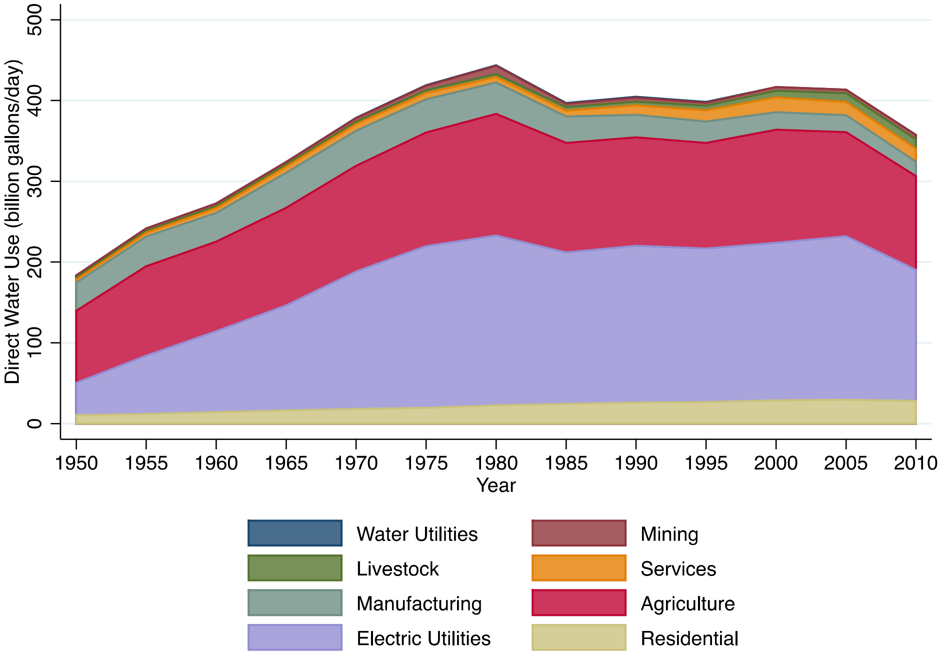
Figure 1 The Changing Structure of Final Demand Spending (as fractions of GDP)



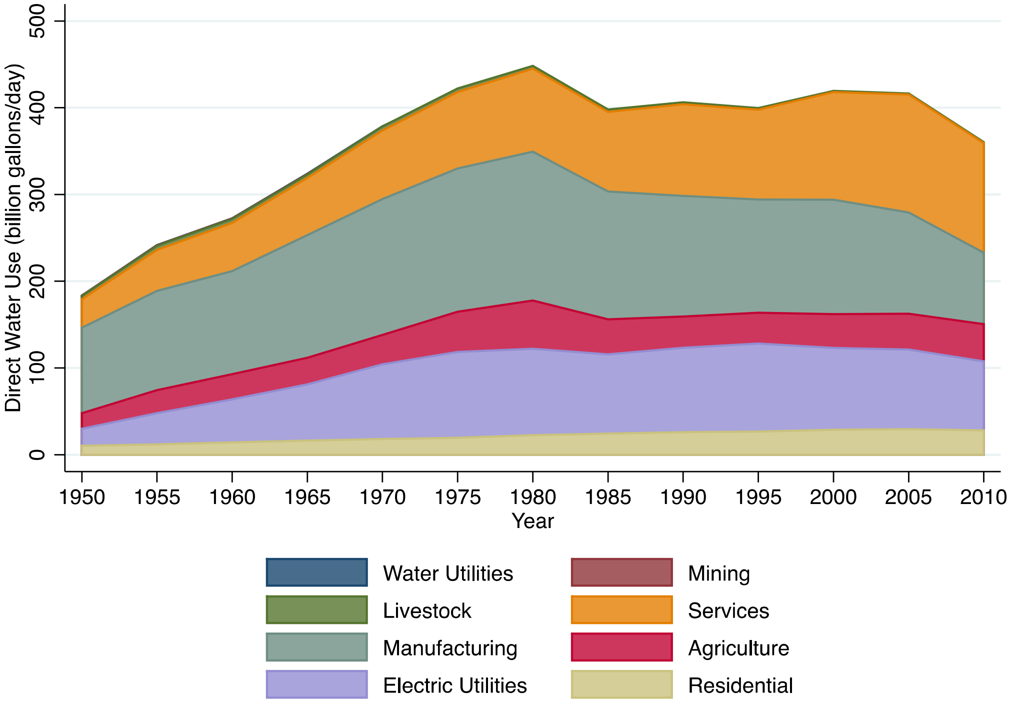
Notes: This figure shows each sector's share of total final demand spending.

Fig. 2 Direct Water Use



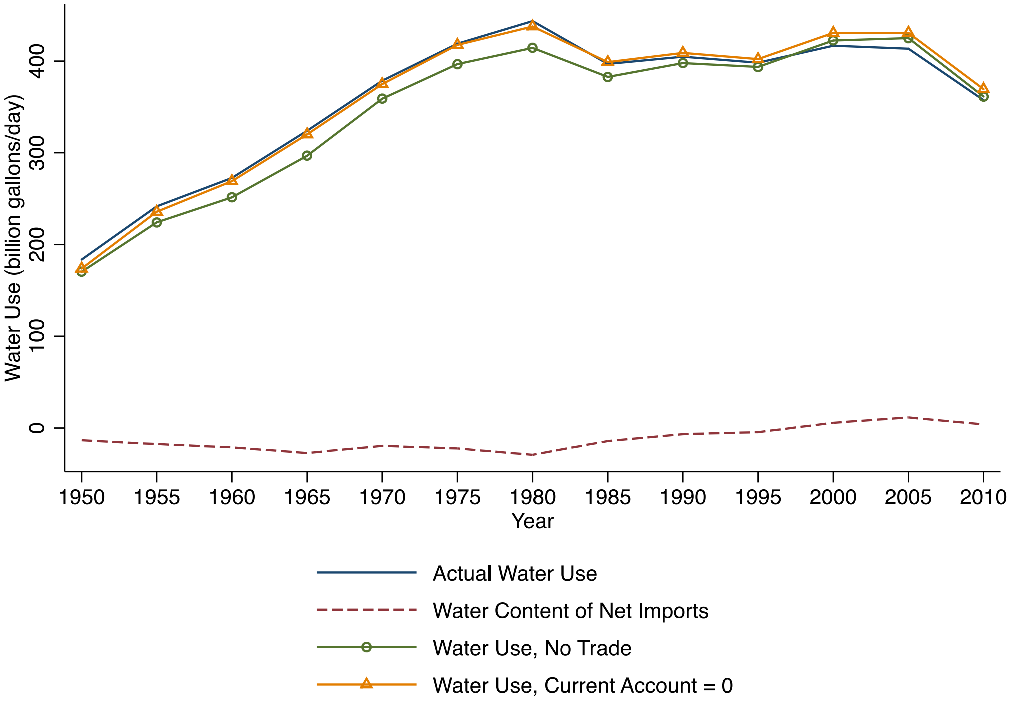
Notes: Data USGS, calculations authors.

Figure 3 Total (Direct and Indirect) Water Use



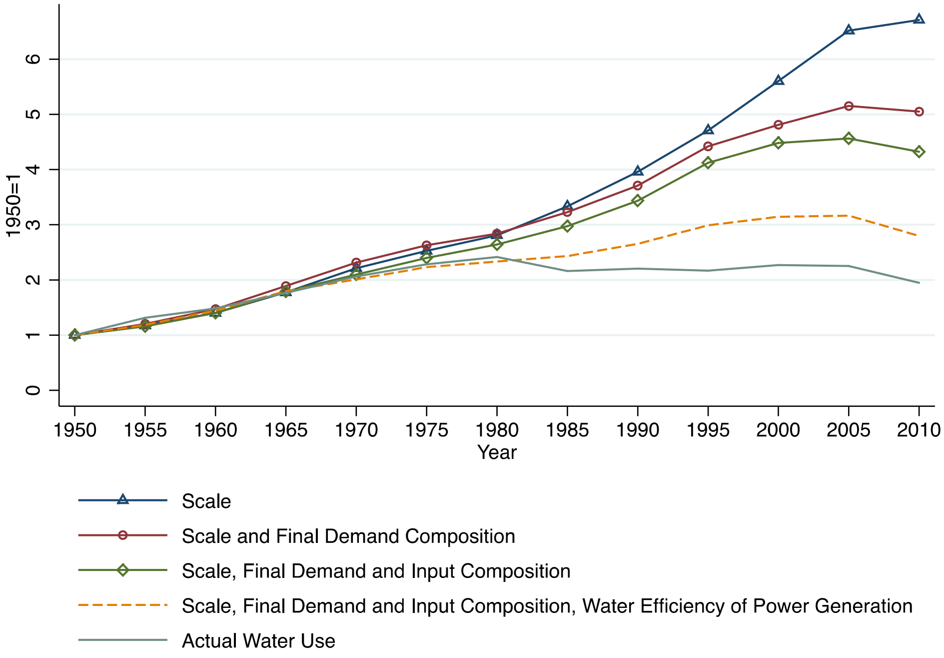
Notes: Data USGS, calculations authors.

Figure 4 Water Content of Net Imports and the Hypothetical Closed Economy



Notes: This figure shows the water content of net imports, actual water use, and hypothetical water use under the two trade scenarios (*Water use of Closed Economy = Actual water use + Water use of net imports*).

Figure 5 Decomposition with Double Deflation



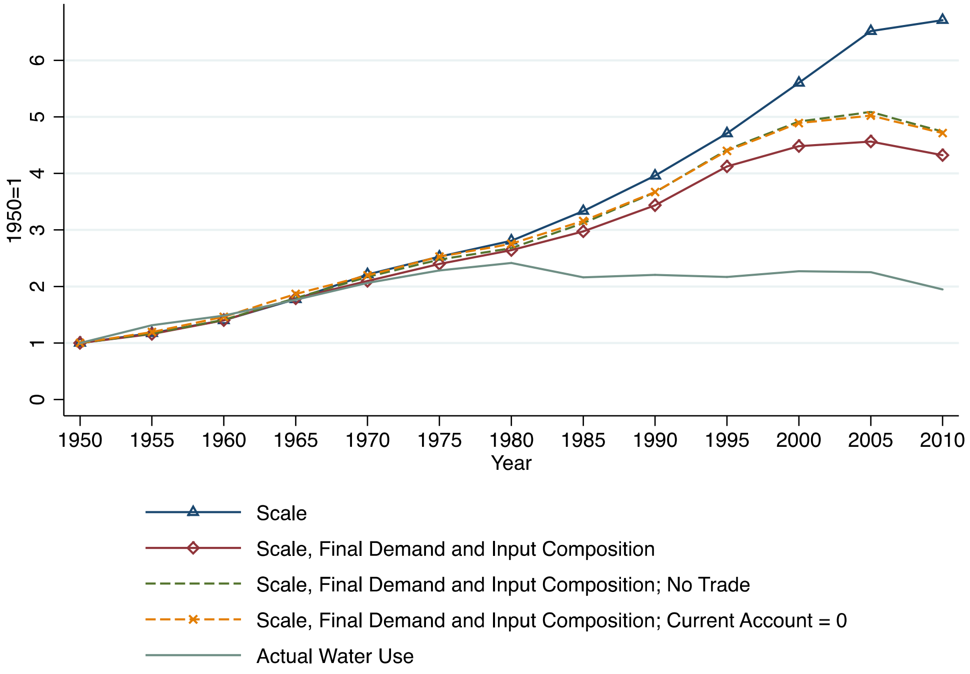
Notes: This figure shows the decomposition using the double deflation method. Actual water use allows all components – scale, final demand and input composition, power generation water efficiency, and technique – to change over time.

Increase in Water Use Since 1950, Allowing the following to change over time	
Scale	6.71
Scale and Final Demand Composition	5.05
Scale, Final Demand and Input Composition	4.32
Scale, Final Demand and Input Composition, and Water Efficiency of Power Generation Sector	2.80
Scale, Final Demand and Input Composition, Water Efficiency of Power Generation Sector, and Technique (Actual Water Use)	1.95

Fraction of Water Productivity Improvement Explained by:	
Final Demand Composition	0.35
Input Composition	0.15
Water Efficiency of Power Generation Sector	0.32
Technique	0.18

Notes: The table reports the size of the effects and the fraction of the overall water productivity improvement explained by each effect for the decomposition shown in the figure above.

Figure 6 Decomposition – Hypothetical Closed Economy



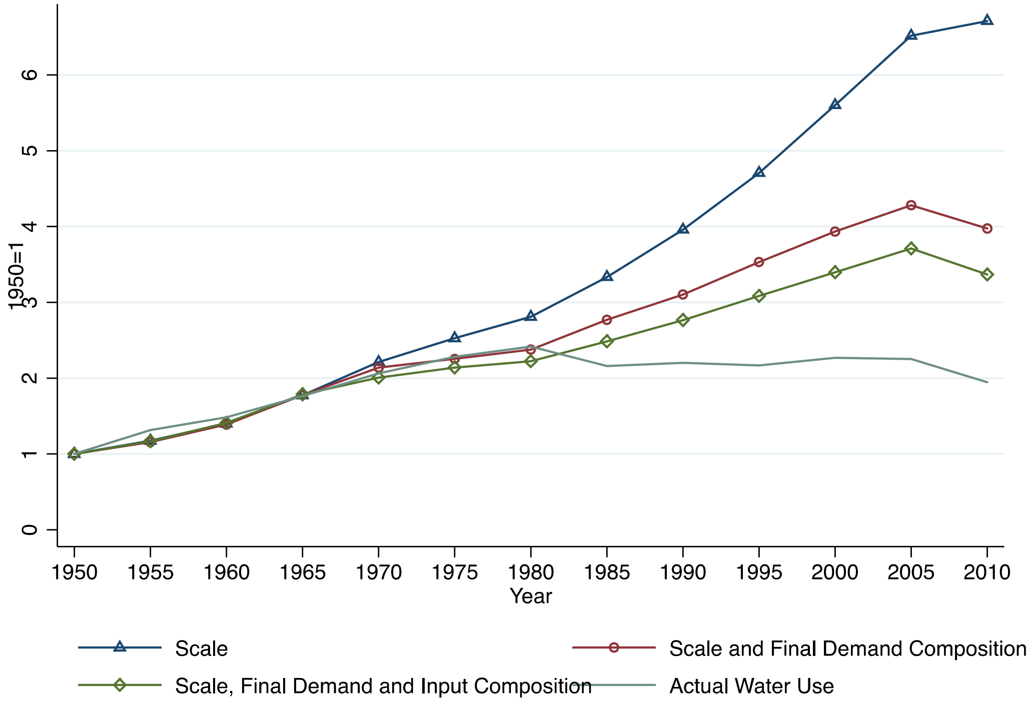
Notes: This figure shows the decomposition using the double deflation method. Actual water use allows all components – scale, final demand and input composition, power generation water efficiency, and technique – to change over time.

Increase in Water Use Since 1950, Allowing the following to change over time:	
Scale	6.71
Scale, Final Demand and Input Composition; No Trade	4.74
Scale, Final Demand and Input Composition; Current Account = 0	4.71
Scale, Final Demand and Input Composition	4.32
Scale, Final Demand and Input Composition, and Technique (Actual Water Use)	1.95

Fraction of Composition Effect Explained by:	
Trade	0.17
Current Account	0.16

Notes: The table reports the size of the effects and the fraction of the final demand and input composition effect explained by each trade scenario for the decomposition shown in the figure above.

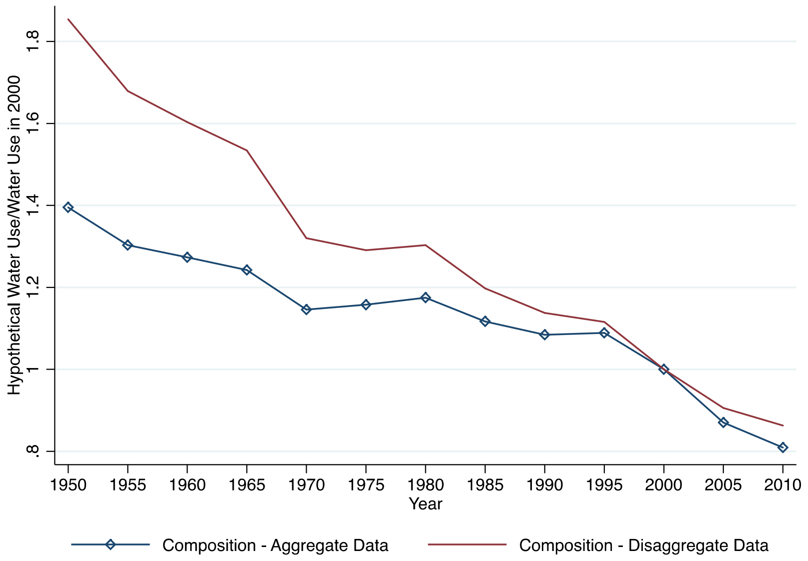
Figure 7 Decomposition with Services and Rest of the Economy



Notes: This figure shows the decomposition using the double deflation method, classifying all non-service sectors as the rest of the economy. Actual water use allows all components – scale, final demand and input composition, power generation water efficiency, and technique – to change over time.

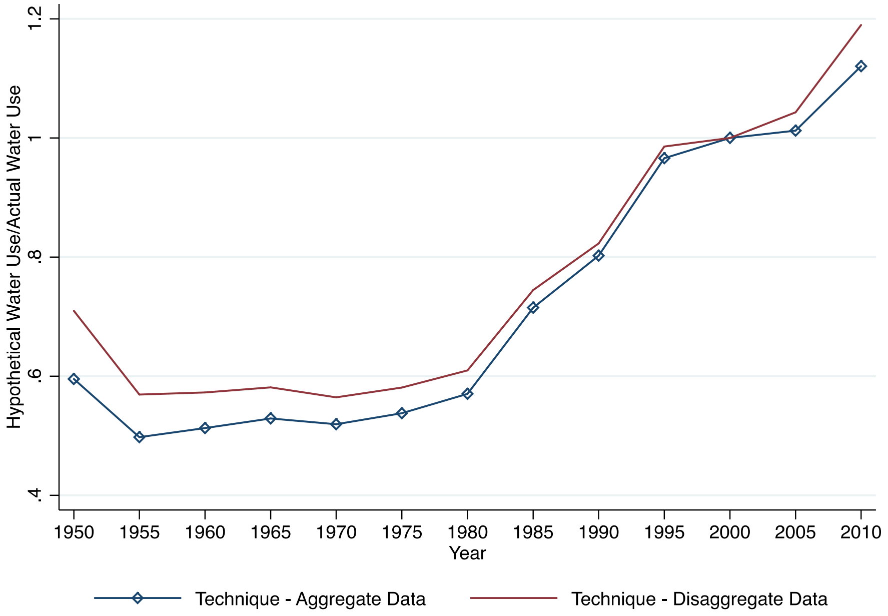
Figure 8 Disaggregation Exercise

8a Changing Composition toward less water-intensive products over time: Aggregate vs. Disaggregate Data.



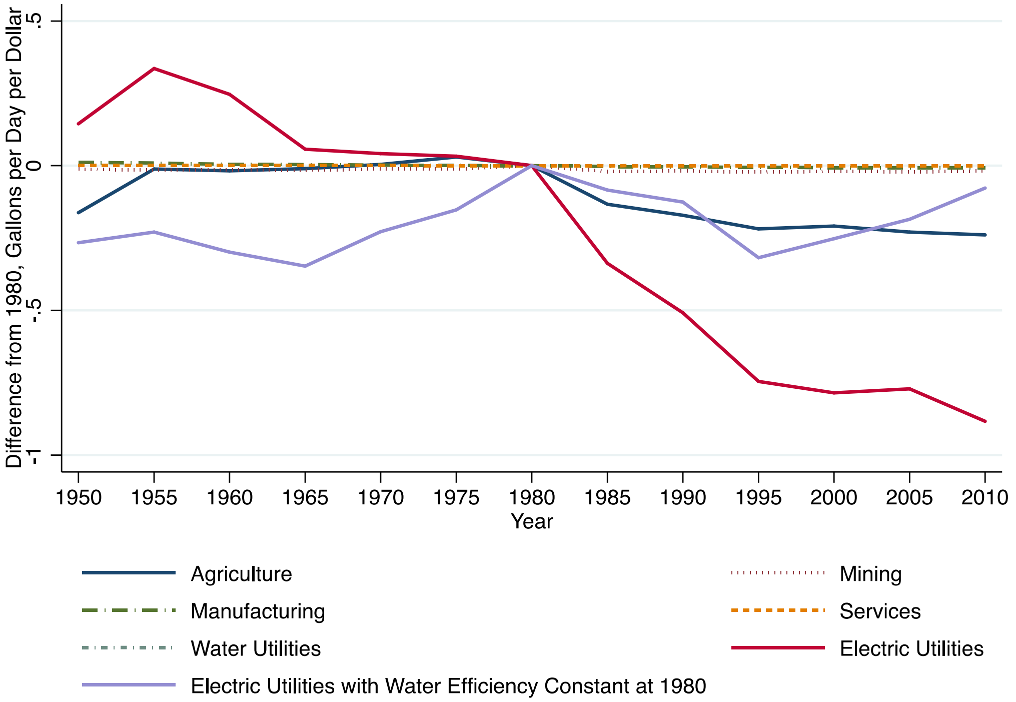
Notes: Own calculations, comparing what water use would have been producing 2000 GDP with 2000 technology but letting the composition (inputs and demand) change over time to actual water use in 2000.

8b Uneven Technological Progress



Notes: Own calculations, comparing what water use would have been producing actual GDP with 2000 technology to actual water use for disaggregate and aggregate data.

Figure 9 Water Intensity across sectors (relative to 1980)



Notes: This figure shows water use per dollar of gross output, **w**, relative to 1980.

Table 1 Measures of Sectoral Water Efficiency Relative to Services (2005)

	Direct Water/Gross Output	Direct Water/Value Added	Total Water/Final Demand
Agriculture	712.9	1,106.4	161.3
Manufacturing	3.5	5.8	4.5
Services	1.0	1.0	1.0

Notes: This table shows measures of water use per dollar of output measure relative to the services sector.

For Online Publication Appendix

In this appendix we discuss in detail some of the data issues.

Assigning publicly supplied water to the sectors:

We assign water use in the Public Supply category—water supplied by water utilities—to the sectors that use the water in the following way:

We first take a fraction of publicly supplied water to be residential use. We take this share to be 0.58, which is based on the relatively stable share of publicly supplied water use that goes to residential users that is given by the USGS for the years 1985-1995 and 2005.[51] We then allocate the remaining publicly supplied water to the sectors using the share of payments by each sector to water utilities from the input-output tables.

Estimating missing water data:

The USGS does not provide data for all sectors in all years. We use the following procedures to estimate the missing values:

Mining

Mining self-supplied water use is included in self-supplied industrial water use for the years 1950-1980. We remove it by taking the ratio of self-supplied to publicly supplied (by water utilities) mining water use for the years 1985-2005 and applying it to publicly supplied mining water use for the missing years.

Commercial (Services)

We use the same procedure as for mining above (using data for the years 1985-1995) to separate commercial self-supplied water use from industrial self-supplied water use for the years 1950-1980. We also use this method to estimate commercial water use for 2000-2005, years for which the USGS does not estimate commercial water use as part of any category.

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[51] The residential share of publicly supplied water is available at: http://water.usgs.gov/watuse/data/2005/index.html

Aquaculture

We remove self-supplied aquaculture water use from self-supplied industrial water use for the years 1950-1980 by applying the growth rate in aquaculture tonnage to aquaculture water use for the years with aquaculture water use data (1985-2005).[52]

Industrial (Manufacturing)

We subtract estimated mining, commercial, and aquaculture water use from self-supplied industrial water use for 1950-1980.

Estimating missing input-output data:

In some years, the input-output tables do not split utilities into water and electric utilities, and net exports are not split into imports and exports. We impute the missing values in the following ways:

Utilities

In 1947 and 1958, electric and water utilities are not split from utilities. We use the 1963 ratio to split the utilities category. The remaining component of utilities, gas utilities, is added back into services.

Specifically: Using the 1963 data, we compute the share of each cell that involves utilities (as producing or consuming sector) that is comprised by electric utilities or water utilities. We apply these shares to the corresponding utilities cells in the 1947 and 1958 input-output tables. To ensure that gross output balances by sector, we leave one row component of utilities empty (we use gas utilities), and compute the value as the difference between gross output computed going across rows and computed going down columns. The final cell (gas utilities x gas utilities) is calculated such that total gross output in the economy is the same as before the split was applied.

Trade

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[52] Aquaculture tonnage available at: http://www.fao.org/figis/servlet/SQServlet?file=/work/FIGIS/prod/webapps/figis/temp/hqp_8806629124250241745.xml&outtype=html

In 1958, 1963, and 1967, net exports are not divided into exports and imports.

To split net exports into exports and imports: We compute the growth rate of imports for each sector: Agriculture, Livestock, Mining, Manufacturing, and Services (Water and Electric Utilities assumed same rate of growth as Services). Goods import data are SITC Rev. 1 from the WITS database (World Integrated Trade Solution). Services import data are from the Balance of Payments from the BEA. We apply the growth rates back from 1972 to compute imports for 1958, 1963, and 1967. The trade data is not available prior to 1963, so we apply the 1963-1967 growth rate to compute imports in 1958. Exports are computed as the sum of the estimated import levels and net exports (from the input-output tables).

Concordance of Input-Output Tables Over Time

To match the sectors over time, we match the input-output sectors for the 1997 data with the NAICS categories and convert to SIC using a concordance from the BEA. We then convert the SIC categories to the 1992 input-output classification, also using a concordance from the BEA. The mapping from NAICS to the 1992 input-output sectors is not one-to-one. In cases where one NAICS category maps to many 1992 input-output sectors we distribute the value in the NAICS category according to the relative sizes of the 1992 input-output sectors within a NAICS category.

Appendix Tables and Figures

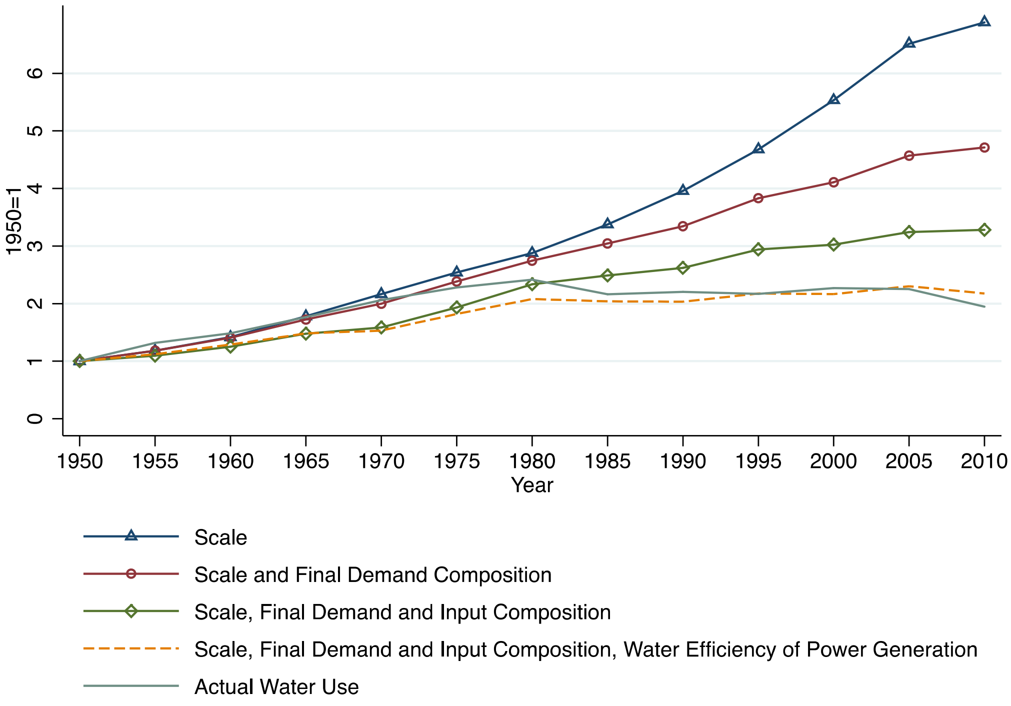
Table A1 Scaling Factor for the Aggregate Water Content of Trade

	Exports	Imports
1950	1.21	0.95
1955	1.44	0.89
1960	1.52	0.86
1965	1.49	0.88
1970	1.17	0.85
1975	1.01	0.80
1980	0.96	0.75
1985	1.01	0.78
1990	0.98	0.79
1995	0.94	0.75
2000	0.90	0.72

2005	0.93	0.79
2010	0.83	0.75

Notes: This table reports the scaling factors used to adjust the aggregate water content of exports and imports.

Figure A1 Decomposition with GDP Deflator



Notes: Decomposition using the GDP deflator. Actual water use allows all components – scale, final demand and input composition, power generation water efficiency, and technique – to change over time.

Increase in Water Use Since 1950, Allowing the following to change over time:	
Scale	6.89
Scale and Final Demand Composition	4.71
Scale, Final Demand and Input Composition	3.28
Scale, Final Demand and Input Composition, and Water Efficiency of Power Generation Sector	2.18
Scale, Final Demand and Input Composition, Water Efficiency of Power Generation Sector, and Technique (Actual Water Use)	1.95

Fraction of Water Productivity Improvement Explained by:	
Final Demand Composition	0.44
Input Composition	0.29
Water Efficiency of Power Generation Sector	0.22
Technique	0.05

Notes: The table reports the size of the effects and the fraction of the overall water productivity improvement explained by each effect for the decomposition shown in the figure above.