Environmental Science & Technology

pubs.acs.org/est Article

Assessing the Progress toward a Water-Efficient Economy in the United States from 1985 to 2015

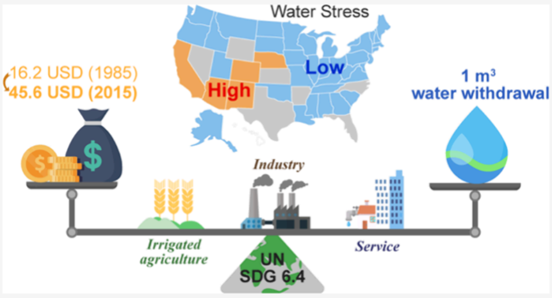
Yan Du, Ranran Wang,* and Julie B. Zimmerman*

Cite This: *Environ. Sci. Technol.* 2024, 58, 8696−8708

Read Online

ACCESS | Metrics & More | Article Recommendations | SI Supporting Information

ABSTRACT: United Nations Sustainable Development Goal 6 tackles the long-neglected economic dimension of water utilization by monitoring nations' water use efficiency (WUE). However, it is imperative to emphasize the need for consistent spatial-temporal subnational WUE estimates, rather than relying solely on recent national trends, which can obscure crucial water use concerns and improvement opportunities. Here, a time series analysis of national, state, and sectoral (e.g., industrial, service, and agriculture) WUE from 1980 to 2015 was developed by compiling the most comprehensive and disaggregated water and economic data from 3243 US counties and 50 US states. The US total WUE increased by 181% from 16.2 (1985) to 45.6 USD/m^3 (2015), driven by service sector WUE enhancements. The increased industry and service WUEs in most states were more strongly correlated with decreased per capita water withdrawal than with economic growth. Simultaneously, reductions in agriculture WUE were observed in 18 states potentially because of the complicated interaction of diverse factors specific to local communities. Expanding WUE gaps between affluent and less affluent states, and persisting WUE gaps between water-abundant andwater-scarce states highlight the need to advance policies to support under-resourced communities in effective water planning and water pricing for advancing equitable development.



KEYWORDS: *water use efficiency (WUE), water scarcity and water stress, sectoral water withdrawal, measuring and tracking Sustainable Development Goals (SDGs), spatial-temporal analysis on water productivity, equitable development*

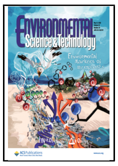
1. INTRODUCTION

Water is a fundamental resource that supports life in the biosphere[1,2] while sustaining economic prosperity and well-being.[3,4] Many communities are currently experiencing water scarcity, and this issue is likely to worsen. Factors like population and affluence growth and climate change will intensify the competition for water across domestic, industrial, and agricultural needs.[5−8] With growing emphasis on overall well-being per unit of utilized water resources, the United Nations (UN) adopted "change in water use efficiency (WUE) over time" as one indicator (i.e., Indicator 6.4.1) of progress toward Sustainable Development Goal (SDG) 6 (i.e., "Ensure availability and sustainable management of water and sanitation for all").[9] Measured in gross economic value added per volume of freshwater withdrawal (e.g., US dollars per cubic meter, USD/m^3), WUE is intended to support sustainable water use by tracking its contribution to economic productivity. Inverse of water intensity (i.e., the volume of water per unit of economic output) in some other studies,[10] higher WUEs are indicative of society withdrawing less water to achieve economic development.

Here, it is vital to clarify the differences among water use, withdrawal, and consumption, which are common terms in the field of water management, yet their definitions and usages are frequently inconsistent and confusing. Water withdrawal refers to the abstraction of water from natural sources, including surface water bodies and underground aquifers, with a significant portion typically returned to the environment, while water consumption is the evapotranspiration of withdrawn water essentially lost to the immediate water cycle and not available for reuse.[11] In UN's WUE metrics, water withdrawal is preferred over consumption primarily because it more accurately captures the impacts of productive activities in the industry and the service sectors, some with significant water requirements but low water consumption, on the availability of water resources.[9] The term "water use" in this paper broadly refers to the utilization of water for various purposes without further specifications.

Despite the heightening spotlight on WUEs, however, achieving optimal policy design, implementation, and assessment to support the goal of increasing WUE is impeded by insufficient water use data and incongruent approaches to determining the economic efficiency of water use. Through the

Received: November 5, 2023
Revised: April 18, 2024
Accepted: April 18, 2024
Published: May 8, 2024



https://doi.org/10.1021/acs.est.3c09219
Environ. Sci. Technol. 2024, 58, 8696−8708

UN-Water Integrated Monitoring Initiative for SDG 6, for the first time, the UN systematically quantified the global average WUE, which showed a gradual increase from 17.4 (2015) to 19.4 USD/m^3 (2019).[12] In its latest progress report on the change in WUE, the UN highlighted the significant intercountry variations, ranging from <1 USD/m^3 in a few Central and Southern Asian countries to >300 USD/m^3 in Switzerland and the United Kingdom in 2018.[13] These variations could largely be ascribed to the wide disparities in the purposes of the water withdrawn, as irrigation and cooling in powerplants are typically the predominant water users.[12] Yet, spatial-temporal dynamics and local phenomena that guide policymaking and governmental investments at subnational levels are hidden by the averaging of the global- and national-scale WUE assessments.[14] More in-depth intercountry analyses and further understanding of the temporal trends of national WUEs, however, are obstructed by some well-known yet commonly neglected water data challenges. Long and consistent time series information on water use has only been collected in a few countries, while inaccurate measurement and reporting are common in official water use statistics.[13,14]

Even within the United States, where water data are relatively comprehensive with decades of records, there exists significant opportunities for enhancements in data collection and reporting that would facilitate more precise associations of water use with specific activities at more disaggregated levels. This is critical for understanding changes in water use and water use efficiency in response to economic transformations, such as the rapid expansion of the electronics industry.[15] A prior study employed the System of Environmental-Economic Accounts for Water (SEEA-Water) to develop accounts for water use and productivity (defined similarly as WUE) in the US from 2000 to 2015, showing a 65−73% increase in the overall national water productivity.[16] It recognized and made efforts to partially address the issues of incomplete water data availability and the overly generalized water use categories in reporting. However, the accuracy and comprehensiveness of the water productivity estimates were still compromised by (1) not accounting for public water supply deliveries to individual sectors and commercial water use that yields considerable economic benefits in light of structural shifts toward services and technology and (2) misaligning active irrigation water use with total agricultural value added (i.e., not excluding the rainfed portion), resulting in an overestimation of total agricultural water productivity across the US. While decomposition analyses on changes in US water use employing an input-output approach exist,[11,16] further investigation into the impacts of key physical and socio-economic factors on changes in water use efficiencies at the subnational level within the US was not pursued, which undermines the relevance of the conveyed information in local, regional, and state policymaking as well as water management and investment decisions.

Other existing studies primarily focus on the agricultural water use productivity based on the unit weight of crop or livestock per volume of water used.[17,18] These efforts, thus, obfuscate economic outcomes from targeted water-saving irrigation technologies and best farm management practices. Knowledge regarding the efficiency of water use in other main economic activities remains notably limited and often lacks depth, despite industrial and service activities projected to be leading contributors to growth in global water demand.[19−21] As such, existing studies are limited in their ability to quantify the interdependence between water use and economic gains, thus impeding efforts to identify or predict the relative decoupling of water use and growth, a point from which further economic growth can be achieved without a corresponding increase in water use. Though a similar concept was applied to urban water use and population growth,[22] decoupling from an economic perspective is essential not only for managing water resources sustainably but also for mitigating water-related conflicts and promoting equitable development through minimizing negative social and economic consequences associated with water scarcity. Despite its vital role in sustainable development, the current literature provides insufficient guidance in creating more effective policies and programs to support this goal due to a lack of robust underlying spatial-temporal disaggregated data.

Building upon the existing work, a more holistic analysis that involves the consistent quantification of national and state total and disaggregated sectoral (i.e., irrigated agriculture, industry, and service) WUEs in the United States was conducted for the period 1985−2015, in an effort to (1) understand the current levels and the evolution of US WUEs, (2) decompose and examine potential contributors to WUE changes, (3) explore spatial-temporal patterns and trends in WUEs, particularly considering economic and water stress contexts, and (4) on a broader scale assess implications for sustainable water management and development under the UN SDG framework. This was achieved by rigorously estimating lacking water use data and linking water use accounts with detailed economic estimates of gross value added at the highest granularity level achievable, in alignment with the UN's WUE assessments. It was found that the WUE of US service activities is about 1800 times higher than agricultural activities and 100 times higher than industrial activities on average in 2015. Amid the overall increasing trends of state-level WUEs over time, there are increasing gaps in the economic productivity of total water use between affluent and less affluent states, as well as between water-abundant and water-stressed states. This observation is in stark contrast to the widely held hypothesis that WUE would be nudged higher as water scarcity prompts active and innovative political and technological solutions to alleviate water stress. To elucidate the underlying drivers for the WUE differences and changes observed from cross-sector and spatial-temporal analyses, decomposition and multivariate regression analyses were conducted to quantify the relationship between WUE and SDG-relevant key variables (e.g., economic growth, water withdrawal, and water scarcity) and of other contextual characteristics (e.g., temporal effects indicating technological improvements). The presence of vast disparities across regions in their natural conditions and productive norms that have shaped the current economic systems is a crucial context, and the pursuit of a high total WUE as the sole goal in water allocation is inappropriate. In fact, by providing a thorough background of US WUEs in the past and present, this study focuses on drawing the attention of national and state stakeholders to sectoral WUE improvements through a variety of means beyond direct reduction in water withdrawal, such as natural-based solutions and green infrastructure, and raises the consideration of equitable development given significant national differences in affluence and water resources. The results can enable decision-makers to make informed choices on water conservation and allocation, especially given growing natural and human pressures that adversely impact water quantity and quality with significant social equity implications.

2. MATERIALS AND METHODS

In this study, the definitions and methodologies formulated by the UN were strictly followed to assess WUEs within the US in order to ensure coherency and comparability with the global endeavors. The approach commenced with delineating the geographical scope of the study and critical features further characterizing subnational regions within the US in Section 2.1. Rigorous processing of water withdrawal and gross value added (GVA) data at disaggregated levels were conducted, with an exposition of primary assumptions and estimations detailed in Sections 2.2 and 2.3. Lastly, total and sectoral WUEs were calculated through equations in Section 2.4 that build upon the variables prepared in preceding sections.

2.1. State Groups. Except for the District of Columbia, all 50 states of the United States are within the scope of this study. States were classified based on the water stress level and GVA. Specifically, this study used the US Baseline Water Stress Levels by States (i.e., low, low-medium, medium-high, high, and extremely high, corresponding to a state's water demand consuming less than 10, 10−20, 20−40, 40−80, and more than 80% of its available water resources, respectively), evaluated by Water Resources Institute (WRI)'s Aqueduct 3.0 that translated hydrological data into holistic water risk scores through robust models,[23,24] and the average state GVA per capita during 1985−2015.[25] States with low and low-medium water stress were considered as "water-abundant", while those with high and extremely high water stress were "water-scarce". The "affluent" state group consists of the 10 states with the highest average GVA per capita during 1985−2015, while the "less affluent" state group consists of the 10 states with the lowest average GVA per capita during 1985−2015. Specific compositions of state groups are shown in SI, Table S1 and Figure S1.

2.2. Water Withdrawal Data for Different Sectoral Uses. The United States Geological Survey (USGS) provides one of the most comprehensive and consistent US water use data at national and local levels. The USGS county-level water use data during 1980−2015 were summed to the state level,[26] and the USGS water use categories were grouped into the three main water use sectors analyzed in this study: agriculture, industry, and service. In general, fresh and saline water withdrawn from surface water and groundwater sources for uses in irrigation, livestock, and aquaculture is classified as agricultural water use, that for uses in industry, mining, and thermoelectric power is classified as industrial water use, and that for commercial uses (e.g., hotels, restaurants, and office buildings) and domestic uses delivered through public suppliers is classified as service water use (see SI, Table S2 for primary USGS water use categories included in computations). The three major sources of water counted in each subsector are self-supplied withdrawals (except for domestic water use), public supply through water delivery systems, and system losses. The aggregated values of "public use and losses" reported were allocated to individual subsectors in proportion to their corresponding publicly supplied shares. Lacking further details from the USGS on the (relative) volumes of water used for public services (e.g., firefighting) and water lost in conveyance systems, the combined data, which were about 11−15% of the US national total water withdrawn for public supply before 2000, were treated as that for losses only. The inclusion of the potentially overestimated losses in all categories of water withdrawal values leads to relatively conservative estimates for water use efficiency.

The reported categories of water use estimates have changed two times since 1985, resulting in some data unavailability or inconsistency that may affect the estimated WUE values. For example, water withdrawals for fish hatcheries, which were included in commercial water withdrawal before 2000, are now classified as part of aquaculture. This change expanded the irrigated agriculture water use and could possibly be one source of the small declines in irrigated agriculture water use efficiencies observed in some states in 2000.

Additionally, neither self-supplied commercial water withdrawals nor public supply of water withdrawn for individual sectoral use other than domestic water use has been reported by the USGS since 1995. Thus, total water withdrawals for commercial uses, classified as part of service water use, were estimated for each state from 2000 onward assuming that (1) the share of self-supplied water withdrawal in total water withdrawal in the commercial subsector, (2) the share of "public use and losses" in total water withdrawal for public supply, and (3) the share of commercial public supply of water withdrawn in total water withdrawal for public supply all remained constant for years after 1995, the most recent year with a detailed set of water withdrawal data at the subsectoral level released by the USGS. These share values exhibited reasonable stability in the years preceding 2000, with ranges of 16−25, 16−18, and 17.5−21.5%, respectively, for each fraction. Although the assumption of their constancy in subsequent years may introduce deviations from real-world conditions, the commercial subsector represents a key component of service water use and should not be entirely excluded from WUE analyses owing to data unavailability. With both the historical ratios and water data in the corresponding years, the commercial water withdrawals, CO_t, was then estimated for every state in year t (t = 2000, 2005, 2010, or 2015):

$$\mathrm{CO}_t = (\mathrm{CO}_{\mathrm{PS},t} + \mathrm{CO}_{\mathrm{losses},t})/(1 - \mathrm{ratio}_{\frac{\mathrm{CO\_Wtotl}}{\mathrm{CO}_{1995}}}) \tag{1}$$

where $\mathrm{CO}_{\mathrm{PS},t}$ is the publicly supplied water withdrawn for commercial use in year t, $\mathrm{CO}_{\mathrm{losses},t}$ is the losses of water withdrawn for commercial use in year t, and $\mathrm{ratio}_{\frac{\mathrm{CO\_Wtotl}}{\mathrm{CO}_{1995}}}$ is the ratio of self-supplied (reported as CO_Wtotl) to total (compiled) water withdrawn for commercial use in 1995.

Using the same notations* (if applicable) as in the 2015 USGS county-level water use data set,[2]

$$\mathrm{CO}_{\mathrm{PS},t} = [\mathrm{PS\_Wtotl}_t \times (1 - \mathrm{ratio}_{\frac{\mathrm{losses}}{\mathrm{PS}},1995}) - \mathrm{DO\_PSDel}_t] \times \frac{\mathrm{ratio}_{\frac{\mathrm{CO\_PSDel}}{\mathrm{PS}},1995}}{1 - \frac{\mathrm{DO\_PSDel}_t}{\mathrm{PS\_Wtotl}_t}} \tag{2}$$

where $\mathrm{PS\_Wtotl}_t$ is the total water withdrawal for public supply reported in year t, $\mathrm{ratio}_{\frac{\mathrm{losses}}{\mathrm{PS}},1995}$ is the ratio of losses to total water withdrawal for public supply in 1995, $\mathrm{DO\_PSDel}_t$ is the water withdrawal for deliveries from public supply for domestic use reported in year t, and $\mathrm{ratio}_{\frac{\mathrm{CO\_PSDel}}{\mathrm{PS}},1995}$ is the ratio of water withdrawal for deliveries from public supply for commercial use to total water withdrawal for public supply in 1995.

Moreover,

$$\mathrm{CO}_{\mathrm{losses},t} = \mathrm{PS\_Wtotl}_t \times \mathrm{ratio}_{\frac{\mathrm{losses}}{\mathrm{PS}},1995} \times \frac{\mathrm{CO}_{\mathrm{PS},t}}{1 - \mathrm{ratio}_{\frac{\mathrm{losses}}{\mathrm{PS}},1995}} \tag{3}$$

*Small variations in the specific notation for the same attribute may exist across USGS data sets of different years.

A rule of thumb followed was that historical ratios were not used as substitutes for data with readily available values in the original USGS data sets of the corresponding years. While deviations from reported data were potentially minimized for better data consistency, negative or abnormally small (compared with other years) water withdrawal values were possible as a result of the adopted computation methods and need to be excluded from all relevant analyses. This was the case for Maryland and West Virginia in 2005 and for Wyoming in 2015; their service water withdrawals invalidated subsequent evaluations of service and total water use efficiency in 2005 and 2015, respectively, while the three states remain in their corresponding state groups for WUE trend analyses across years.

Lastly, the reported water use estimates in million gallons per day were converted to the annual water withdrawal volumes in cubic meters.

2.3. Real Gross Value-Added Data for Different Sectors.

GVA is the preferred economic metric for WUE quantifications in this study, as it measures the value added by each unit of water input in production processes at the sectoral level and excludes double counting of intermediate inputs. The US annual GVA by state, reported as the real gross domestic product in chained dollars, was obtained from the United States Bureau of Economic Analysis (US BEA) for 1980–2015.[25] The aggregate and industry-specific value added data for the years 1980, 1985, 1990, and 1995 were originally reported in chained dollars with a 1997 base year based on the Standard Industrial Classification (SIC) (1972 SIC used for years 1980 and 1985 and 1987 SIC used for years 1990 and 1995), while those for 2000, 2005, 2010, and 2015 were originally reported in chained dollars with a 2012 base year based on the 2012 North American Industry Classification System (NAICS). In order to stay consistent in industry classifications in the two systems, the economic statistics reported at the most disaggregated levels during 1980–1995 were regrouped using the NAICS-to-SIC or SIC-to-NAICS concordance tables established by the NAICS Association, so that they were all labeled by NAICS Codes (see Table S3 in the SI). By reconstituting industry categories and their subcategories with different levels of index disaggregation based on their definitions under individual standards, this study minimized potential systematic discrepancies in the calculations of GVA data for each of the three major sectors.

All economic data were converted to 2015 US dollars. Based on the NAICS Codes from the US BEA (for data after 1997) or the method stated above (for data before 1997), the Series IDs used to retrieve the corresponding annual average producer price indexes (PPIs) were identified from the online database of the US Bureau of Labor Statistics (US BLS). The PPI ratio (r_PPI) used to adjust the base year and convert an economic statistic into a value in 2015 dollars was calculated using the retrieved PPIs:

$$\mathrm{r\_PPI} = \mathrm{PPI}_{2015}/\mathrm{PPI}_{2012} \text{ or } \mathrm{PPI}_{2015}/\mathrm{PPI}_{1997} \tag{4}$$

Moreover, the gross value added (GVA) information in 2015 dollars is

$$\mathrm{GVA}_{2015\$} = \mathrm{r\_PPI} \times \mathrm{GVA}_{1997\$ \text{ or } 2012\$} \tag{5}$$

where $\mathrm{GVA}_{2015\$}$, $\mathrm{GVA}_{2012\$}$, and $\mathrm{GVA}_{1997\$}$ are the gross value added in 2015, 2012, and 1997 USD, respectively.

Due to the transition from the SIC system to the NAICS at the start of this century, the evaluation and publication of PPIs for many SIC industries and their subcategories were discontinued. In such cases, the discontinued Series ID in the SIC system was first matched with the currently used Series ID in the NAISC that best represented the previous industry (sub)category. Then, the PPI in year 1997 and the PPI in the last year reported (PPI_{t*}; if the annual average PPI was unavailable, the last monthly PPI reported was used instead) for the underlying industry (sub)category were found based on the discontinued Series ID. The implicit price deflators for the annual GVA database of US BEA provided deflator values in the last year that PPI was available for the discontinued category ($\mathrm{pDeflator}_{t*}$) and in year 2015, with the same base year (2012 in most cases). Therefore, the GVA data in 2015 dollars for discontinued industry (sub)categories in earlier years were calculated using the modified formula:

$$\mathrm{GVA}_{2015\$} = (\mathrm{PPI}_{t^*}/\mathrm{PPI}_{1997}) \times (\mathrm{PPI}_{2015}/\mathrm{pDeflator}_{t^*}) \times \mathrm{GVA}_{1997\$} \tag{6}$$

After converting the GVA data into 2015 US dollars, the GVA data for individual NAICS major industry categories for each studied year were aggregated into the three sectors for calculating total and sectoral water use efficiencies.

State population data for each relevant year were also obtained from the US BEA for all per capita water use and per capita GVA calculations.

2.4. Water Use Efficiency (WUE) Calculations.

The sectoral WUEs were calculated by eq 7:

$$\mathrm{WUE}\text{-}J_t = GVA_{2015\$,J,t}/V_{J,t} \tag{7}$$

where WUE-J_t is the water use efficiency for, $\mathrm{GVA}_{2015\$,J,t}$ is the annual gross value added of, and $V_{J,t}$ is the annual volume of water withdrawn for uses insector J (A = agriculture, I = industry, and S = service sector) in year t (in 2015 USD/m^3).

Consistent with the UN's definition of WUE-A, the water use efficiency for irrigated agriculture specifically, disaggregated rainfed and irrigated economic data of commodity crops in individual states were obtained from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS).[27] In practice, the aquaculture and the livestock subsectors accounted for a relatively small amount of total agriculture water withdrawn compared with irrigated products, withdrawing 2–9, 2–2.4, and 120–130 billion gallons of water per day, respectively, during 1985–2015;[11] thus, the total agriculture water withdrawn was reasonably approximated as the water withdrawn for irrigation. Because statistics of the value added of irrigated agriculture were only available since 1997 and every five years, the irrigated-to-total-sales-value ratios for each year were calculated, and linear interpolations were applied to fill in the data gaps for 2000 and years onward. The average value of the five available entries of this ratio in 1997–2017 was multiplied by the total agricultural value added to estimate the irrigated portion in 1985, 1990, and 1995. Through these processes, the study best matched the economic values generated purely by irrigation with the amount of water withdrawn for irrigation to comply with the UN's WUE method.

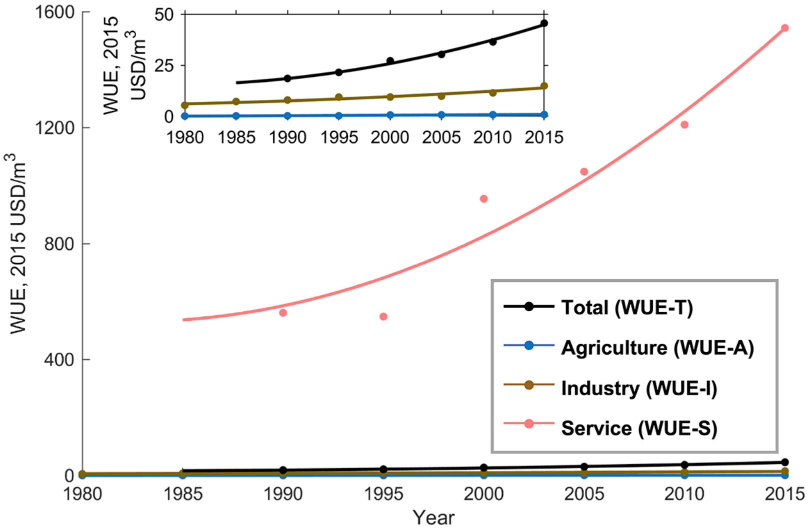


Figure 1. US national total, agriculture, industry, and service water use efficiencies (WUEs). Data points show the national total and sectoral WUEs every five years from 1980 to 2015. Lines are obtained by fitting a second-degree polynomial regression to each of the four sets of WUE estimates. The inset is zoomed in on the *y*-axis to highlight the national total, agriculture, and industry WUEs. All estimates of national WUE and changes are available in the SI, Table S5.

The total WUE (WUE-T) was calculated as the weighted sum of sectoral water use efficiencies:

$$\text{WUE-T}_t = \text{WUE-A}_t \times \text{P}_{\text{A},t} + \text{WUE-I}_t \times \text{P}_{\text{I},t} + \text{WUE-S}_t \times \text{P}_{\text{S},t} \tag{8}$$

where WUE-T_t is the total (i.e., all-sector) water use efficiency in year t (in 2015 USD/m^3); P_A, P_I, and P_S are the proportions of water withdrawn by agriculture, industry, and service sectors over the total water withdrawal, respectively, in year t.

Changes in variables are the differences in their end-year (i.e., 2015) and initial-year values (i.e., 1985), denoted by "Δ". The dominant driving force to the change in WUE between the change in water withdrawal and in gross value added (both normalized by population here, i.e., as ΔWW pc and ΔGVA pc) was determined by the relative magnitude of the two effects that show the amount of the WUE change attributable to the factors. The effects in USD/m^3, $\text{effect}_{\text{GVA}}$ and $\text{effect}_{\text{WW}}$, are computed by eqs 9 and 10:

$$\text{effect}_{\text{GVA}} = \frac{\Delta\text{GVA pc}}{\text{WW pc}_{1985}} + 0.5 \times \Delta\text{GVA} \times \left(\frac{1}{\text{WW pc}_{2015}} - \frac{1}{\text{WW pc}_{1985}}\right) \tag{9}$$

$$\text{effect}_{\text{WW}} = \text{GVA pc}_{1985} \times \left(\frac{1}{\text{WW pc}_{2015}} - \frac{1}{\text{WW pc}_{1985}}\right) + 0.5 \times \Delta\text{GVA pc} \times \left(\frac{1}{\text{WW pc}_{2015}} - \frac{1}{\text{WW pc}_{1985}}\right) \tag{10}$$

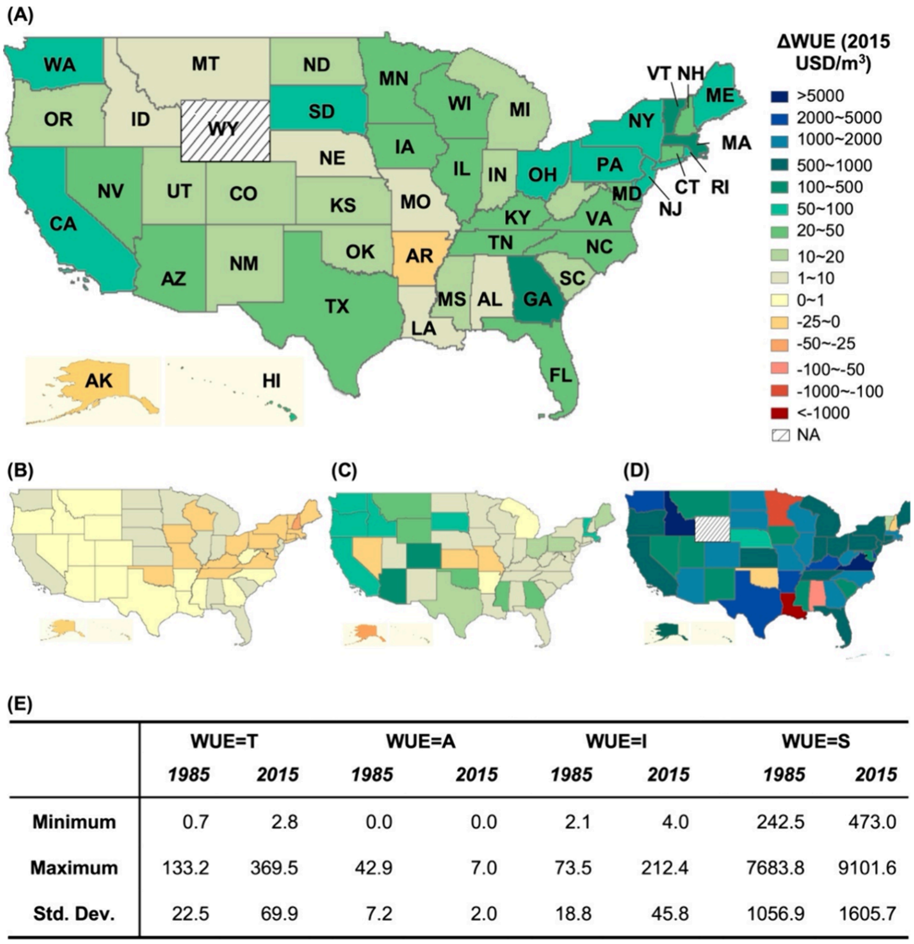
The subscripts denote the initial- or end-year values. The first terms delineate the isolated influence of a change in either factor solely (while the other is held constant) on the change in WUE, and the second terms provide an average measure of the overall effect of both factors' changes. The sum of $\text{effect}_{\text{GVA}}$ and $\text{effect}_{\text{WW}}$ balances the quantity of WUE change.

3. RESULTS AND DISCUSSION

The current and historical levels of US national and state WUEs are presented and discussed in Sections 3.1 and 3.2, with a focus on the observed spatial-temporal changes. A number of physical and socio-economic factors correlated with variations in WUEs are closely examined in Section 3.3. Section 3.4 extends the analysis to explore WUE trends displayed between state groups with differing wealth and water endowment, offering important insights into sustainable and equitable development on a broader scale. Finally, Section 3.5 compares the results obtained in this study with those reported by the UN and discusses deficiencies in UN's current method, highlighting opportunities for future enhancements in estimating this indicator.

3.1. Increasing US National Water Use Efficiencies.

The US national total and sectoral WUEs have improved significantly since 1985 (Figure 1). From 1985 to 2015, the national total WUE (WUE-T) increased by 181%, from 16.2 to 45.6 USD/m^3 (all WUE estimates from this study are in constant 2015 US dollars, see Section 2.3). The growth aligns with the tripling of the total economic productivity of water withdrawals from approximately 13 USD/m^3 in 1985 to more than 39 USD/m^3 in 2015 (both in 2020 US dollars) found in a comparable US-based study.[8] This improvement in WUE-T was achieved as national water withdrawal stabilized while national economic growth continued, indicating a relative decoupling of economic growth from water withdrawal. Despite slower economic growth over 2005−2015, the gradual decline in national water withdrawal in this same period led to an accelerated WUE-T improvement, implying a relatively distinct tendency of economic growth becoming less reliant on water use. Complementary quantifications on states' degrees of decoupling using the Tapio decoupling index method provided further evidence for this observation (see SI, Table S4(a) for state-level results and Table S4(b) for classification criteria in Tapio's method).[28] Due to scope constraints here, in-depth



	WUE=T		WUE=A		WUE=I		WUE=S	
	1985	*2015*	*1985*	*2015*	*1985*	*2015*	*1985*	*2015*
Minimum	0.7	2.8	0.0	0.0	2.1	4.0	242.5	473.0
Maximum	133.2	369.5	42.9	7.0	73.5	212.4	7683.8	9101.6
Std. Dev.	22.5	69.9	7.2	2.0	18.8	45.8	1056.9	1605.7

Figure 2. State-level total (A), agricultural (B), industrial (C), and service (D) WUE changes from 1985 to 2015 (in 2015 USD/m^3). (A–D) share the same color scale legend in (A). (E) Descriptive statistics showing cross-state WUE variations in 1985 and 2015. Wyoming was excluded from the total and service sectoral analyses involving 2015 data (see Section 2.2). All state-level WUE results are in SI, Table S6(a). Primary value inputs to WUE calculations using eq 4 in Materials and Methods, including state-level water withdrawals and gross value added, as well as state population data, are available in SI, Table S6(b).

assessment on the results and additional analyses on decoupling status necessitate a subsequent study.

Similarly, the WUE of each of the three main economic sectors (e.g., agriculture, industry, and service) also improved from 1985 to 2015, but the levels of the sectoral WUE differ significantly. The WUE in the agriculture sector (WUE-A), industry sector (WUE-I), and service sector (WUE-S) increased by 0.6 (295%), 7.7 (106%), and 965.4 USD/m^3 (167%), respectively. In 2015, the WUE-A, WUE-I, and WUE-S were estimated at 0.9, 14.9, and 1543.6 USD/m^3, respectively, making WUE-S 3 orders of magnitude larger than WUE-A and 2 orders of magnitude larger than WUE-I. Service not only has the highest WUE among the three main sectors but also experienced the most significant absolute increase in WUE. The amount of sectoral water use, however, displays an inverse relationship with the estimated sectoral WUE, with the service using the least amount of water (<4% of total water withdrawals in the study period) in the US. Moreover, agriculture WUE showed the most significant relative growth (in percentages) since 1985. However, in addition to agricultural innovations during this period, those gains may be attributed to a changed industry classification system adopted by the US BEA in 1997 and modifications in the water use classification by the USGS in 2000 (see Sections 2.2 and 2.3). Assumptions about unavailable data might have additional direct and indirect effects on the WUE estimates as elaborated in Materials and Methods.

3.2. Increasingly Heterogeneous WUEs across States.

Most states improved their WUE-Ts from 1985 to 2015, by as much as 350.7 USD/m^3 in Massachusetts. This trend is consistent with the decreased per capita total water withdrawals (WW pc) observed in 44 out of the 50 states over the same time period. Alaska and Arkansas are the only exceptions, where the gross value added of water use decreased by 22.1 and 1.0 USD per cubic meter of water withdrawn, respectively (Figure 2A). Similarly, most states improved their WUE-Is and WUE-Ss, by 200–600% (Figure 2C,D). Notably, the absolute changes of WUE-S were significant with big contrasts among states, from an increase of 8089.2 USD/m^3 in Virginia to a decrease of 6340.8 USD/m^3 in Louisiana over the 30-year period. Unlike these nationwide improvement patterns, in 2015, agriculture WUEs in 18 states were 7–97% lower than their 1985 levels (Figure 2B).

While the WUE-Ts, WUE-Is, and WUE-Ss grew nationwide, the heterogeneous total and sectoral WUEs among the 50 states in 1985 grew increasingly divergent by 2015 (Figure 2E). In 2015, the total WUEs across states differed by more than 100 times, ranging from 2.8 (Idaho) to 369.5 (Massachusetts) USD/m^3. For industry and service WUEs, the ranges were 4.0 (Nebraska) to 212.4 (Colorado) USD/m^3

https://doi.org/10.1021/acs.est.3c09219

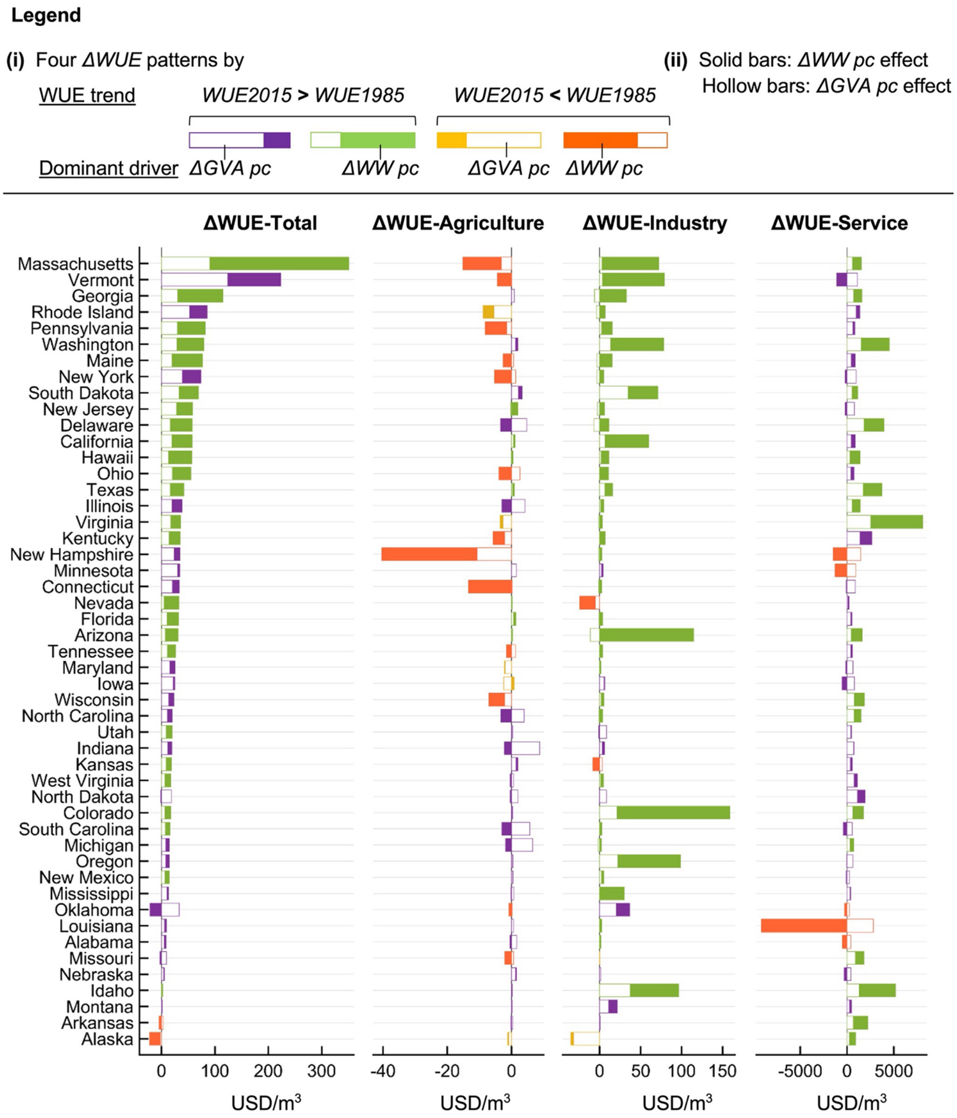


Figure 3. Two-factor decomposition of total, industrial, and service WUE changes between 1985 and 2015 at the state level. Changes in gross value added per person (ΔGVA pc) and changes in water withdrawal per person (ΔWW pc) represent the immediate drivers of the WUE changes. In the bar chart, the lengths of solid and hollow portions represent the quantified WUE change effects attributable to WW pc and GVA pc, respectively (see Materials and Methods). The four colors indicate the four possible combinations of WUE change, considering the direction of change (either improvement or degradation) and the primary driver (either ΔGVA pc or ΔWW pc): (1) increased WUE driven by increased GVA pc (purple bars), (2) increased WUE driven by decreased WW pc (green bars), (3) decreased WUE driven by decreased GVA pc (yellow bars), and (4) decreased WUE driven by increased WW pc (orange bars). Focusing on the driving factor, a predominantly hollow bar signifies that ΔGVA mainly drives the WUE change. Conversely, a bar with a more colored solid area suggests that ΔWW pc is the primary influence on the WUE change. Detailed results are available in SI, Table S7.

and 473.0 (Oklahoma) to 9101.6 (Virginia) USD/m^3, respectively, in 2015, representing differences of more than 50 times and 20 times, respectively.

3.3. Driving Forces to WUE Variations across States and Time. WUE changes from 1985 to 2015 (ΔWUE) are intuitively related to two immediate factors: ΔWW pc and ΔGVA pc, i.e., changes in water withdrawal per capita and changes in gross value added per capita, respectively, in the same period. A larger portion of ΔWUE across the states was found to better correlate with ΔWW pc than ΔGVA pc (Figure 3) (see Materials and Methods). The improvements of state-level WUEs, especially WUE-Ts and WUE-Is, were primarily related to WW pc declines from 1985 to 2015. This is consistent with the wide investment in and implementation of water-saving infrastructure and practices in industrial facilities.[29,30] The largest industrial water users in the US are thermoelectric power plants that extract both fresh and saline water (with freshwater constituting the majority) for cooling purposes, which accounted for 41% of national total water withdrawals in 2015. From 2010 to 2015, the cooling water withdrawal decreased by 18%, owing to a shift from once-through to recirculating cooling, enhanced aquatic life protections, and power plant closures.[11,31,32] Moreover, both GVA pc growths and WW pc declines played a crucial role in state-level WUE-S improvement. The service sector increasingly generates more economic values with no or proportionately less additional water requirements, as information technology grew to take an increasingly large share of the

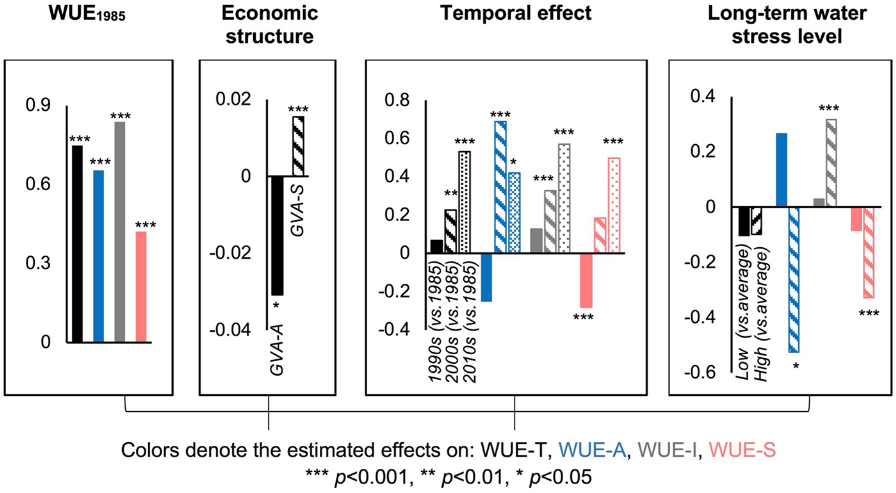


Figure 4. Effects of four potential stressors on total and sectoral WUEs estimated from state-level WUE results and variables observed every five years, 1985−2015. "WUE_{1985}" shows the sensitivities of state total and sectoral WUE growths to their WUE levels in 1985, i.e., the path dependency effect. "Economic structure" shows the sensitivities of WUE-T to a GVA shift from industry to agriculture or from industry to service. "Temporal effect" shows the variations in total and sectoral WUEs in specific decades compared to their values in 1985. "Long-term water stress level" captures differences in state average WUEs (i.e., during 1985−2015) if it faces high water stress or low water stress compared to average water stress (see Section 2.1). Complete statistical analysis results from the multivariate regression and the data inputs are available in SI, Table S8(a,b).

economy and has even provided critical support in water use reduction in all sectors through smart water systems, etc.[33,34]

As for the WUE-A, two-factor decompositions reveal that increases in agricultural ΔWW pc dominantly contribute to WUE-A decreases observed in the 18 states, while the WUE-A improvements are mainly linked to the growth in agriculture GVA pc. Notably, all water-scarce states improved their WUE-A from 1985 to 2015. Nearly all states with decreased WUE-A were water-abundant states, mostly in the Northeast, indicating that they were withdrawing more water to grow crops and/or raise livestock that did not bring a proportional increase in economic gains. Meanwhile, the practice of supplemental irrigation has gained prevalence as an adaptation strategy among farmers in the Northeastern US in response to the augmented drought risk from climate change-induced phenomena, such as higher temperatures, longer growing seasons, and prolonged dry periods.[35] The growing water withdrawal for supplemental irrigation to optimize yields and buffer effects of rainfall variability in this traditionally humid region may have led to the states' decreased WUE-As. To develop more informed agricultural policies, the results indicate the need for an in-depth investigation on factors contributing to changes in agricultural water use efficiency, including but not limited to irrigation technologies.

A multivariate regression analysis was conducted to systematically test and quantify how a number of physical and socio-economic stressors (i.e., independent variables) shaped the WUEs (i.e., dependent variables) across states over time (see SI, Table S8). With ΔGVA pc controlled, four driving forces were observed to have affected WUE by influencing ΔWW pc (Figure 4). First, the past matters. Variations in the state total and sectoral WUEs are positively associated with their historical WUE levels (i.e., WUEs in 1985), while such a path dependency is the least significant for service WUEs. Second, shifting economic structure affects WUE-T: a 1% shift from industry to agriculture in total GVA is associated with a 3% reduction of WUE-T ($p < 0.05$), whereas a 1% shift from industry to service in GVA is associated with a 2% increase of WUE-T ($p < 0.001$). Third, the temporal effects estimated for total and sectoral WUEs could be signs of nationwide technology-led WW decreases over time. By 2015, they contributed to a 53% increase in WUE-T ($p < 0.001$), a 42% increase in WUE-A ($p < 0.05$), a 57% increase in WUE-I ($p < 0.001$), and a 50% increase in WUE-S ($p < 0.001$) since 1985. The implementation of national standards mandating water efficiency in domestic appliances (e.g., faucets, toilets, and washers) may have been a primary contributor to WUE-S enhancements since the enactment of the Energy Policy Act of 1992.[36,37] Technology-led WUE improvement may be simultaneously present. Water-saving innovations, such as the microwave- and ultrasound-based processes in the water-intensive food processing industry, significantly reduced water requirements.[38] Rapidly advancing information technology promotes massive changes in the service sector, such as transitions to digital-based businesses and automation,[39] which, combined with emerging efforts in sustainable business practices,[40] can reduce water requirements.

Of note is that a state's long-term water endowment influences its WUEs. Except for the industry sector, states facing high water stress did not necessarily achieve higher WUE compared to states with abundant water resources. This observation is likely due to a multitude of factors, some of which are specific to local conditions (e.g., maladaptation of water-efficient technologies and inappropriate governance). One potential explanation for this could be that water-abundant states have the ability to distribute their water resources across various economic activities, including high-value-added productions. Moreover, on average, the water-scarce states had a 53% lower WUE-A and a 32% lower WUE-S than other states (Figure 4).This observation failed to support a widely held hypothesis that resource scarcity may incentivize greater efficiency.[41,42] This theory implies that states stressed by water scarcity would be more likely to proactively seek and succeed in implementing effective economic, social, and/or technological innovations aimed at enhancing water use efficiencies, compared to water-abundant

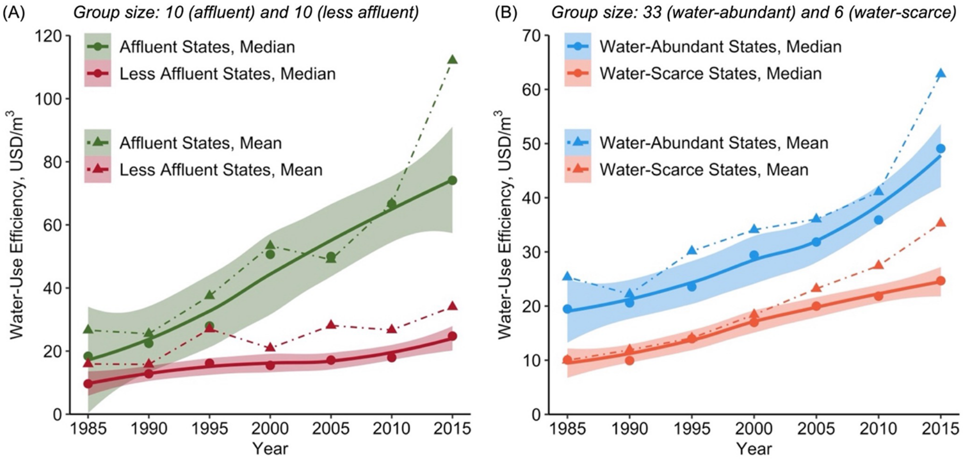


Figure 5. Trends of WUE-T changes for (A) affluent (green) and less affluent (red) states and for (B) water-abundant (blue) and water-scarce (orange) states during 1985−2015. Solid lines with colored confidence intervals (CI = 95%) in both graphs are smoothed regressions on the median and mean WUE-T estimates for each state group, using the locally weighted smoothing method. Note that the *y*-axes of (A) and (B) are not shown on the same scale, and the two pairs of state groups have different state counts. The WUE-T estimates for individual states in each group and the corresponding statistics are available in SI, Table S9.

states with less resource constraints. The relatively high WUE-Is of water-scarce states may partly be attributed to the fact that most of them are located in the West, a region known for its advanced manufacturing industries with knowledge-based operation modes.

3.4. Diverging Trends of WUEs between State Groups. This study revealed for the first time a diverging temporal trend, i.e., enlarging gaps of WUE-T between affluent and less affluent states (Figure 5A; see Section 2.1 for details on state groups). From 1985 to 2015, the affluent states used water increasingly more efficiently than the less affluent states (Figure 5A): their WUE-T difference expanded from less than 10 to nearly 90 USD/m^3 in 2015. Although the two groups started at a similar WUE-T level in 1985, the affluent states increased WUE-T to an average of 112 USD/m^3, while the less affluent states grew WUE-T slowly to a range of 20−30 USD/m^3 in 2015. In other words, for every cubic meter of water withdrawn in 2015, affluent states generated three times more economic value than less affluent states. If this trend extends into the future, less affluent states will face intensifying challenges compared to affluent states in decoupling economic growth from the reliance on water resources and building resilience to the growing risk of water scarcity due to climate change.

Changes in economic structures contributed to the diverging WUE-Ts between the affluent and less affluent states. Intuitively and confirmed by the regression analysis results, WUE-T increases when the economy shifts toward service and decreases when the economy shifts toward agriculture (see SI, Figure S2). Compared to the less affluent states, the affluent states experienced higher growth in the service sector and lower growth in agriculture sector according to the group means and medians. The observed WUE trends characterized by a widening gap between the affluent and less affluent states persistently emerge in repeated analyses with state groups of varying sizes (for instance, groups of 15 and 20 with top and bottom average per capita state incomes), while the magnitude of this gap becomes less pronounced, as expected, when a greater number of states are included. The detailed economic compositions of both state groups each year are shown in SI, Table S9.

Although there is a seemingly diverging WUE-T between water-abundant states and water-scarce states during 1985−2015 (Figure 5B), the evidence is mixed. With effect sizes (Vargha and Delaney *A* measure) ranging between 0.67 and 0.88, the one-tailed unpaired Mann−Whitney *U* tests on the state groups' WUE-T data found that affluent states achieved significantly (CI = 99%) larger WUE-Ts than less affluent states starting from 2010, which indicated an enlarging gap emerging in the most recent decade (see SI, Table S10). The results of the same tests on state groups with different water stress did not support a comparatively strong observation of expanding divergence. Nonetheless, the median WUE-T of water-abundant states was about 2−3 times that of water-scarce states over the entire study period (see SI, Table S9), which suggests that water-scarce states have not made more efficient use of their water than the water-abundant states. This finding shows limited evidence for the common perception that water stress would drive up WUEs through effective implementation of a series of measures designed to reduce water and/or raise production values, such as technological innovations, regulation promulgation, and public education. Similar observation (i.e., spatial mismatch between water stress and WUE) was made in the northwestern region of China, where water scarcity did not appear to prompt efficiency.[43] This may stem from the long-term, complex interplay of diverse political, socio-economic, and technological factors that hold significant pertinence to local contexts, including but not limited to weak political will, ineffective enforcement of water regulations, misaligned incentives for stakeholders bearing the costs (e.g., farmers may not see the direct benefits of investing in efficient irrigation if the cost savings or yield improvements are marginal or long-term), inadequate public awareness of the benefits, and issues on the access to, as well as the suitability and the adaptation of, certain water-saving technologies to local conditions.[42,44] As previously analyzed, a state's economic structure assumes a critical role in its water use dynamics. For example, despite its water scarcity, Nebraska had the largest irrigated agricultural land (i.e., 8.6 million acres accounting for 14.8% of all US irrigated cropland in 2017) among all states[45] and the third lowest total WUE (i.e., 9.3 USD/m^3) in 2015. Given that irrigated agriculture represents a major demand on water resources, Nebraska may face substantial challenges in elevating its WUE-A and WUE-T, if the current economic structure persists and if traditional, water-intensive irrigation practices dominate. An in-depth understanding of the intricate interconnections among all factors is required for addressing the low WUEs in water-stressed regions through locally targeted water management strategies.

3.5. Comparing with the UN's WUE Estimation: Alignment and Discrepancies. There are some differences between the WUE values in this study and those reported in the UN's 2018 Progress Report for the same year 2015.[46] The 2015 US national WUE-T reported by the UN was 33.4 USD/m^3, versus 45.6 USD/m^3 reported here. Significant differences exist between the 2015 agriculture and service WUEs reported by the UN (0.4 and 206.1 USD/m^3, respectively) and estimated in this study (0.86 and 1543.55 USD/m^3, respectively), while the WUE-I here (14.9 USD/m^3) is close to the UN value (13.5 USD/m^3).[46] Such differences in WUE estimates may come from inconsistencies in (1) the sources of raw economic and water data (the UN included data from international institutions, such as the World Bank, while data used for this study were gathered from US government sources only), (2) the granularity of raw data (for better accuracy, this study employed a bottom-up approach, summing up the state-level economic data and the county-level water abstraction data to obtain the national WUE values), and (3) the accounting methods for raw data (sectors were classified and the economic data were processed at further disaggregated levels based on the NAICS, instead of the International Standard Industrial Classifications of All Economic Activities Rev. Four adopted by the UN).[46] Additionally, the UN's aggregated national figures could mask underlying heterogeneities apparent at regional levels, and an in-depth understanding of the UN's data practices is needed to further clarify estimation discrepancies, particularly in service WUEs.

While this study adopted the UN's method for subnational WUE quantifications, it should be noted that the current SDG indicator system has received criticisms regarding its capacity and efficacy in accurately reflecting progress toward the aspirations captured in the SDG targets. For indicator 6.4.1, two treatments warrant further scrutiny in particular: the exclusion of rainfed agriculture from the monitoring process and the adoption of water withdrawal instead of water consumption as water use accounts.[47] In fact, the relatively narrow definition of "water use" by the UN makes these two issues interrelated. Due to a lack of consistent time series of US consumptive water use data at subnational levels over the time span in this study, water consumption-based WUEs were not quantified and analyzed. However, comparisons between WUEs calculated using the two different water use categories could add substantial value to the comprehensive understanding of changes in water scarcity risk over time, as water consumption measures may better reflect the human impact on water availability and the real effectiveness of policies and programs on water scarcity alleviation, especially when WUEs are evaluated by water basin, water source, etc.[47,48] In addition, monitoring a more inclusive agricultural WUE is essential for climate change adaptation, which helps identify regions most vulnerable to changes in precipitation patterns and supports the development of adaptive strategies to maintain agricultural productivity.

The WUEs analyzed in this study depart from traditional water productivity metrics commonly used by stakeholders and policymakers to assess water use efficiencies. In agricultural practices, for instance, "irrigation water withdrawal per unit area" and "ratio of water available for crops to total water withdrawal" conventionally gauge the physical productivity of irrigation water use.[41] Recently, thanks to the SDG 6, scientific literature and international reports have begun to adopt value-added-based WUE metrics, focusing on the economic aspects of water use that were previously overlooked. It is crucial to bridge the physical and economic metrics to effectively leverage and communicate their complementary insights.

3.6. Implications. This study underscores the importance of water use efficiency (WUE) as one measure of effective allocation of limited water resources. The results show that although the total US WUE has at least doubled in the past 30 years and is continuing to improve, significant and increasing differences exist between states and sectors, raising equity concerns and opportunities to transfer best practices from one context to another. Efficient water use may be more critical for less affluent states, yet their WUE-Ts have fallen further behind. Efficient water use is also essential for water-scarce states, yet they had lower WUE-Ts on average than water-abundant states over the three-decade analysis period. This analysis identifies the structure of state-level economies as a potential driver of the diverging and inequitable trends, highlighting the opportunity to evolve current water and economic policies within states with low WUEs. Moreover, the patterns and trends in the contributions of WUE changes, attributed to different physical and socio-economic stressors in the US, may provide insights into the dynamics of future WUEs in and across other countries.

Furthermore, this study improved quantification of WUEs over time, using more detailed and better-documented water use and economic data sets than previous studies. Therefore, the resultant spatial-temporal patterns and underlying drivers are more robust, reliable, and specific than previous reports, with the WUEs and changes consistently quantified for the largest domestic sample set (i.e., all 50 US states) over the most extended period (i.e., three decades). Moreover, the calculation framework adopted in this study avoids the water use data imputations employed in earlier studies with almost complete state coverage and few gaps in the time series. However, this work also highlights some limitations in the current SDG indicator system, particularly regarding the exclusion of rainfed agriculture, the adoption of water withdrawal instead of water consumption for water use accounts, and the implications of market failures on the full valuation of water.

Global subnational WUE monitoring enables consistent comparisons and refined benchmarking, bolstering local water use resilience and sustainability efforts. The diverging trends of WUE between affluent and less affluent states raise concerns about growing disparity gaps. If this trend goes global, developing nations with limited capacity to invest in water-efficient development could become increasingly vulnerable to natural and developmental adversities compared to developed economies. Less affluent countries, despite water stress struggles, may continue to allocate water for comparatively water-intensive, low-value-added productions that constrain sustainable growth. Furthermore, they may face intensified water pressure as the affluent countries and states can effectively "virtually" buy and consume water from less affluent communities through imports of goods and service.[49]

The research highlights the importance of addressing current limitations in SDG 6-WUE methodologies and exploring the negative relationship between water stress levels and agricultural WUEs in future studies. A systematic investigation of the physical and socio-economic stressors driving WUE changes and their implications at a global scale is strongly indicated. This is vital for advancing technological improvements that enhance water use efficiency in industries. The anticipated escalation in industrial water demand, projected to dominate the global surge in water withdrawal by 20−30% by 2050 due to the industrialization of emerging economies, underscores the urgency and necessity of this research.[20,50−52] Such a comprehensive assessment, while accounting for the diverse productive, social, and natural contexts in different countries and subnational regions concerning water resources, shall also encompass the intricate interplay of environmental, social, and economic factors within a holistic, systems-based framework.

■ ASSOCIATED CONTENT

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the paper, its Supporting Information file, and the following publicly available data sets: The baseline water stress levels of US states are available from the World Resources Institute (WRI)'s Aqueduct 3.0 at https://www.wri.org/data/aqueduct-global-maps-30-data and a figure produced by the WRI in a relevant commentary in 2019, which is now in SI, Figure S3. The US county-level estimated use of water data for every five years during 1980−2015 is available from the US Geological Survey at https://water.usgs.gov/watuse/data/. The state-level real annual gross value added in chained dollars from the US Bureau of Economic Analysis accessed in 2020 has been superseded and is now archived at https://apps.bea.gov/regional/histdata/. The USDA NASS provides the commodity crop sales values in the database at https://quickstats.nass.usda.gov/. The SIC to NAICS concordance and the NAICS to SIC concordance that help match the industrial categories are available from the NAICS Association at https://www.naics.com/sic-naics-crosswalk-search-results/. Lists of codes for industry (sub)-categories in both the Current Series and the Discontinued Series (SIC basis) that assist in finding the PPIs across years are available from the US Bureau of Labor Statistics (US BLS) at https://www.bls.gov/help/hlpforma.htm#PC. The One-screen Data Retrieval Tool developed by US BLS at https://www.bls.gov/data/ serves the same purpose. The PPIs were retrieved using the Series Report Data Retrieval Tool of the US BLS at https://data.bls.gov/cgi-bin/srgate and from the US BEA at https://apps.bea.gov/iTable/?reqid=19&step=3&isuri=1&1921=survey&1903=13.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c09219.

> Detailed US national and state water use, economic growth, water use efficiency data for spatial-temporal analyses, statistical analyses, and figure productions, including intermediate data for water use efficiency quantification and statistical parameters, as well as additional information on state groupings and industry classifications (XLSX)

■ AUTHOR INFORMATION

Corresponding Authors

Ranran Wang − *Institute of Environmental Sciences (CML), Leiden University, Leiden 2333 CC, The Netherlands;* orcid.org/0000-0001-7786-3179; Phone: +31 71 527 4924; Email: r.wang@cml.leidenuniv.nl

Julie B. Zimmerman − *Department of Chemical and Environmental Engineering, Yale University, New Haven, Connecticut 06511, United States; School of the Environment, Yale University, New Haven, Connecticut 06511, United States;* orcid.org/0000-0002-5392-312X; Phone: +1 (203) 432 9703; Email: julie.zimmerman@yale.edu

Author

Yan Du − *Department of Chemical and Environmental Engineering, Yale University, New Haven, Connecticut 06511, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.3c09219

Author Contributions

Y.D., R.W., and J.B.Z. conceived the original idea of the presented study and planned the methodology. Y.D. compiled and processed data and performed computations. R.W. verified the analytical methods. Y.D. analyzed the results, and R.W. and J.B.Z. aided in interpreting them. Y.D. prepared the draft manuscript. R.W. and J.B.Z. supervised the whole study, provided critical feedback, and helped shape the research, analysis, and the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Gleick, P. H.; Palaniappan, M. Peak water limits to freshwater withdrawal and use. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 11155−11162.

(2) Dieter, C. A.; Linsey, K. S.; Caldwell, R. R.; Harris, M. A.; Ivahnenko, T. I.; Lovelace, J. K.; Maupin, M. A.; Barber, N. L.*Estimated Use of Water in the United States County-Level Data for 2015 (ver. 2.0, June 2018)*: U.S. Geological Survey data release. (2018). DOI: 10.5066/F7TB15V5.

(3) Abbott, B. W.; Bishop, K.; Zarnetske, J. P.; Minaudo, C.; Chapin, F. S., III; Krause, S.; Hannah, D. M.; Conner, L.; Ellison, D.; Godsey, S. E.; Plont, S.; Marçais, J.; Kolbe, T.; Huebner, A.; Frei, R. J.; Hampton, T.; Gu, S.; Buhman, M.; Sayedi, S. S.; Ursache, O.; Chapin, M.; Henderson, K. D.; Pinay, G.; et al. Human domination of the global water cycle absent from depictions and perceptions. *Nat. Geosci.* **2019**, *12*, 533−540.

(4) White, I.; Howe, J. The mismanagement of surface water. *Appl. Geogr* **2004**, *24*, 261−280.

(5) Poff, N. L.; Brown, C. M.; Grantham, T. E.; Matthews, J. H.; Palmer, M. A.; Spence, C. M.; Wilby, R. L.; Haasnoot, M.; Mendoza, G. F.; Dominique, K. C.; Baeza, A. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Clim Change* **2016**, *6*, 25−34.

(6) Schewe, J.; Heinke, J.; Gerten, D.; Haddeland, I.; Arnell, N. W.; Clark, D. B.; Dankers, R.; Eisner, S.; Fekete, B. M.; Colón-González, F. J.; Gosling, S. N.; Kim, H.; Liu, X.; Masaki, Y.; Portmann, F. T.; Satoh, Y.; Stacke, T.; Tang, Q.; Wada, Y.; Wisser, D.; Albrecht, T.; Frieler, K.; Piontek, F.; Warszawski, L.; Kabat, P. Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci. U.S.A.* **2014**, *111*, 3245−3250.

(7) Wiedmann, T.; Lenzen, M.; Keyßer, L. T.; Steinberger, J. K. Scientists' warning on affluence. *Nat. Commun.* **2020**, *11*, 3107.

(8) Gleick, P. H.; Cooley, H. Freshwater Scarcity. *Annu. Rev. Env Resour* **2021**, *46*, 319−348.

(9) UN. Sustainable Development Goals - Goal 6: Ensure access to water and sanitation for all. https://www.un.org/sustainabledevelopment/water-and-sanitation (2015).

(10) Debaere, P.; Kurzendoerfer, A. Decomposing US Water Withdrawal since 1950. *J. Assoc Environ. Resour Econ* **2017**, *4*, 155−96.

(11) Dieter, C. A.; Maupin, M. A.; Caldwell, R. R.; Harris, M. A.; Ivahnenko, T. I.; Lovelace, J. K.; Barber, N. L.; Linsey, K. S.*Estimated use of water in the United States in 2015*: U.S. Geological Survey Circular. (**2018**). DOI: 10.3133/cir1441.

(12) UN Department of Economic and Social Affairs. *The Sustainable Development Goals Report 2022*. (UN Department of Economic and Social Affairs: New York, USA, 2022). https://unstats.un.org/sdgs/report/2022/.

(13) UN Food and Agriculture Organization & UN Water. *Progress on change in water-use efficiency. Global status and acceleration needs for SDG indicator 6.4.1*. (UN Food and Agriculture Organization: Rome, Italy, 2021). DOI: 10.4060/cb6413en.

(14) Gleick, P. H. Water use. *Annu. Rev. Env Resour* **2003**, *28*, 275−314.

(15) Bagstad, K. J.; Ancona, Z. H.; Hass, J.; Glynn, P. D.; Wentland, S.; Vardon, M.; Fay, J. Integrating physical and economic data into experimental water accounts for the United States: Lessons and opportunities. *Ecosyst. Serv.* **2020**, *45*, No. 101182.

(16) Avelino, A F. T.; Dall'erba, S. What Factors Drive the Changes in Water Withdrawals in the U.S. Agriculture and Food Manufacturing Industries between 1995 and 2010? *Environ. Sci. Technol.* **2020**, *54*, 10421−10434.

(17) Abedinpour, M.; Sarangi, A.; Rajput, T. B. S.; Singh, M.; Pathak, H.; Ahmad, T. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agric. Water Manag.* **2012**, *110*, 55−66.

(18) Aleixandre-Tudó, J. L.; Castelló-Cogollos, L.; Aleixandre, J. L.; Aleixandre-Benavent, R. Emerging topics in scientific research on global water-use efficiency. *J. Agric. Sci.* **2019**, *157*, 480−492.

(19) Boretti, A.; Rosa, L. Reassessing the projections of the World Water Development Report. *npj CleanWater* **2019**, *2*, 15.

(20) OECD. *OECD Environmental Outlook to 2050: The Consequences of Inaction*. (OECD Publishing: Paris, France, 2012). DOI: 10.1787/9789264122246-en.

(21) UN-Water.*The United Nations World Water Development Report 2021: valuing water*. (UN Educational, Scientific and Cultural Organization: Paris, France, 2021). https://unesdoc.unesco.org/ark:/48223/pf0000375724.

(22) Richter, B. D.; Benoit, K.; Dugan, J.; Getacho, G.; LaRoe, N.; Moro, B.; Rynne, T.; Tahamtani, M.; Townsend, A. Decoupling Urban Water Use and Growth in Response to Water Scarcity. *Water.* **2020**, *12*, 2868.

(23) Hofste, R. W.; Kuzma, S.; Walker, S.; Sutanudjaja, E. H.; Bierkens, M. F. P.; Kuijper, M. J. M.; Sanchez, M. F.; Beek, R. V.; Wada, Y.; Rodríguez, S. G.; Reig, P.*Aqueduct 3.0: Updated Decision-relevant Global Water Risk Indicators*. (World Resource Institute, 2019). DOI: 10.46830/writn.18.00146.

(24) World Resource Institute. *Aqueduct Global Maps 3.0 Data data sets*. (2019). https://www.wri.org/data/aqueduct-global-maps-30-data.

(25) US Bureau of Economic Analysis. *Annual Gross Domestic Product (GDP) by State: Real GDP in chained dollars data sets (1985−2015)*. (accessed in 2020). https://apps.bea.gov/regional/histdata/.

(26) US Geological Survey. Water-use data available from USGS (1985−2015 publication data for counties) data sets. https://water.usgs.gov/watuse/data/ (2018).

(27) *US Department of Agriculture*. (US Department of Agriculture National Agricultural Statistics Service, 1985−2015). https://quickstats.nass.usda.gov/.

(28) Tapio, P. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transp Policy.* **2005**, *12*, 137−151.

(29) Klemeš, J. J. Industrial water recycle/reuse. *Curr. Opin. Chem. Eng.* **2012**, *1*, 238−245.

(30) Castro Oliveira, M.; Iten, M.; Matos, H. A. Review on Water and Energy Integration in Process Industry: Water-Heat Nexus. *Sustainability* **2022**, *14*, 7954.

(31) US Environmental Protection Agency. Vol. *40* CFR 9, 122, 123, 124 & 125 (ed US Environmental Protection Agency) 65255−65345 (2001). https://www.federalregister.gov/documents/2001/12/18/01-28968/national-pollutant-discharge-elimination-system-regulations-addressing-cooling-water-intake.

(32) US Environmental Protection Agency. Vol. *40* CFR 122 & 125 (ed US Environmental Protection Agency) 48299−48439 (2014). https://www.federalregister.gov/documents/2014/08/15/2014-12164/national-pollutant-discharge-elimination-system-final-regulations-to-establish-requirements-for.

(33) Radhakrishnan, V.; Wu, W.IoT Technology for Smart Water System. *in 2018 IEEE 20th International Conference on High Performance Computing and Communications 1491−1496*; (Institute of Electrical and Electronics Engineers, 2018). DOI: 10.1109/HPCC/SmartCity/DSS.2018.00246.

(34) Gupta, A. D.; Pandey, P.; Feijóo, A.; Yaseen, Z. M.; Bokde, N. D.Smart Water Technology for Efficient Water Resource Management: A Review. *Energies13* (**2020**). 6268.

(35) Sweet, S. K.; Wolfe, D. W.; DeGaetano, A.; Benner, R. Anatomy of the 2016 drought in the Northeastern United States: implications for agriculture and water resources in humid climates. *Agric. For. Meteorol.* **2017**, *247*, 571−581.

(36) Dziegielewski, B.*National Survey of Commercial, Industrial and Institutional Water Efficiency Programs*. (American Water Works Association, 2016). https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Technical%20Reports/AWWAsUtilitySurveyofCIIWaterEfficiencyProgramsReport.pdf?ver=2021-05-21-123004-88.

(37) H.R.776 - 102nd Congress (1991−1992): Energy Policy Act of 1992, H.R.776, 102nd Cong. (1992), https://www.congress.gov/bill/102nd-congress/house-bill/776.

(38) Egilmez, G.; Kucukvar, M.; Tatari, O. Sustainability assessment of US manufacturing sectors: an economic input output-based frontier approach. *J. Clean. Prod.* **2013**, *53*, 91−102.

(39) Porokhovskiy, A. Digitalization and productivity. *USA & Canada: ekonomika, politika, kultura* **2019**, *5*, 24.

(40) Agrawal, R.; Wankhede, V. A.; Kumar, A.; Upadhyay, A.; Garza-Reyes, J. A. Nexus of circular economy and sustainable business performance in the era of digitalization. *Int. J. Product. Perform.* **2022**, *71*, 748−774.

(41) Doeffinger, T.; Hall, J. W. Water Stress and Productivity: An Empirical Analysis of Trends and Drivers. *Water Resour. Res.* **2020**, *56*, e2019WR025925 DOI: 10.1029/2019WR025925.

(42) Khair, S. M.; Mushtag, S.; Reardon-Smith, K.; Ostini, J. Diverse drivers of unsustainable groundwater extraction behaviour operate in an unregulated water scarce region. *J. Environ. Manage.* **2019**, *236*, 340−350.

(43) Zhang, L.; Ma, Q.; Zhao, Y.; Chen, H.; Hu, Y.; Ma, H.China's strictest water policy: Reversing water use trends and alleviating water stress. *J. Environ. Manage.345* (**2023**). 118867.

(44) Scheierling, S.; Treguer, D. Enhancing Water Productivity in Irrigated Agriculture in the Face of Water Scarcity. *Choices* **2016**, *31*, 1−10.

(45) US Department of Agriculture National Agricultural Statistics Sevice, 2017 Census of Agriculture. (US Department of Agriculture). https://www.nass.usda.gov/Publications/AgCensus/2017/index.php#full_report.

(46) UN Food and Agriculture Organization & UN Water. *Progress on Water-use Efficiency: Global baseline for SDG indicator 6.4.1*. (UN Food and Agriculture Organization: Rome, Italy, 2018). https://www.

unwater.org/publications/progress-water-use-efficiency-global-baseline-sdg-indicator-641.

(47) Guppy, L.; Mehta, P.; Qadir, M. Sustainable development goal 6: two gaps in the race for indicators. *Sustain. Sci.* **2019**, *14*, 501−513.

(48) Marston, L. T.; Lamsal, G.; Ancona, Z. H.; Caldwell, P.; Richter, B. D.; Ruddell, B. L.; Rushforth, R. R.; Davis, K. F. Reducing water scarcity by improving water productivity in the United States. *Environ. Res. Lett.* **2020**, *15*, No. 094033, DOI: 10.1088/1748-9326/ab9d39.

(49) Wang, R.; Hertwich, E.; Zimmerman, J. B. (Virtual) Water Flows Uphill toward Money. *Environ. Sci. & Technol.* **2016**, *50*, 12320−12330.

(50) Burek, P.; Satoh, Y.; Fischer, G.; Kahil, M. T.; Scherzer, A.; Tramberend, S.; Nava, L. F.; Wada, Y.; Esiner, S.; Flörke, M.; Hanasaki, N.; Magnuszewski, P.; Cosgrove, B.; Wiberg, D.*Water Futures and Solution: Fast Track Initiative (Final Report)*. (International Institute for Applied Systems Analysis: Laxenburg, Austria, 2016). https://pure.iiasa.ac.at/id/eprint/13008/.

(51) UNESCO World Water Assessment Programme. *The United Nations world water development report 2019: leaving no one behind*. (2019). https://unesdoc.unesco.org/ark:/48223/pf0000367306.

(52) International Energy Agency. *Water-Energy Nexus*. (International Energy Agency: Paris, France, 2017). https://www.iea.org/reports/water-energy-nexus.