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Analysis of water–energy nexus and trends in support of the Sustainable Development Goals: A study using longitudinal water–energy use data

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Abstract

Water and energy are two critical natural resources necessary for human activities and socioeconomic development. Water and energy systems are highly interdependent, and water efficiency and energy efficiency are two related indicators for the United Nations' Sustainable Development Goals. It is critical to improve energy–water use efficiency to sustain socioeconomic development while reducing adverse effects on natural resources, society and the environment. By using longitudinal energy–water use data for China over the past 21 years, this paper develops a temporo-spatial study to address key issues and introduce analytical approaches needed to understand the water–energy nexus and support integrated resource planning and management to achieve the Sustainable Development Goals. Decomposition analysis indicates that the production effect was the dominating factor contributing the increase in the country's energy–water use, while energy–water efficiency is the major factor slowing the growth of the country's energy–water use. Changes and trends analyses show that the country's energy intensity, water intensity, and water/energy ratio significantly decreased from 1999 to 2019, but the rate of decline has slowed. The disparities of the country's provincial energy intensities, water intensities, and water/energy ratios significantly decreased with economic growth. Results suggest that improving energy–water efficiency is critical for the country to curb increasing energy and water use and achieve resource and environmental protection targets with rapid economic development. The disparities between regional energy-water efficiencies can be reduced along with economic growth, while an overheated economy can widen the disparities and result in unsustainable and inefficient utilization of resources. Government coordination, targets and policy as part of the efficiency governance system are critical for continuous energy–water efficiency improvement and directly influence the implementation and effectiveness of energy–water efficiency policy.

Keywords: sustainable development, water–energy nexus, energy efficiency, water efficiency, equity, disparity

1. Introduction

Water and energy are two critical natural resources necessary for human activities. Intensive human activities and economic development require large amounts of water and energy, and have been exerting increased pressure on natural resources and environmental systems. With increasing water consumption, water shortages have triggered a series of ecological and environmental problems. Similarly, the energy-related emissions caused by the huge amount of fossil energy consumption worldwide (IEA, 2021) have significant impacts on global climate change.

Energy and water systems are highly interdependent. Water is used in almost all phases of energy production; energy is required for water extraction, conveyance, delivery, and diverse uses, as well as wastewater treatment (U.S. DOE, 2014). On the one hand, as water resource scarcity and variability become more prominent worldwide (U.S. DOE, 2014), more energy is required to provide a sufficient, high-quality, and reliable water supply. On the other hand, as energy demands persistently grow, energy production and electricity generation require more water to operate, putting more pressure on the already scarce water resources (Zhu et al., 2020) in many regions worldwide.

Research on this water–energy nexus (WEN) has received increased attention from the scientific and policy communities (Dai et al., 2018). Dai et al. (2018) reviewed 35 case studies based on an extensive survey of recent literature on the WEN and indicated the need to improve classification and comparison of the capacities, strengths, and weaknesses of existing approaches. Ding et al. (2020) conducted a comprehensive literature review on the WEN by using a citation-based approach and established a directional network in terms of citation relationships; they found that the current research focuses on the understanding of water–energy coupling relations in macroscopic national systems. Ahmad et al. (2020) systematically reviewed the WEN from the perspective of energy efficiency, and that review could be helpful in planning and efforts to minimize water and energy consumption to achieve maximum efficiency in urban water systems. They also adopted an integral theory framework to examine the interconnectivity among existent variables of the WEN and help identify the relationships among different dimensions related to the WEN for future demands.

The concept of a WEN has been extended to many research areas, such as water–energy–food nexus (Endo et al., 2017; Venghaus and Hake, 2018), water–energy–climate/carbon nexus (Escriva-Bou et al., 2018; Zhou et al., 2019), water–energy–waste nexus (Friedrich et al., 2020), water–energy–pollution nexus (Kumar and Saroj, 2014), and water–energy–land nexus (Hibbard et al., 2014; Howells et al., 2013; ODI et al., 2012). The core of each of these extended nexuses is the WEN (Wang et al., 2021a). Wang et al. (2021a) systematically reviewed these extended WENs and developed a framework which includes five components that are essential for extended WEN analysis, modelling, and assessment: "(i) development of standards, (ii) public data sharing, (iii) innovation of method applications, (iv) new technologies and solutions, and (v) possible emergent scenarios that impact the nexus".

One main reason for the increasing interest and diversity on the WEN is that it is highly related to the United Nations' Sustainable Development Goals (Giannetti et al., 2020a; Giannetti et al., 2020b; Wang et al., 2021a). As two basic and critical natural resources, water and energy are fundamental factors for socioeconomic development. However, unsustainable production and energy–water use (EWU) patterns and inequality (Satyro et al., 2022; Wang et al., 2021b), combined with increases in already excessive use of water and energy resources, lead to serious consequences, such as resource depletion and environmental degradation, and put at risk the healthy environment which is needed for sustainable development (U.N. Environment, 2019). Improving energy efficiency (EE) and water use efficiency is thus critical for addressing the climate change, economic growth, energy security, clean water, and environment protection challenges related to sustainable development.

This temporo-spatial study aims to address key issues and introduce analytical approaches needed to understand the WEN and support integrated resource planning and management and efficiency governance to achieve the Sustainable Development Goals.

The rest of this paper is organized as follows: Section 2 reviews the WEN and Sustainable Development Goals, Section 3 introduces the methodologies, Section 4 describes data and their sources, Section 5 presents the main results, Section 6 provides further discussions, and Section 7 offers conclusions with remarks.

2. Water–energy nexus and Sustainable Development Goals

Environment-friendly sustainable economic growth and equity are two important aspects of the United Nations' Sustainable Development Goals (U.N. DSDG, 2021). Economic growth is critical to achieve some of the most important goals, such as "no poverty" and "decent work." One the one hand, economic growth needs to continue and even accelerate to achieve the related goals; on the other hand, economic growth requires utilization of various natural resources such as water and energy, and unsustainable uses of these natural resources cause various adverse effects on regional and global environments. In many regions worldwide, the availability and quality of water and energy resources are great challenges and potential limiting factors to sustain economic growth. Therefore, water and energy resources must be used efficiently in a clean and environmentally friendly way to support sustainable economic growth and environmental protection.

Equity is one important principle for the Sustainable Development Goals, and one equity target is "equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance" (U.N. DSDG, 2021). On the one hand, socioeconomic development and an increasing population requires more natural resources and thus puts greater pressure on the already stressed water and energy resources. On the other hand, water scarcity and/or energy poverty are great challenges to many countries and regions worldwide (Parton, 2018; Sadath and Acharya, 2017), and access to clean water—as well as affordable and clean energy—requires concentrated efforts, as well as financial and technological aid for many countries and regions. Reducing inequity for an inclusive water and energy resources development and utilization for all is a great challenge to the sustainable development and global efforts on climate change mitigation (Dooley et al., 2021; Groce et al., 2011; LCDIDC, 2013).

Coordination mechanisms are one of the three main aspects of EE governance system and directly influences the quality and effectiveness of EE policy outcomes (IEA, 2010). Coordination is essential for achieving sustainability, equity, and environmental-friendliness goals, given the natural and socioeconomic disparities and imbalances between different countries or regions in the world. Coordinated development is thus an important policy tool to reduce disparities and imbalances for sustainable, inclusive, and environmentally friendly socioeconomic growth (City of Minneapolis, 2019; Kuhn, 2016). Furthermore, coordinated development could help effectively allocate resources and equitably access resources, thus optimizing economic development (Kuhn, 2016).

To achieve the Sustainable Development Goals through equitable and environmentally-sustainable development, it is important to analyze EWU patterns and trends and disparities, assess the relationship between economic growth and EWU, identify EWU best practices, and estimate water and energy savings potential. A more holistic analytical approach will support the integrated water–energy system management and optimization needed for sustainable development.

China is currently the largest energy consumer and carbon emitter (IEA, 2020; U.S. EIA, 2021) and has the second largest water withdrawals in the world (FAO, 2021). As a result, China's EWU has a substantial impact on global environmentally related sustainable development. Due to this huge impact on the climate and environment, and increasing global efforts on achieving environmentally related sustainable development goals, China's EWU and their nexus have received worldwide attention. Li et al. (2019) employed the logarithmic mean Divisia index (LMDI) method to decompose the driving forces of water and energy consumption in China from 2011 to 2015 to investigate the linkage between water and energy consumption changes. They found that the growth of population and gross domestic product (GDP) per capita were main factors driving water and energy consumption, while the reduction of intensity was the main factor inhibiting water and energy consumption. Duan and Chen (2020) employed structural decomposition analysis to decompose the water consumption of different end users from 1990 to 2014 into six energy related factors to probe the driving factors of the WEN in China, and they found that consumption volume was the main contributing factor for the increase of the total energy related water consumption and energy intensity (EI, in terms of energy consumption per unit of GDP) was the major driving factor for reducing the water consumption of all consumers. Gu et al. (2016) employed a footprint methodology to quantify energy consumption in nine different wastewater treatment plants in south China from a WEN perspective, and they found that higher capacity and appropriate technology of the wastewater treatment plants would lead to a higher gray water footprint reduction. Smith et al. (2018) reviewed the literature on energy for water in urban China and identified feasible suggestions for reducing and recovering energy in the country's urban water systems. Perera and Zhong (2017) analyzed the trade-off between the water and energy sectors in China and proposed several recommendations to ensure the long-run sustainability of the WEN related policies and planning. Zhou et al. (2019) investigated the WEN in China based on comprehensive, bottom-up technology characterizations. Their results underscored the growing interconnection between water and energy in China, and they also found that low-carbon energy resources (except inland nuclear) usually save substantial water. Zhu et al. (2020) assessed the efficiency of water use (WU) for power generation and water transfer and losses embodied in the West–East electricity transmission project in China, and they found that water resources sustainability was affected by the rapid energy developments in western China. Jin et al. (2021) examined the water use of electricity production and virtual water transfer via electricity transmission between Chinese provinces, and they found that a large volume of water was withdrawn for electricity production and virtually traded through the electricity transmission system in China. Huber-Lee and Handly (2019) examined the policy coherence between the water and energy sectors, as well as the degree to which policies in one sector work synchronously with the other sector. They found that higher synchronization would result in greater reliability of the sectors and the resources.

Although China is the largest energy consumer in the world and has the second largest water withdrawals, the spatial and temporal distribution of water and energy resources is highly uneven in the country. China contains multiple climate zones; hydrologic conditions in the country vary greatly from place to place and time to time, and energy resources are quite unevenly distributed across the country. With a significantly different regional population and economic development, China's EWU is highly imbalanced spatially and temporally, and water scarcity and/or energy poverty are among the greatest challenges to many of the country's regions (Jiang, 2009; Lin and Wang, 2020; Ma et al., 2020; Tang and Liao, 2014). Furthermore, China's historical single-minded focus on economic growth together with uncoordinated economic development among provinces has caused serious environment and inefficient resource allocation problems, and has widened the disparities between urban and rural areas and between various provinces (Kuhn, 2016). Therefore, China's regional and temporal disparities and imbalances make it necessary to analyze and understand China's WEN and trends and disparities, spatially and temporally, at both a national and regional level, over a sufficiently long term, to help: (i) benchmark water–energy efficiency spatially and temporally, (ii) assess the spatial and temporal disparities in water–energy efficiency, (iii) identify energy–water conservation potential, (iv) coordinate economic development and resources allocation, and (v) develop policies to support equitable and sustainable development. However, to our knowledge, there have been very few studies that address this research with high-resolution spatial and temporal granularity to account for China's regional imbalances in economic development and resource utilization. The insights from this research provides helpful lessons learned to better support coordinated energy–water development in China, but these lessons can also be readily applied to other emerging countries that rely heavily on water and energy resources to develop their economy.

This study quantifies the contributing factors for the changes and trends of EWU and WEN, reveals the changes and trends in water and energy intensities, and evaluates WEN related disparities. This paper contributes to the literature in the following aspects. First, it uses high-resolution spatial and temporal granularity over a 21-year period to account for WEN and regional imbalances in economic development and resource utilization. Second, it captures nonlinear dynamics in WEN and driving forces for the changes and trends in WEN and relationship with the economic development. Third, it measures changes and trends in WEN and related disparities in both relative and absolute terms, which provides insights into changes and trends in WEN constrained by resources, environment, and sustainability.

3. Methodology

In this section, the methodologies used for the study are briefly reviewed. More specifically, EWU indicators and water/energy ratio (WER) are defined in Section 3.1, decomposition analysis is discussed in Section 3.2, curvilinear regression models for trends analysis are introduced in Section 3.3, and disparity measures are reviewed in Section 3.4.

3.1. Energy and water use indicators and water/energy ratio

Note that the WEN in one region is dynamic and may experience some rapid or substantial changes over some periods, and it is thus important to view the WEN from the perspective of spatiotemporal systems.

Consider a region Ω that consists of *N* nonoverlapping subregions Ω_i for $i=1,2,\cdots,N$, or formally, $\Omega=\bigcup_{i=1}^{N}\Omega_i$, and $\forall i\neq j$, $\Omega_i\bigcap\Omega_i=\varnothing$. For example, a country consists of *N* states or provinces. Let $E_{i,t}$, $W_{i,t}$, and $Y_{i,t}$ denote respectively the energy use (EU), WU, and economic yield (e.g., gross domestic product, GDP) of the subregion Ω_i ($i=1,2,\cdots,N$) in period *t*.

Define the (economic) EI $I_{i,t}^{(eE)}$ of the subregion Ω_i ($i=1,2,\cdots,N$) in period *t* as:

$$I_{i,t}^{(eE)}=E_{i,t}/Y_{i,t}\text{ , for } i=1,2,\cdots,N. \tag{1}$$

Similarly, we define the water intensity (WI) $I_{i,t}^{(eW)}$ of the subregion Ω_i ($i=1,2,\cdots,N$) in period *t* as:

$$I_{i,t}^{(eW)}=W_{i,t}/Y_{i,t}\text{ , for } i=1,2,\cdots,N. \tag{2}$$

Note that the above energy and water intensities could be used to evaluate and benchmark the EWU efficiencies of the subregion.

To investigate the nexus between WU and EU, we define the WU-to-EU ratio (in brief, WER) $R_{i,t}^{(WE)}$ of the subregion Ω_i ($i=1,2,\cdots,N$) in period *t* as:

$$R_{i,t}^{(WE)}=W_{i,t}/E_{i,t}\text{ , for } i=1,2,\cdots,N. \tag{3}$$

Similarly, define energy/water ratio (EWR) $R_{i,t}^{(EW)}$, which is the reciprocal of the WER $R_{i,t}^{(WE)}$.

Define the following aggregate variables and indicators of the region Ω, which is an aggregation of the *N* nonoverlapping subregions Ω_i for $i=1,2,\cdots,N$:

$$W_t\text{ – WU of the region } \Omega \text{ in time } t,\ W_t=\sum_{i=1}^{N}W_{i,t}\text{ ,} \tag{4}$$

$$E_t\text{ – EU of the region } \Omega \text{ in time } t,\ E_t=\sum_{i=1}^{N}E_{i,t}\text{ ,} \tag{5}$$

$I_t^{(eE)}$ – EI of the region Ω in time *t*, $I_t^{(eE)} = E_t / Y_t$, (6)

$I_t^{(eW)}$ – WI of the region Ω in time *t*, $I_t^{(eW)} = W_t / Y_t$, (7)

$R_t^{(WE)}$ – WER of the region Ω in time *t*, $R_t^{(WE)} = W_t / E_t = \sum_{i=1}^{N} W_{i,t} / E_t$. (8)

Note that WER or EWR can be considered as a general indicator that describes some overall WEN characteristics of a region over some period. Together with EIs and WIs, WER or EWR can help analyze EWU characteristics and efficiencies and trends of a region, as well as disparities between different regions of a country or subregions of a region. It is worth noting that some researchers (Duan and Chen, 2020) used the term *water–energy nexus coefficient* to indicate the WER; herein the terms *water/energy ratio* and *energy/water ratio* are preferred, as they are more clear in terms of mathematical expression and meaning.

3.2. Logarithmic mean Divisia index (LMDI) decomposition

Decomposition analysis, especially logarithmic mean Divisia index (LMDI) decomposition, can be utilized to investigate and analyze the contributing factors for the changes in an aggregated variable (Ang, 2005). LMDI has been widely used in energy- and water-related research (Hasanbeigi et al., 2013; Ke et al., 2012; Li et al., 2019; Zhao et al., 2014; Zhou et al., 2020).

Let *V* be an aggregate and assume that there are *n* factors contributing to changes in *V* over time. The *n* factors are associated with *n* variables denoted by $x_1, x_2, \cdots, x_n$. Let subscript *i* be a subcategory of the aggregate and the relationship $V_{i,t} = x_{1,i,t} x_{2,i,t} \cdots x_{n,i,t}$ holds at the subcategory level in period *t* (Ang, 2005). The general index decomposition analysis identity is given by Equation 9 (Ang, 2005):

$$V_t = \sum_i V_{i,t} = \sum_i x_{1,i,t} x_{2,i,t} \cdots x_{n,i,t} \ . \tag{9}$$

Consider that the aggregate changes from $V_{t_1} = \sum_i x_{1,i,t_1} x_{2,i,t_1} \cdots x_{n,i,t_1}$ in period *t*1 to $V_{t_2} = \sum_i x_{1,i,t_2} x_{2,i,t_2} \cdots x_{n,i,t_2}$ in period *t*2. Decompose the difference between V_{t_2} and V_{t_1} in additive decomposition (Ang, 2005):

$$\Delta V_{tot} = V_{t_2} - V_{t_1} = \Delta V_{x_1} + \Delta V_{x_2} + \cdots + \Delta V_{x_n} + \Delta V_r , \tag{10}$$

where the ΔV_{tot} represents the total or overall change, ΔV_{x_i} ($i = 1, 2, \cdots, n$) is the effect associated with the *i*th factor, and ΔV_r denotes a residual term (crossing term). Ang (Ang, 2005) proposed the following LMDI approach:

$$\Delta V_{x_k} = \sum_i L(V_{i,t_2}, V_{i,t_1}) \ln(x_{k,i,t_2} / x_{k,i,t_1}) , \tag{11}$$

where function $L(\cdot,\cdot)$ is defined as

$$L(a,b) = (a - b) / (\ln a - \ln b) . \tag{12}$$

Note that the LMDI is a type of "perfect decomposition" approach because the residual term ΔV_r is zero, which helps avoid the difficulty of having to interpret the residual term (Ang, 2005).

The above LMDI decomposition approach (Ang, 2005, 2015) can be used to quantify the contribution of each factor of interest to changes in WU, EU, and WER of a study region over some analysis period.

Consider the region Ω that consists of N nonoverlapping subregions Ω_i for $i = 1, 2, \cdots, N$. The EU E_t, WU W_t, and WER $R_t^{(WE)}$ of the region Ω in period t can be expressed as:

$$E_t = \sum_{i=1}^{N} Y_t \cdot \frac{Y_{i,t}}{Y_t} \cdot \frac{E_{i,t}}{Y_{i,t}}, \tag{13}$$

$$W_t = \sum_{i=1}^{N} Y_t \cdot \frac{Y_{i,t}}{Y_t} \cdot \frac{W_{i,t}}{Y_{i,t}}, \tag{14}$$

$$R_t^{(WE)} = \frac{W_t}{E_t} = \sum_{i=1}^{N} \frac{E_{i,t}}{E_t} \cdot \frac{Y_{i,t}}{E_{i,t}} \cdot \frac{W_{i,t}}{Y_{i,t}}. \tag{15}$$

Note that in equations (13)–(15), $Y_{i,t} / Y_t$ for $i = 1, 2, \cdots N$ reflects the economic structure of the region Ω in period *t*, $E_{i,t} / Y_{i,t}$ is the EI of the subregion Ω_i ($i = 1, 2, \cdots N$) in period *t*, $W_{i,t} / Y_{i,t}$ is the WI of the subregion Ω_i ($i = 1, 2, \cdots N$) in period *t*, $E_{i,t} / E$ for $i = 1, 2, \cdots N$ reflects the inter-subregion structure of the energy use of the region Ω in period *t*, $Y_{i,t} / E_{i,t}$ is the reciprocal of EI of the subregion Ω_i ($i = 1, 2, \cdots N$) in period *t* and reflects the economic EE.

It is clear that the LMDI approach can be applied to the above index decomposition problems governed by equations (13)–(15), as these equations are just some special cases of Equation (9).

Note that, in most cases, it is not correct to interpret the LMDI decomposition as causal effects because LMDI is a index decomposition method to quantify the contribution of each factor of interest (also known as a *contributing factor* or *driving force*) to the changes in an aggregated variable and is not a causal model.

3.3. Curvilinear regression

Regression analysis is one widely used method for investigating and estimating changes and trends in a time series (Wooldridge, 2015). Linear changes and trends are often preferred for their simplicity. However, in water- and energy-related applications, changes and trends are often not linear or approximately linear in nature, and a linear change or trend assumption may not be applicable in these cases. Curvilinear regression models (Seber and Wild, 2003) or locally weighted regression models (Cleveland and Devlin, 1988) are often required to investigate and estimate nonlinear changes and trends, as well as other relationships between dependent variables and explanatory variables.

Polynomial regression, such as quadratic or cubic regression, is one type of common curvilinear regression models. It should be noted that, in most cases, high-order polynomial functions (an order of five or higher) are generally not preferred, in order to avoid potential overfitting and other undesirable artifacts (Gelman and Imbens, 2019).

Royston and Altman (1994) proposed fractional polynomial regression models to increase the flexibility in modeling curve shapes compared to the low-degree conventional polynomial models while reducing undesirable artifacts of high-order polynomial models.

Let x denote an independent variable, and let x^0 equal the natural log of x rather than 1 (i.e., $x^0 = \ln x$). Let $h_0(x) = 1$ and $p_0 = 0$, a fractional polynomial (FP) model with powers $\mathbf{p} = (p_1 \le p_2 \le \cdots \le p_m)$, usually denoted as FP*m*, can be defined as in Equation (16) (Royston and Sauerbrei, 2008):

$$\varphi_m^*(x;\mathbf{p}) = \beta_0 + \varphi_m(x;\mathbf{p}) = \sum_{j=0}^{m} \beta_j h_j(x), \tag{16}$$

where $$h_j(x) = \begin{cases} x^{p_j} & , \ if \ p_j \ne p_{j-1} \\ h_{j-1}(x)\ln x, & if \ p_j = p_{j-1} \end{cases}, \tag{17}$$

for $j = 1, 2, \cdots, m$.

With the above FP*m* model, a much wider range of curve shapes can be obtained than with regular low-degree polynomials. The fractional polynomial regression models are used to analyze the changes and trends of WI, EI, and WER in this study.

3.4. Disparity measures

The disparity is evaluated using common inequality measures that can be used to make comparisons with different distributions (Haughton and Khandker, 2009; Sitthiyot and Holasut, 2020; UNCTAD, 2019). Herein, two relative inequality measures are considered, specifically the Gini index and general entropy (GE) measure (Haughton and Khandker, 2009; World Bank, 2014), and two absolute inequality measures, specifically standard deviation and the absolute Gini index (Niño-Zarazúa et al., 2017).

The Gini index is derived from the Lorenz curve, which is a cumulative frequency curve that compares the distribution of a specific variable (e.g., GDP per capita) with the uniform distribution that represents equality (Haughton and Khandker, 2009). The absolute Gini index is defined as the multiplication of Gini index by sample mean value.

Another class of relative inequality measures is the GE measure, which is defined as (Haughton and Khandker, 2009):

$$\mathrm{GE}(\alpha) = \frac{1}{N\alpha(\alpha-1)} \sum_{i=1}^{N} \left[\left(\frac{y_i}{\bar{y}} \right)^{\alpha} - 1 \right], \alpha \ne 0,1, \tag{18}$$

$$\mathrm{GE}(0) = \frac{1}{N} \sum_{i=1}^{N} \ln\left(\frac{\bar{y}}{y_i} \right), \tag{19}$$

$$\mathrm{GE}(1) = \frac{1}{N} \sum_{i=1}^{N} \frac{y_i}{\bar{y}} \ln \frac{y_i}{\bar{y}}. \tag{20}$$

where $y = \{y_1, y_2, \cdots, y_N\}$ is the variable or characteristic of interest and $\bar{y}$ is the mean of *y*. The values of GE measures range between zero and infinity, with zero indicating an equal distribution and higher values indicating higher levels of inequality. Note that the well-known Theil index is part of the GE class measure, of which GE(0) is the “Thiel’s L” or “mean log deviation” measure, and GE(1) is “Theil’s T” index or “Theil index” (U.N. DESA, 2015).

Generally speaking, relative inequality measures are scale-invariant (i.e., invariant to equiproportional changes) and can be used to evaluate disproportionate changes in the distributions, while absolute inequality measures are translation-invariant (i.e., invariant to uniform additions or subtractions to original individuals in the distribution) and can be used to evaluate changes in different absolute amounts to individuals in the distributions (Bellù and Liberati, 2006; Manfred, 2017; Niño-Zarazúa et al., 2017). This study therefore uses both relative inequality measures (specifically Gini index and GE(1) index) and absolute inequality measures (specifically standard deviation and absolute Gini index) to analyze the disparity and uneven changes in regional WIs, EIs and WERs.

4. Data

This study uses longitudinal data (also known as panel data) related to economic development and energy–water data of China. The longitudinal data on economics, EU, and WU spanned over the 21 years (from 1999 to 2019) and over 30 Chinese provinces. Table 1 lists the statistical regions for the 30 Chinese provinces. The four major data sources are the *China National Data* (NBS, 2022), *China Statistical Yearbook* (NBS, various years-b), *China Energy Statistical Yearbook* (NBS, various years-a), and *China Water Resources Bulletin* (MWR, various years) in various years.

Table 1. Statistical regions for the 30 Chinese provinces included in the case study.

Statistical Regions	Provinces
North China	Beijing (11), Tianjin (12), Hebei (13), Shanxi (14), Inner Mongolia (15)
Northeast China	Liaoning (21), Jilin (22), Heilongjiang (23)
East China	Shanghai (31), Jiangsu (32), Zhejiang (33), Anhui (34), Fujian (35), Jiangxi (36), Shandong (37)
South Central China	Henan (41), Hubei (42), Hunan (43), Guangdong (44), Guangxi (45), Hainan (46)
Southwest China	Chongqing (50), Sichuan (51), Guizhou (52), Yunnan (53)
Northwest China	Shaanxi (61), Gansu (62), Qinghai (63), Ningxia (64), Xinjiang (65)

Note: The code such as "(11)" in parentheses is the ISO 3166-2:CN code for the 30 provinces of China (ISO, 2013).

Note that: (1) EU in the case study specifically refers to the total final energy consumption statistics in the *China Energy Statistical Yearbook*; (2) Shan et al. (2018) and Shan et al. (2020) have compiled most of the Chinese energy data for the years 1997 to 2017 based on the *China Energy Statistical Yearbook,* so this study used their compiled dataset for the years 1999–2017 but added EU data for the years of 2018–2019 and inter-provincial energy imports and exports data for the years 1999–2019 based on *China Energy Statistical Yearbook*; (3) WU in the case study refers to the total WU statistics in the *China Water Resources Bulletin*, which includes agricultural, industrial, living, and ecological WU (MWR, various years); and (4) the *China Water Resources Bulletin* includes water use data for 31 Chinese provinces, but we did not include Tibet in the case study due to a lack of sufficient energy data for Tibet.

Also note that the 2000–2002 energy consumption data for Ningxia and 2002 energy consumption data for Hainan were not reported due to some unpublished reasons. An interpolation method was therefore used to impute the missing data by referring to the electricity consumption data of Ningxia in 1999–2003 and of Hainan in 2001–2003.

For each variable of interest (such as total final provincial energy use) in the longitudinal data, the temporal dimension is 21 (years) and the spatial dimension is 30 (provinces), i.e., each variable of interest has 630 (i.e., 21 times 30) data points.

5. Results

From 1999 to 2019, both China's EU and WU increased, while both EI and WI decreased. The LMDI method was utilized to decompose the changes in China's EU, WU and WER to quantify the contribution of each contributing factor (driving force) to the changes, and the fractional polynomial regression models were used to analyze the changes and trends of China's EI, WI and WER during this period. The disparities in China's provincial EIs, WIs and WERs were also measured during this period.

5.1 Energy use and intensity

Figure 1 shows the decomposition of the annual and cumulative changes of China's EU during the period 1999–2019. Figure 2 shows the annual changes of China's EI and corresponding trends and disparity analysis results. Table 2 lists the overall fractional polynomial regression model fit for China's EI during the period 1999–2019. As suggested by figures 1 and 2, the changes of China's EU and EI in 1999–2019 could be approximately classified into the following four periods.

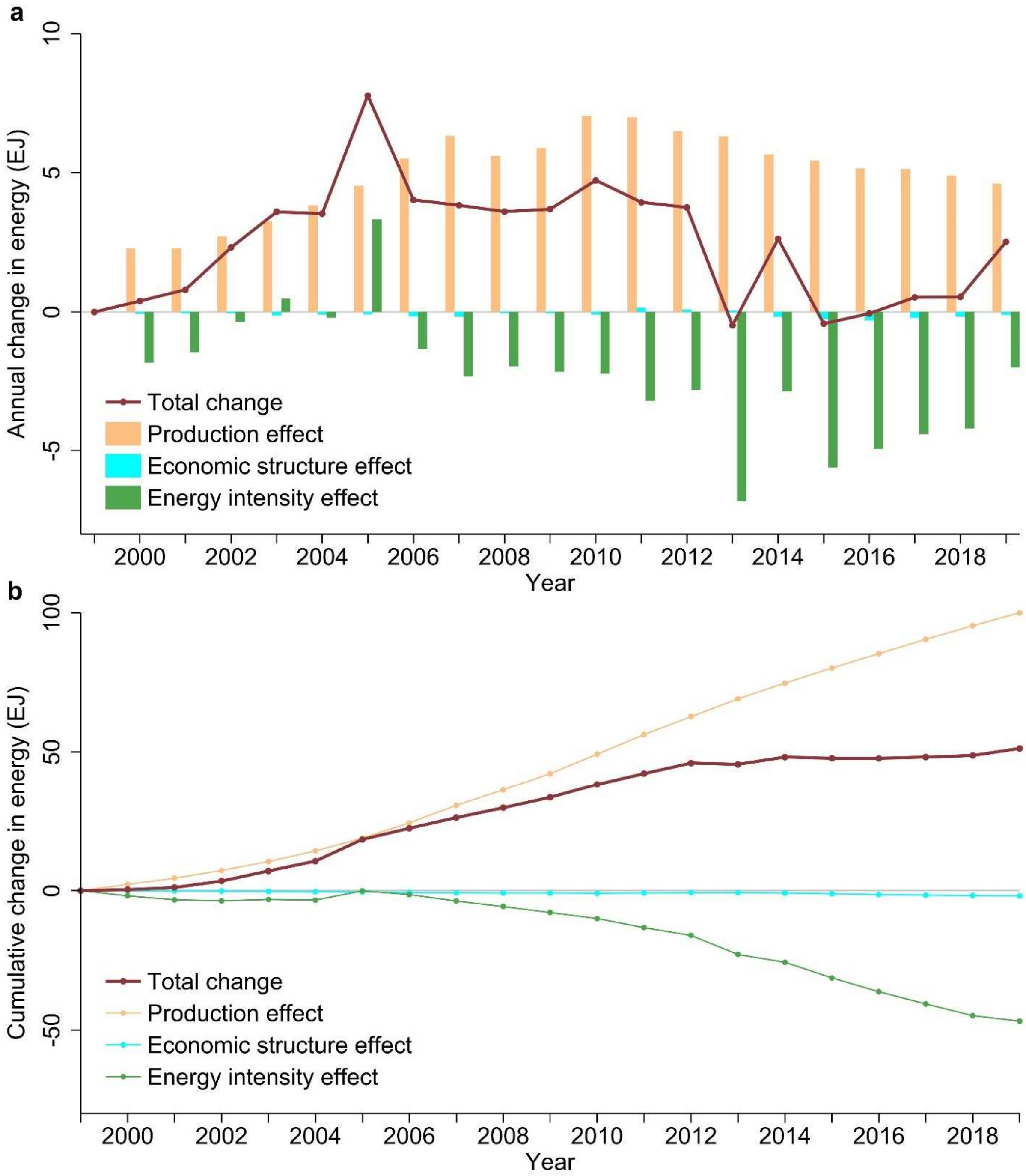

Figure 1. (**a**) Decomposition of the annual change of China's energy use, 1999–2019. (**b**) Decomposition of the cumulative change of China's energy use, 1999–2019. The year 1999 is the starting point for the calculation. Annual change is the change from immediate prior year to a given year. Cumulative change is the sum of annual incremental change from 1999 to a given year.

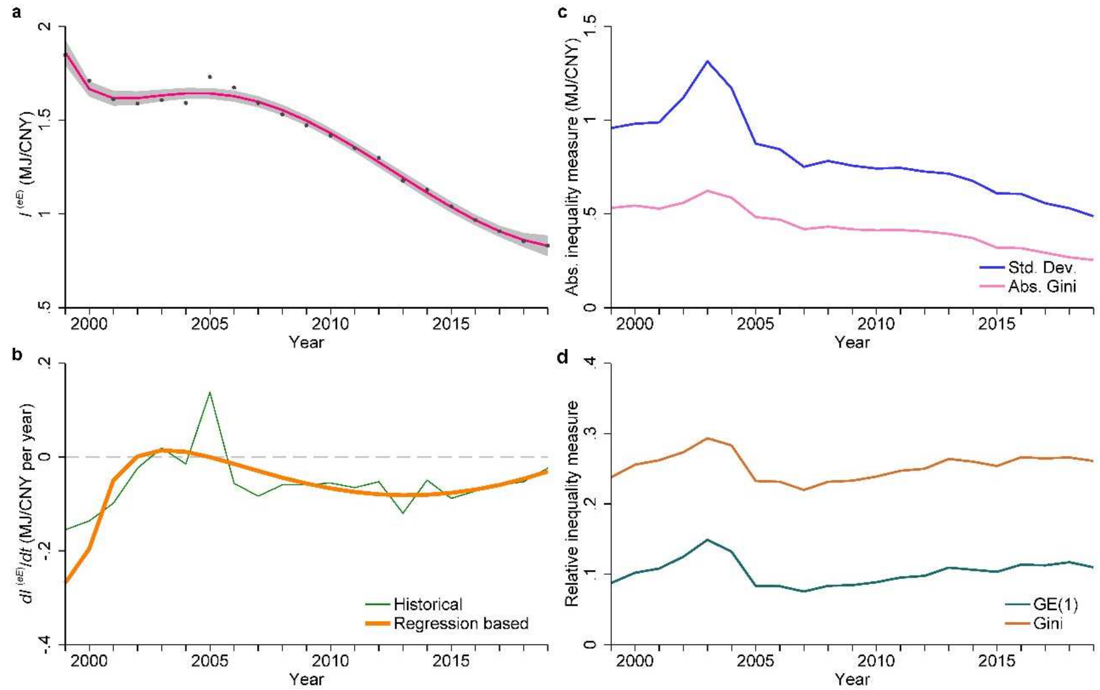

Figure 2. (**a**) China's national energy intensity, $I^{(eE)}$, 1999–2019. The black points denote historical data, the pink line denotes trends estimated by fractional polynomial regression models, and the light grey ribbon denotes a 95% confidence interval. (**b**) Numerical derivative of China's national energy intensity, $dI^{(eE)}\big/dt$, 1999–2019. (**c**) Absolute inequality measure of China's provincial energy intensities, including standard deviation and absolute Gini index, 1999–2019. (**d**) Relative inequality measures of China's provincial energy intensities, including general entropy (GE) measure GE(1), and Gini index, 1999–2019.

Table 2. Overall fractional polynomial regression model fit.

	National energy intensity	National water intensity	National water/energy ratio
Number of observations: N	21	21	21
F-value: $F(df_1, df_2)$	$F(4,16) = 425.58$	$F(4,16) = 9247.89$	$F(4,16) = 2173.65$
F-critical value for α=0.05	3.0069	3.0069	3.0069
p-value: Prob > F	0.0000	0.0000	0.0000
R-squared	0.9907	0.9996	0.9982

(1) Period of 1999–2002

During the period of 1999–2002, China's economy continued its fast-paced growth from its economic reform and "open door" policy that started in the late 1970s. As shown in Figure 1, China's EU increased during this period, and the production effect was the main factor for the growth in EU while the EI effect was the main factor slowing the growth of energy use. Because the production effect was much larger than the EI effect, and the economic structure effect was negligible during this period, EU significantly increased during this period.

As shown in Figure 2a and Figure 2b, the national average EI significantly decreased during this period, indicating that the average annual growth rate of EU was slower than the growth rate of GDP. As shown in Figure 2c and Figure 2d, both absolute and relative inequality measures increased from 1999 to 2002, indicating that the disparity between provincial EIs increased during this period. Put differently, both absolute gaps and relative disproportionate differences between provincial EIs increased from 1999 to 2002 with the fast-paced economic growth.

(2) Period of 2003–2005

China's economy became overheated in 2003–2005. As shown in Figure 1, the production effect began to increase rapidly from 2003 and was the major contributing factor for the rapid growth of EU. The EI effect in 2003 also became positive and contributed to the growth in energy use. As a result, China's EU increased dramatically from 2003 to 2005.

As shown in Figure 2a and Figure 2b, the decreasing trend of national EI was reversed from 2003. The national EI in 2003 and 2005 was respectively higher than that in 2002 and 2004, indicating that the EE significantly decreased during this period. As shown in Figure 2c and Figure 2d, both the absolute and relative inequality measures peaked in about 2003, indicating that disparities between provincial EIs dramatically increased with the overheated Chinese economy during this period. Put differently, both absolute gaps and relative disproportionate differences between provincial EIs dramatically increased during this period. The widened disparities, together with the dramatic increase of EU and reversal of the declining trend of EI, indicating that development during this period was energy-inefficient and uncoordinated, and thus unsustainable.

(3) Period of 2006–2012

To curb the fast growth of EU, China set a 20% EI reduction target from 2006 to 2010 over the 2005 level, and implemented the Top-1000 Enterprises Energy-Saving Program and the Ten Key Energy-Conservation Projects during this period (Ke et al., 2012). The implementation and effectiveness of these policy initiatives were monitored and evaluated previously (Ke et al., 2012).

As seen in Figure 1, China's EU continued to grow significantly from 2006 to 2012 with the rapid economic growth. The production effect increased rapidly until 2012 and was the major contributing factor (driving force) for the rapid growth of EU. The EI effect was the major factor slowing the growth of energy use, but was significantly outpaced by the production effect. The economic structure effect was negligible during this period. As a result, the country's energy use grew rapidly during this period.

As shown in Figure 2a and Figure 2b, China's EI began to decrease significantly again beginning in 2006, corresponding to the 20% reduction target. Note that, from 2006 to 2010, China decreased its EI by 19.1%, just shy of the 20% target (Ke et al., 2012). As shown in Figure 2c and Figure 2d, the absolute inequality measures showed a decreasing trend and the relative inequality measures were lower than the peak around 2003, indicating that disparities between provincial EIs decreased during this period.

(4) Period of 2013–2019

China set a 16% EI reduction target from 2011 to 2015 over the 2010 level (Casey and Koleski, 2011), and regulated reform of the natural gas market and electricity pricing mechanism during the period of 2011–2015.

As shown in Figure 1, the growth of China's EU slowed during the period of 2013–2019 compared to the fast-paced growth since 2003, showing a sign that the growth of China's EU began to slow after a rapid growth period. As shown in Figure 1, the production effect continued to be largely positive and contributed to the growth of the energy use, but the EI effect was largely negative and effectively slowed the growth of energy use. The economic structure effect became negative and contributed to the slowdown of the growth of EU since 2013, indicating that the share of large energy consuming provinces slightly decreased during this period beginning in 2013. As a result, the country's EU only slightly increased from 2013 to 2019 over the 2012 level.

As shown in Figure 2a and Figure 2b, China's EI continued to decrease during this period, but showed a sign of slowing after the mid-2010s. Figure 2c shows that the absolute inequality measures of China's provincial EIs decreased during this period. Figure 2d shows that the relative inequality measures of China's provincial EIs generally stagnated around the 2013 level.

In summary, the country's EI significantly decreased from 1999 to 2019, except for the period of 2003–2005, when the country's economy became overheated, while EU increased significantly during the period 1999–2019. Decomposition analysis shows that the production effect was the major contributing factor for the growth of EU, and the EI effect was the major contributing factor for slowing the growth of EU. Changes and trends analyses suggest that EI generally followed a decelerated declining trend (in terms of absolute decrease), indicating that EI would likely continue to decrease—but at a much slower pace—in the near future. The disparities between provincial EIs decreased in terms of absolute inequality measures from 1999 to 2019, indicating that the absolute gaps between provincial EIs decreased from 1999 to 2019. The disparities between provincial EIs peaked in about 2003 in both absolute terms and relative terms, suggesting that the overheated economy could have widened the disparities between provincial EIs.

5.2 Water use and intensity

Figure 3 shows the decomposition of the annual and cumulative changes of China's WU during the period 1999–2019. Figure 4 shows the annual changes of China's WI and corresponding trends and disparity analysis results. Table 2 lists the overall fractional polynomial regression model fit for China's WI during the period 1999–2019. As suggested by Figure 3 and Figure 4, the changes of China's WU and WI in 1999–2019 could be approximately classified into the following three periods, although the changes of WU were not as significant as those of EU.

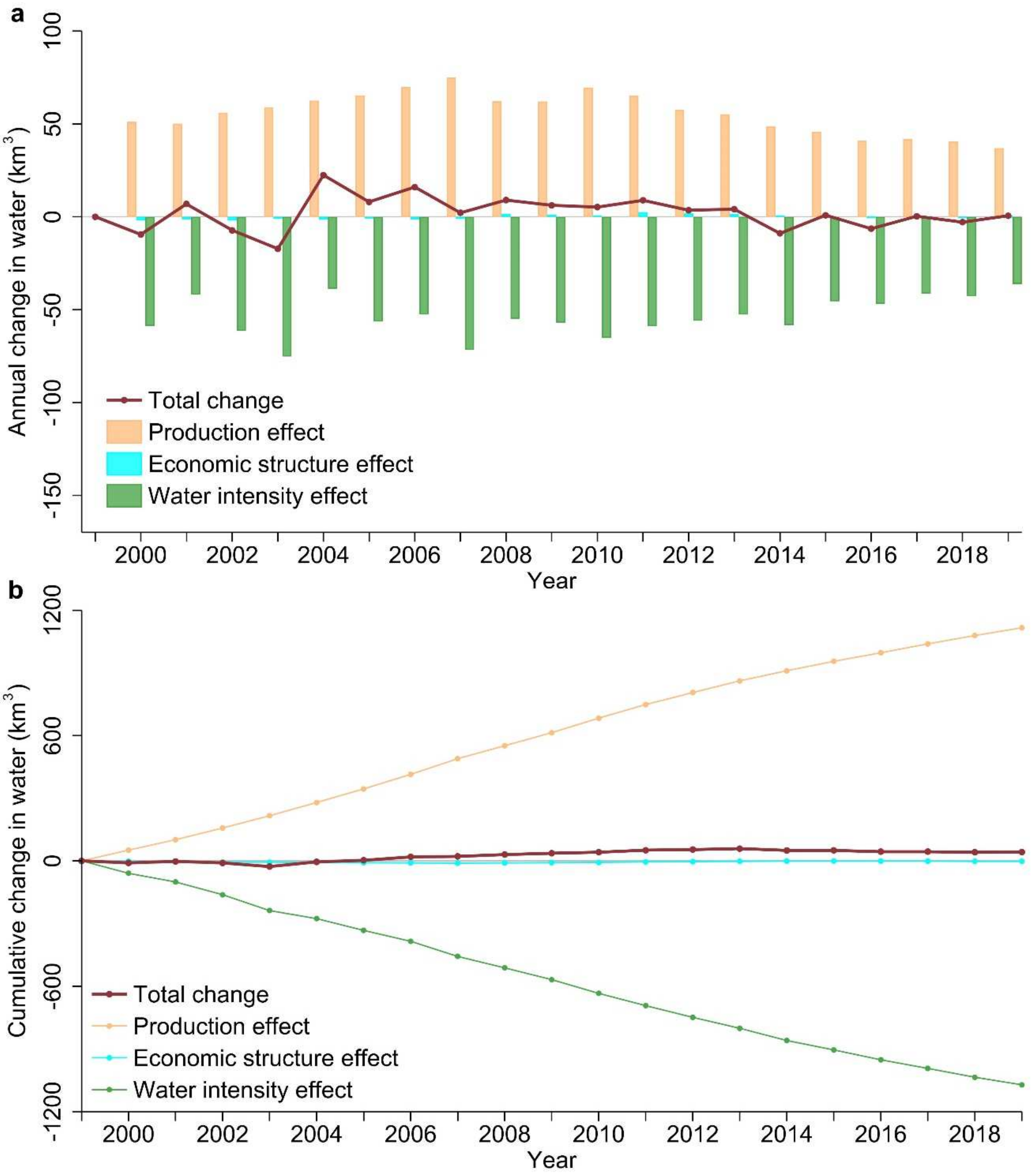

Figure 3. (**a**) Decomposition of the annual change in China's water use, 1999–2019. (**b**) Decomposition of the cumulative change in China's water use, 1999–2019. The year 1999 is the starting point for the calculation. Annual change is the change from immediate prior year to a given year. Cumulative change is the sum of annual incremental change from 1999 to a given year.

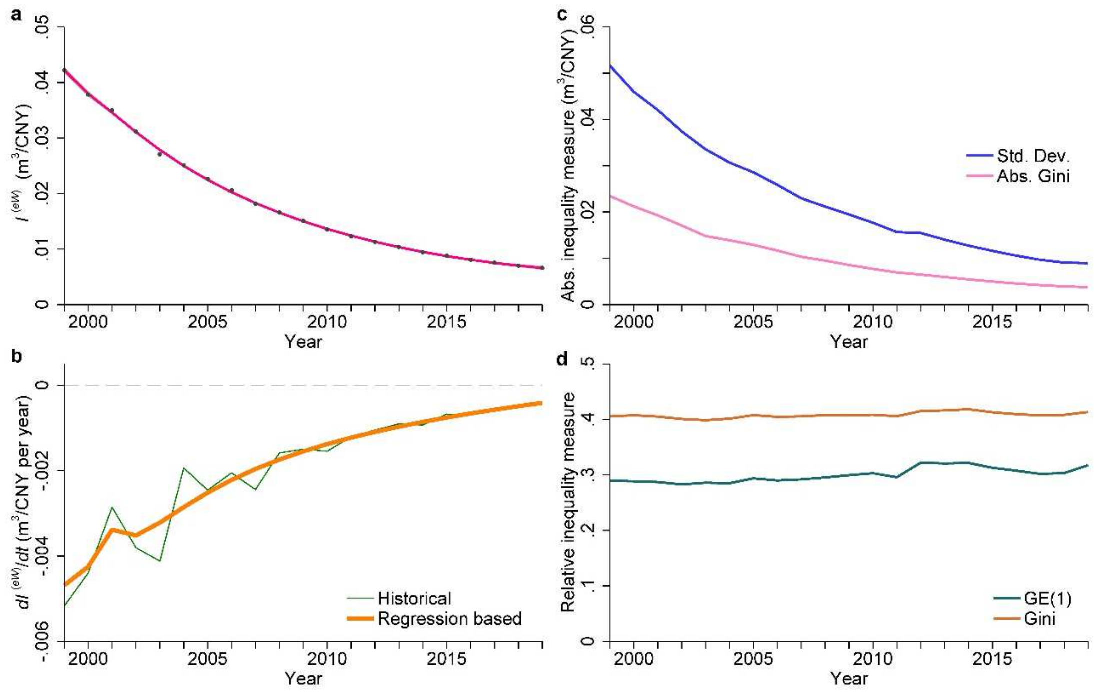

Figure 4. (**a**) China's national water intensity, $I^{(eW)}$, 1999–2019. The black points denote historical data, the pink line denotes trends estimated by fractional polynomial regression models, and the light grey ribbon denotes a 95% confidence interval. (**b**) Numerical derivative of China's national water intensity, $dI^{(eW)}/dt$, 1999–2019. (**c**) Absolute inequality measures of China's provincial water intensities, including standard deviation and absolute Gini index, 1999–2019. (**d**) Relative inequality measures of China's provincial water intensities, including general entropy (GE) measure GE(1), and Gini index 1999–2019.

(1) Period of 1999–2003

China's total WU decreased during the period of 1999–2003. As shown in Figure 3, the production effect was the main factor for the growth in WU, while the intensity effect was the main factor slowing the growth of water use. The economic structure effect was negligible during this period. As shown in Figure 4a and Figure 4b, China's WI rapidly decreased during this period.

As shown in Figure 4c and Figure 4d, both the absolute and relative inequality measures of China's provincial WIs slightly decreased during this period, indicating that the disparities between provincial WIs slightly decreased. Put differently, both absolute gaps and relative disproportionate differences between provincial WIs became smaller during this period.

(2) Period of 2004–2013

China set a target of reducing water consumption per unit of industrial value added by 30% and increasing water efficiency coefficient in agricultural irrigation to 0.5 over the period of 2006–2010 (Casey and Koleski, 2011). In 2011, China further set national "Three Red Lines (TRL)" targets for the years 2015, 2020 and 2030: the first target consists of caps on China's water withdrawals at national, provincial, and subprovincial levels, the second target consists of two indices of water productivity respectively for industrial use and agricultural irrigation, and the third target is to improve ambient water quality (Nickum et al., 2017). TRL is considered as one ambitious environmental policy initiative (Nickum et al., 2017).

As shown in Figure 3, China's total WU increased during the period of 2004–2013. The positive production effect was the major contributing factor (driving force) for the growth of WU, while the negative WI effect was the major contributing factor to slow the growth of water use. The economic structure effect was slightly positive and contributed to the growth of water use in some years, such as in 2011–2012.

As shown in Figure 4a and Figure 4b, China's WI continued to rapidly decrease, but at a decelerated pace during this period. As shown in Figure 4c and Figure 4d, the absolute inequality measures of China's provincial WIs continued to decrease from 2004 to 2013, indicating that the absolute gaps between the provincial WIs generally decreased during this period. It is worth noting that the relative inequality measures of China's provincial WIs increased from 2003 to 2005 and locally peaked around 2005, which aligned with the overheated China's economy during the period 2003–2005.

(3) Period of 2014–2019

During the period of 2014–2019, China's WU stopped the growth that had begun in 2004 and began to decrease again over the 2013 level. As shown in Figure 3, the production effect continued its growth during this period, but it was outpaced by the intensity effect (in terms of absolute values). As a result, the country's WU slightly decreased from 2014 to 2019 over the 2013 level.

As shown in Figure 4a and Figure 4b, China's WI continued to decrease, but at a clearly decelerated pace (in terms of absolute decrease) during this period. As shown in Figure 4c and Figure 4d, both the absolute and relative inequality measures of China's provincial WIs slightly decreased from 2014 to 2019 compared to the 2013 level, indicating that the disparities between the country's provincial WIs continued to decrease during this period but showed a sign of potential stagnation.

In summary, China's WI significantly decreased, while WU slightly increased from 1999 to 2019. Decomposition analysis shows that production effect was the major contributing factor for the growth of WU, and the WI effect was the major contributing factor for slowing the growth of WU. Changes and trends analyses suggest that WI generally followed a decelerated declining trend (in terms of absolute decrease) during the period of 1999–2019, indicating that the WI would likely continue to decrease—but at a much slower pace—in the near future. The disparities between provincial WIs significantly decreased in terms of absolute inequality measures from 1999 to 2019, indicating that the absolute gaps between provincial WIs became smaller from 1999 to 2019, along with the economic growth.

5.3 Water/energy ratio

Figure 5 shows the decomposition of the annual and cumulative changes of China's WER during the period 1999–2019. Figure 6 shows the annual changes of China's WER and corresponding trends and disparity analysis results. Table 2 lists the overall fractional polynomial regression model fit for China's WER during the period 1999–2019. As suggested by figures 5 and 6, the changes of China's WER in 1999–2019 can be approximately classified into three periods: 1999–2005, 2006–2012, and 2013–2019.

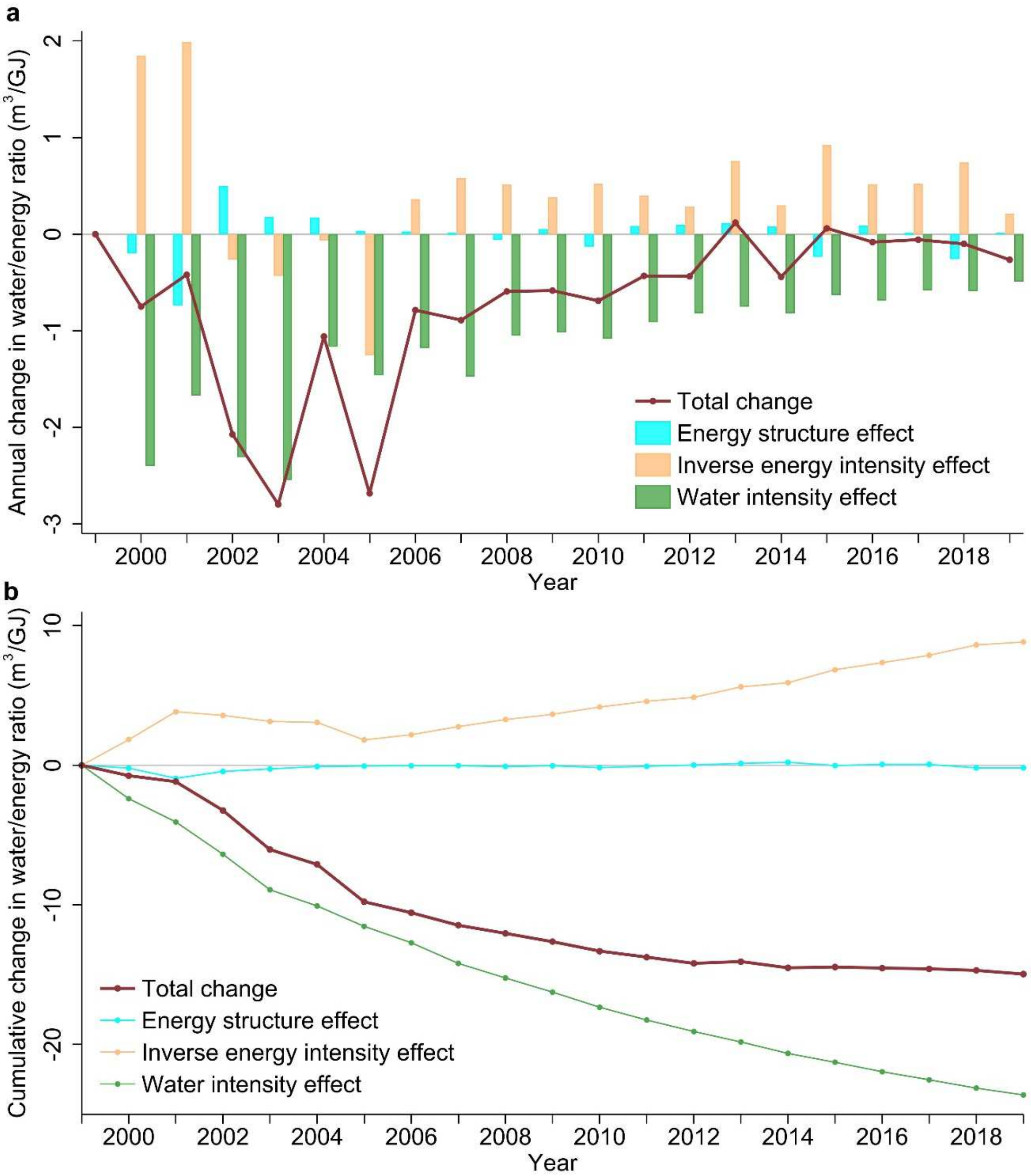

Figure 5. (**a**) Decomposition of the annual change in China's water/energy ratio, 1999–2019. (**b**) Decomposition of the cumulative change in China's water/energy ratio, 1999–2019. The year 1999 is the starting point for the calculation. *Annual change* is the change from immediate prior year to a given year. *Cumulative change* is the sum of annual incremental change from 1999 to a given year.

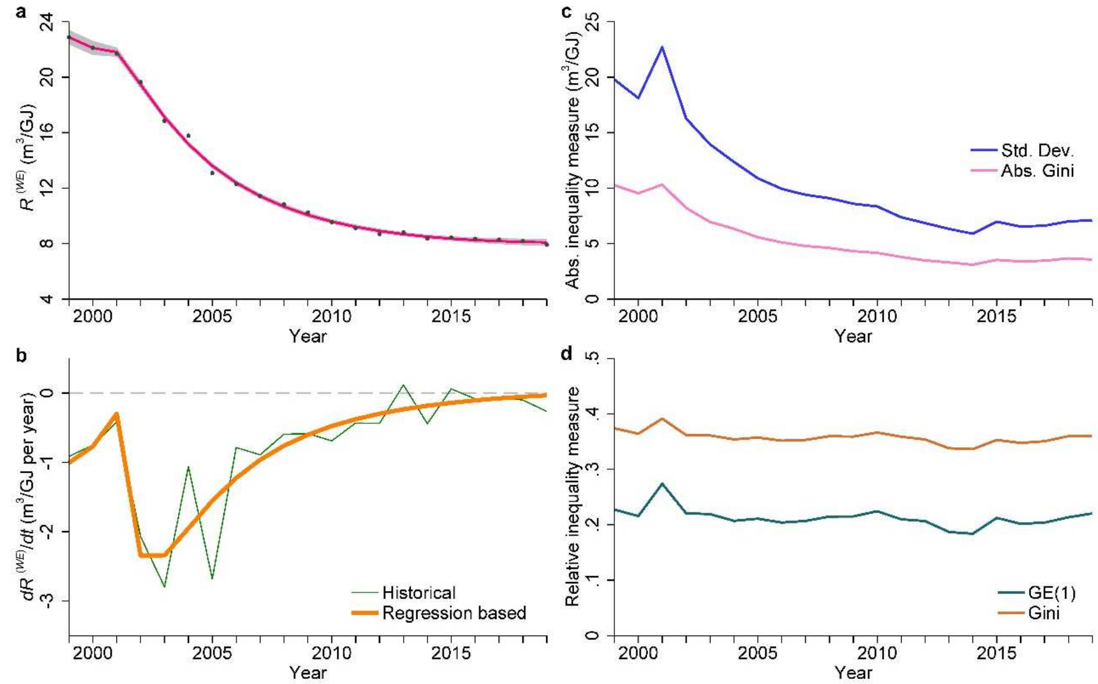

Figure 6. (**a**) China's national water/energy ratio, $R^{(WE)}$, 1999–2019. The black points denote historical data, the pink line denotes trends estimated by fractional polynomial regression models, and the light grey ribbon denotes a 95% confidence interval. (**b**) Numerical derivative of China's national water/energy ratio, $dR^{(WE)}/dt$, 1999–2019. (**c**) Absolute inequality measures of China's provincial water/energy ratios, including standard deviation and absolute Gini index, 1999–2019. (**d**) Relative inequality measures of China's provincial water/energy ratios, including general entropy (GE) measure GE(1), and Gini index, 1999–2019.

(1) Period of 1999–2005

China's WER decreased significantly during the period of 1999–2005. As shown in Figure 5, the WI effect was the main factor for the decrease in WER, while the inverse EI effect was the main factor for slowing the decrease in WER. Because the WI effect was much larger (in terms of absolute value) than the inverse EI effect, the WER showed a decreasing trend during this period.

As shown in figures 6a and 6b, China's WER decreased rapidly during this period. Figures 6c and 6d show that both the absolute and relative inequality measures of China's provincial WERs generally decreased from 1999 to 2005 but experienced some large fluctuations in early 2000s, indicating that the disparities between the provincial WERs were lower by 2005 compared to the 1999 level. Put differently, both the absolute gaps and relative disproportionate differences between provincial WERs became smaller by 2005 compared to the 1999 level.

(2) Period of 2006–2012

China's WER continued its decrease during the period 2006–2012 but at a slower pace compared to the period 1999–2005. As seen in Figure 5, the WI effect contributed to the decrease in WER, while the inverse EI slowed the decrease in the WER. The energy structure effect was negligible during this period.

As shown in figures 6a and 6b, China's WER continued to decrease, but at a slower pace during this period. Figures 6c and 6d show that the disparity between China's provincial WERs continued to decrease in both absolute and relative terms during this period.

(3) Period 2013–2019

China's WER continued its decreasing trend during the period 2013–2019 but at a clearly slower pace (in terms of absolute decrease) compared to the period of 2006–2012. As shown in Figure 5, the WI effect was the main factor for the decrease in water/energy ratio, while the inverse EI effect was the main factor for slowing the decrease in WER. The energy structure effect contributed to the decrease of the water/energy ratio in a couple of years since mid-2010.

As shown in figures 6a and 6b, China's WER only slightly decreased during this period and showed a sign of potential stagnation. Figures 6c and 6d show that both the absolute and relative inequality measures of China's provincial WERs generally stagnated during this period.

In summary, China's WER significantly decreased from 1999 to 2019. Decomposition analysis shows that the WI effect was the main factor for the decrease in the WER, while the inverse EI effect was the main factor for slowing the decrease in WER. Changes and trends analyses suggest that the WER generally followed a decelerated declining trend similar to WI during the period of 1999–2019, indicating that the WER would likely continue to decrease—but at a much slower pace—in the near future. The disparity between provincial WERs significantly decreased in terms of absolute inequality measures from 1999 to 2019, indicating that the absolute gaps between provincial water/energy ratios became smaller from 1999 to 2019, along with the economic growth.

6. Discussions

Economic growth is one of the key factors to achieving some sustainable development goals such as poverty eradication, equity, and decent work (U.N. DSDG, 2021). Energy and water are two critical resources and potential limiting factors for economic growth. Greater efforts should thus be made to improve overall energy–water efficiency (EWE) to support sustainable economic growth while reducing the adverse effect on natural resources and the environment.

EE and water use efficiency are two important indicators for the United Nations' Sustainable Development Goals (U.N. DSDG, 2021). More specifically, EE is one of the indicators for Goal 7—affordable and clean energy, and water use efficiency is one of the indicators for Goal 6—clean water and sanitation.

As demonstrated in this study, China's EWE improved significantly during the period of 1999–2019. It is important for China to curb increasing EWU and achieve resource and environmental protection targets with rapid economic development. It is worth noting that the country's *water use efficiency elasticity* from 1999 to 2019 was greater than one, indicating that the improvement of water efficiency outpaced the country's economic growth during this period. This suggests that there is a relatively lower risk of water becoming a limiting or adverse factor for economic growth (FAO and UN Water, 2021), as long as water resources are managed and developed in a sustainable way.

The changes of EWE (measured by energy–water intensity) in China over time suggest that: (i) EWE is the major factor slowing the growth of the country's EWU; (ii) the country's EWE has been improved significantly but at a decelerated pace in terms of absolute changes; and (iii) the country's EWE improved rapidly when the efficiency level was relatively low, and the improvement significantly slowed when the efficiency level became relatively high (Zhao et al., 2014).

Clean and energy efficient technology adoption is necessary to reach economic, social, and environmentally sustainable development but relies on effective policies, governance and national circumstances (Aldieri et al., 2021; Drago and Gatto, 2022a; Sadik-Zada and Ferrari, 2020). Research indicated that: (i) energy efficiency, when supported by effective policies and programs, can stimulate innovation and green entrepreneurship (Drago and Gatto, 2022a) ; (ii) there is no unique policy which fits every country and better understanding of industries is crucial for tailoring energy efficiency and adaptation policies for sustainable development (Aldieri et al., 2021), (iii) countries at different economic development stages have different thresholds of environmental degradation, and the stringency of environmental policies is endogenous to this threshold (Sadik-Zada and Ferrari, 2020), and (iv) knowledge spillovers from environmental innovations can reduce inefficiency and thus improve the resilience of economies which determine to invest adequately in the transition to cleaner technologies (Aldieri et al., 2021; Drago and Gatto, 2022b).

EE policies are more likely to succeed with an established and effective EE governance system, which includes the legislative framework, funding mechanisms, institutional arrangements and coordination mechanisms needed to support EE implementation (IEA, 2010). According to IEA (2010), EE governance has three main aspects: enabling frameworks, institutional arrangements and coordination mechanisms. The common coordination mechanisms used to coordinate EE policy implementation and track progress include government coordination across and within different levels, target setting, and policy evaluation. These three components of coordination are critical for continuous EWE improvement and directly influence the implementation and effectiveness of EWE policy.

7. Conclusions

Water and energy are two critical natural resources necessary for human activities and socioeconomic development. It is critical to improve EWU efficiency and optimize resources allocation and utilization in a coordinated and sustainable way to support socioeconomic development while reducing adverse effects on natural resources and the environment. By using longitudinal EWU data for China over the past 21 years, this paper presents a temporo-spatial study to address key issues and introduce analytical approaches needed to understand the WEN. The paper's findings can help support integrated resource planning and management to achieve the Sustainable Development Goals, and provide lessons learned for improving integrated energy-water management in China and globally.

Results show that the country's EI significantly decreased from 1999 to 2019, except for the period of 2003–2005 when the country's economy became overheated, while its EU significantly increased during the period 1999–2019. Decomposition analysis shows that the production effect was the major contributing factor for the growth of EU, and the EI effect was the major contributing factor for slowing the growth of energy use. Changes and trends analysis suggest that EI generally followed a decelerated declining trend, indicating that EI would likely decrease at a slower and slower pace (in terms of absolute changes). The disparities between provincial EIs were lower (in terms of absolute inequality measures) by 2019 compared to the 1999 level, indicating that the absolute gaps between provincial EIs became smaller by 2019 compared to the 1999 level. However, the fact that the disparities between provincial EIs peaked in about 2003 in both absolute and relative terms suggests that the overheated Chinese economy during the period 2003–2005 could have widened the disparities between provincial EIs during that period.

The country's WI significantly decreased, while its WU slightly increased from 1999 to 2019. Decomposition analysis shows that the production effect was the major contributing factor for the growth of water use, and the WI effect was the major contributing factor for slowing the growth of water use. Changes and trends analysis suggest that WI generally followed a decelerated declining trend during the period of 1999–2019, indicating that the WI would likely decrease at a slower and slower pace (in terms of absolute changes). The disparities between provincial WIs significantly decreased (in terms of absolute inequality measures) from 1999 to 2019, indicating that the absolute gaps between provincial water intensities became smaller from 1999 to 2019 along with the economic growth.

The country's WER significantly decreased from 1999 to 2019. Decomposition analysis shows that the WI effect was the main factor for the decrease in WER, while the inverse EI effect was the main factor for slowing the decrease in WER. Changes and trends analysis suggest that the WER generally followed a decelerated declining trend similar to WI during the period of 1999–2019. The disparities between provincial WERs significantly decreased in terms of absolute inequality measures from 1999 to 2018, indicating that the absolute gaps between provincial WERs became smaller from 1999 to 2019 along with the economic growth.

This study's results suggest that improving EWE is important for the country to curb increasing EWU and achieve its resources and environmental protection targets with rapid economic development. The disparities between regional EWEs can be reduced along with economic growth, but an overheated economy could widen the disparities and result in unsustainable and inefficient resource utilization. Government coordination, target setting and policy evaluation as part of the overall EE governance system are also critical for continuous EWE improvement and directly influence the implementation and effectiveness of EWE policy.

The insights from this study can help stakeholders and analysts better understand the uneven temporo-spatial distribution of the WEN and underlying contributing factors to the WEN in a country or region to support integrated resource planning for equitable and sustainable development. Designing and coordinating EE strategies, policies, and programs that address these disparities can help improve integrated resource planning for the WEN. The insights from this study also could be helpful for emerging economies that rely heavily on water and energy resources to develop their economy while facing sustainability challenges.

While this study can be useful in several ways, it is not exempt from limitations. The longitudinal data used for the study had missing total energy consumption values for two provinces over a few years, which required data imputation. This study adopted an interpolation method to impute the missing total energy consumption by referring to the electricity consumption data. Nevertheless, the data imputation for those two provinces over a few years had very limited effect on the outputs of the study.

Future research may investigate different regions or countries. By using different datasets and/or different variables as well as indicators, different aspects of resources utilization and efficiency governance in support of Sustainable Development Goals could be explored and compared, to support region- or country-specific resources utilization and sustainable development policymaking. Future studies could extend timespan or compare different development stages or economic cycles, to further assess the temporal changes over longer term or different stages or cycles. Future research could also use alternative analytical methods or techniques to broaden or deepen the understanding of the nexus of resources utilization, efficiency governance and economic growth to support achieving Sustainable Development Goals.

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