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Regional difference of water use in a significantly unbalanced developing region

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Abstract

With a service for the most developed economy and dense population in China, the water use of Guangdong province shows distinct regional difference and is subject to multiple driving forces. The regional differences of total water use (TWU) and water use efficiency (WUE) for Guangdong province and its four sub-regions (i.e. Pearl River Dealt region (PRD), Eastern Wing (YD), Western Wing (YX), and Northern Mountain Region (YB)) were quantified by Theil index, and the influence of various variables on WUE was evaluated through multiple linear regression (MLR) models. Overall, Theil index of TWU showed a decreasing trend whereas Theil index of WUE increased in recent decades, suggesting that Guangdong province has experienced an enlarging regional difference of WUE along with a gradually weakened regional difference of TWU. The PRD has the most significant regional differences of WUE and TWU and accounts for a predominated proportion in the total regional difference. Theil indexes of GDP of industry, per capita GDP and per capita value-added by agriculture had positive regression coefficients and were found to have the most significant impact on the regional difference of WUE. This study has the potential to promote a balanced and coordinated regional development in terms of even regional WUE and TWU.

Keywords: Guangdong province; Multiple linear regression model; Regional difference; Theil index; Water use

Highlights

- The detection of the regional water use difference is essential to remove the barriers to regional socioeconomic development and to achieve a balanced and uniform development of an unbalanced developing country like China by implementing a water resources management policy of balanced regional development in terms of WUE and TWU.

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Introduction

Water provides the foundation for regional development, since water resources are crucial for socioeconomic growth, food production and energy generation (Duncan *et al*., 2019; Wang, 2019). In fact, regional water use is more complex and dynamic under climate change and rapid socioeconomic development, and the complexity is even exacerbated by uncertainty in hydrological systems (Xu & Singh, 2004; He *et al*., 2015; Her *et al*., 2019), population and economic growths, industrial structure, policy change and unknown interaction effects (Khatri *et al*., 2018; Wang & Davies, 2018; Sun *et al*., 2019). The different levels of regional socioeconomic development as well as the uneven distribution of water resources has resulted in the inequality of water use that can reflect the degree of regional sustainable development some way (Tan & Liu, 2017; Cole *et al*., 2018; Guo *et al*., 2019). In the face of increasing regional differentiation, a relatively coordinated development, including even regional water resources exploitation in terms of spatial and temporal patterns, is an inevitable requirement for sustainability (He *et al*., 2019). For example, the 19th CPC (Communist Party of China) National Congress (held in 2017) announced that the principal contradiction facing Chinese society has been transformed into one between unbalanced development and the people's ever-growing needs for a better life. Water resources are the basis of Chinese territorial space planning and have a strategic position in the national development. An even water resources exploitation is carried out according to the spatiotemporal evaluations of future water resources and water demands of the country, and determines regional water resources carrying capacity (WRCC). WRCC is the rigid constraint to formulate the balanced development strategy of China and the infrastructure allocation of the nation is improved on the premise of even water resources exploitation. All these contribute to balanced population distribution and regional economy layout over the country. With regard to more balanced water resources exploitation in China at the macro levels, many literature studies have explored the distribution of water use and assessed the spatial inequalities and spillover effects of real water use, virtual water and water footprint on multiple levels (Feng *et al*., 2014; Zhao *et al*., 2014; Sun *et al*., 2017). The spatial patterns and regional differences of inequality in water resources exploitation was also investigated on a national scale (He *et al*., 2019). Many of the above studies have concluded that water use efficiency (WUE) is one of the main drivers of inequality in the agricultural water footprint, which is the largest contributor of the equality of the total water footprint in China, and water shortage or the inequality of water use in China will be alleviated by the transfer of virtual water and the enhancement of WUE. However, the regional difference of water use, being the foundation of virtual water transfer among regions, is still unclear, particularly in a significantly unbalanced developing region. So far, the key factors that drive regional difference of water use are unknown.

Regional water use could show different characteristics in certain developing phases, along with regional population growth and economic development. This is more apparent in an unbalanced developing region. Water use difference between developed and less developed regions could be quantified in terms of WUE and total water use (TWU). WUE and TWU are also the two important indicators of regional water resources exploitation (He *et al*., 2019). Given that the even water resources exploitation is the foundation of the balanced regional development, the even WUE and TWU are essential to promote balanced and coordinated development across the country. WUE could directly show the level of regional water use. Improving WUE has been recognized as one of the two better ways to support sustainable development (Song *et al*., 2018). TWU is also influenced by WUE (Zhao *et al*., 2017). The Chinese Central Government issued 'The Most Stringent Water Management System' (so-called 'Three Red Line Policy') as the annual 'No. 1 Document' in January 2011, to effectively solve the problems of low WUE and water waste (Deng *et al*., 2016; Hong *et al*., 2017; He *et al*., 2019). 'Red line of water use efficiency' and 'Red line of total water use' are the two lines of 'Three Red Line' (the third line is 'Red line of the pollutants releasing into water functional areas'). For example, 'Red line of total water use' has set the maximum amount of TWU for each province of the country in 2020 and 2030. Given the unbalanced development of economy and society in a region, WUE and TWU within a region may show spatiotemporal variation. Such a variation could be intensified by climate change, regional development policy, land use change, etc. Regional difference of water use, on one hand, indicates regional socioeconomic development level, on the other hand, it has compound impacts on regional water security. For example, the sub-region with high TWU and low WUE will consume larger amounts of water resources and produce a great deal of waste water and domestic sewage, face water ecological degradation, water pollution and water shortage exacerbated by fast economy growth and dense population, and therefore exert pressure on water security of the whole region.

Guangdong province is a coastal province with a localized high level of socioeconomic development in China. The development of Guangdong province could be considered as a typical example of China. The province has experienced rapid economic growth and GDP of the province has been ranked at first in many provinces of China since 1988. However, distinct regional disparity and polarization exist in Guangdong province, largely due to the geographic location and regional development policy (Yuan & Wu, 2013). Guangdong remains one of the most economically uneven provinces in China in recent years (Liao & Wei, 2015; Zhang *et al*., 2018). According to the socioeconomic development level and geographic location, Guangdong province was divided into four regions (Figure 1): the Pearl River Delta

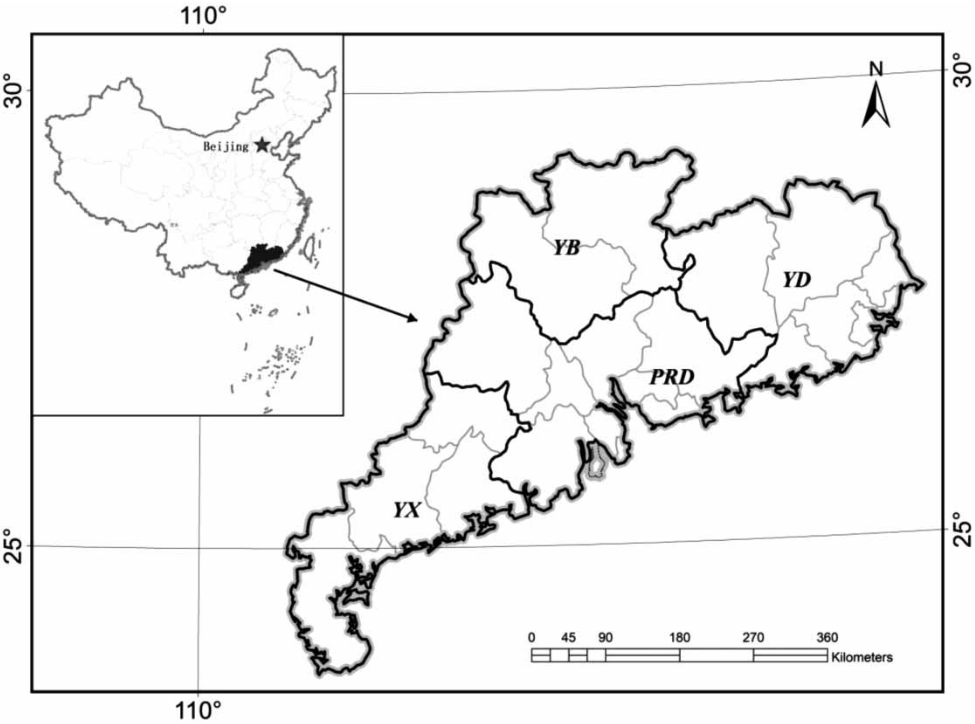

Fig. 1. Location of Guangdong province and the four sub-regions.

region (PRD), the Eastern Wing (YD), the Western Wing (YX), and the Northern Mountain Region (YB), and there is a decreasing pattern of economic development from the PRD to the outer area of YD, YX and YB (Qian & Chen, 2012). Per capita GDP, urbanization rate, and population density of the PRD is remarkably higher than the other three regions. Such an unbalanced development within Guangdong province results in the differences of WUE and TWU among the four regions. Water use difference, in turn, has great impacts on the regional water security of the whole province.

Given this, in the current study, understanding the WUE and TWU of the above four regions in Guangdong province were taken as the research objectives, and the Theil index was used to analyze the change of the differences of WUE and TWU among the whole province and its four regions during 2000–2016. The four regions correspond to the four groups. The regional differences of WUE and TWU of Guangdong province were decomposed into intra-group and inter-group gaps. The purpose of this study is to quantify the regional difference of water use and develop the multiple linear regression model with an application to water use data for Guangdong province, in order to identify important factors influencing such a regional difference of water use. Through identifying the regional difference of water use and the possible drivers behind such difference, the current study contributes to an evaluation of the regional water use level and allocations of the regional water resources and the policy decisions for sustainable water resources exploitation in China. Furthermore, the detection of the regional water use difference is essential to remove the barriers to regional socioeconomic development and to achieve a balanced and uniform development of an unbalanced developing country like China by implementing a water resources management policy of balanced regional development in terms of WUE and TWU.

The paper is organized as follows. A data collection as well as detailed method is explained in the following section. In the Results and discussion section, we mainly compare and discuss the results of regional differences of TWU and WUE indicated by the Theil index and possible driving forces behind such regional differences of water use. Finally, the conclusions are summarized.

Methodology

To reflect the regional differences of TWU and WUE, the Theil index was applied to measure such differences in Guangdong province from 2000 to 2016 at the prefecture level, decomposing the intra-regional and inter-regional differences, and the multiple regression model was used to explore the possible causes of the regional differences of TWU and WUE in Guangdong province.

Data collection

In the current study, a balanced socioeconomic development data and water use data were collected for 21 prefecture levels in Guangdong province from 2000 to 2016. The socioeconomic development data (e.g. gross domestic product (GDP), population, urbanization rate, and effective irrigation area) for the individual prefecture level are available from the Guangdong statistical yearbook. The total water resources (surface and groundwater counted separately), the gross water use data of each sector (i.e. residential, agricultural, industrial and tertiary water use) at prefecture level were obtained from the Guangdong Water Resources Bulletin. The above socioeconomic development data and gross water use data were compiled annually at the prefecture level and issued by the Guangdong Bureau of Statistics (GBS) and the Guangdong Hydrology Bureau, respectively. All the data are publicly available online. For this study, WUE is defined as GDP divided by the total gross water use, according to previous research on water use (Papadopoulou *et al.*, 2016; Hsieh *et al.*, 2019). In this study, WUE was used as a dependent variable to understand the various influencing factors that have impacts on the WUE of each sub-region (Table 1). As shown in Figure 2, the TWU (10^9 m^3) of Guangdong province and the four sub-basins had slight fluctuations before 2012 and decreased after then, while WUE ($/$m^3$) increased steadily throughout the study period from 2000 to 2016. This can be further demonstrated by the standard deviations and variation coefficients of TWU and WUE (Figure 3). Of the ten influencing factors (Table 1 and Figure 4), *GDPI*, *PCVAA* and *PCGDP* have a continuous increasing trend, whereas *WCIAV* has a persistent decrease, and others exhibited yearly variations which differed from the strictly upward or downward temporal trend of *GDPI*, *PCVAA*, *PCGDP* and *WCIAV*. Two key questions are: (i) What are the differences of the four sub-regions in terms of TWU and WUE? and (ii) To what extent can the differences of TWU and WUE be explained by the influencing factors? However, visual inspection

Table 1. Possible influencing factors of WUE.

Dependent variables in the models	Abbreviation	Definitions	Units	Source
Per capita water resources	PWR	$\frac{TWR^b}{TP^c}$	m^3	a: CWRB,CSY; b: CSY
Precipitation	P	–	1	CSY, CWRB
Runoff coefficient	RC	$\frac{TWR^b}{P}$	1	b: CWRB
Total population	TP	–	1	CSY
Per capita GDP	PCGDP	$\frac{TGDP^d}{TP^c}$	$	d: CSY; c: CSY
GDP of industry	GDPI	–	$	CSY
Water consumption per 10,000 yuan of value-added by industry	WCIAV	$\frac{10000TWC^e}{IAV^f}$	m^3	e: CWRB; f: CSY
Per capita value-added by agriculture	PCVAA	–	$	CSY
Water consumption of real irrigation per mu[a]	WCRIM	$\frac{TWCRI^g}{IA^h}$	m^3	g: CWRB, CREDY; h: CSY, CREDY
Per capita domestic water consumption	PDC	$\frac{DWU^i}{TP^c}$	L/d	i: CWRB; c: CSY
Invest in education	IIE	–	$	CSY

Note: CWRB: the China Water Resources Bulletin; CSY: the China Statistical Yearbook; CESY: the China Environmental Statistical Yearbook; CREDY: the China Regional Economic Development Yearbook.
The letter in the upper right of abbreviation represents the data source.
Each variable in the equation above is directly extracted from CWRB, CSY, CESY or CREDY at the provincial level.
[a]mu is a unit of area (= 0.0667 hectares).
[b]TWR*WR* is Total Water Resources, including annual surface and ground water.
[c]TP*P* is Total Population.
[d]TGDP*GDP* is Total Gross Domestic Product.
[e]TWC*WC* is Total Water Consumption, including annual domestic, industrial, agricultural and off-stream water consumption.
[f]IAV*AV* is Industrial Added Value.
[g]TWCRI*WCRI* is Total Water Consumption of Real Irrigation.
[h]IA*A* is Irrigation Areas.
[i]*DWU*TEIA is Domestic Water Use.

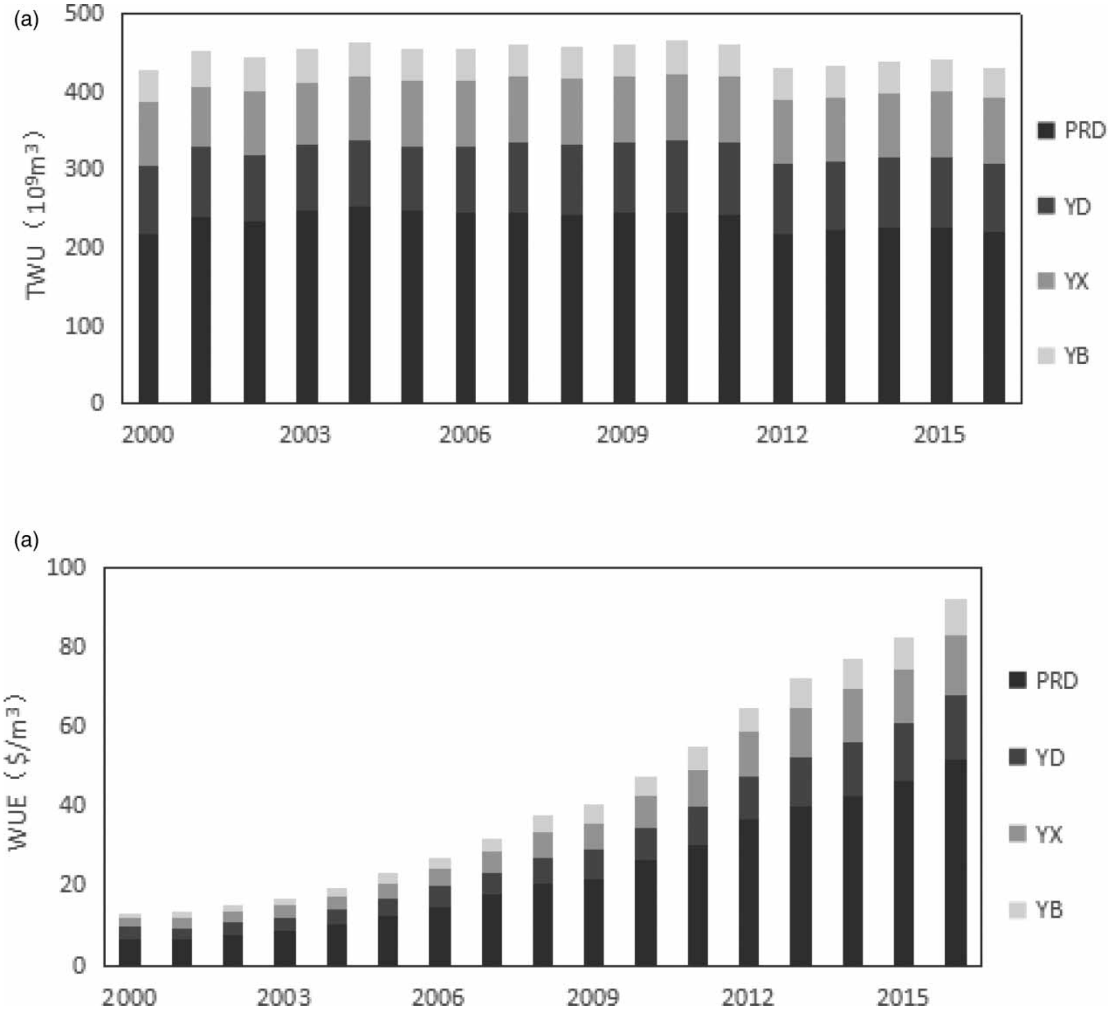

Fig. 2. TWU and WUE for the four sub-regions in Guangdong province from 2000 to 2016. (a) TWU, (b)WUE.

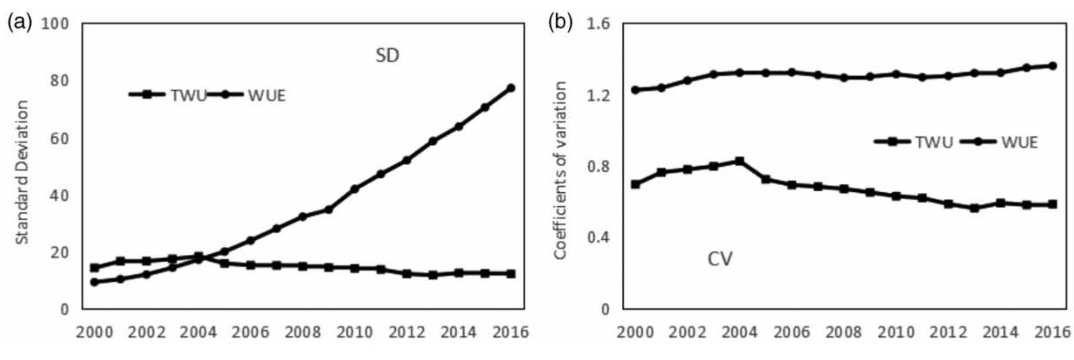

Fig. 3. Variations of TWU and WUE for Guangdong province.

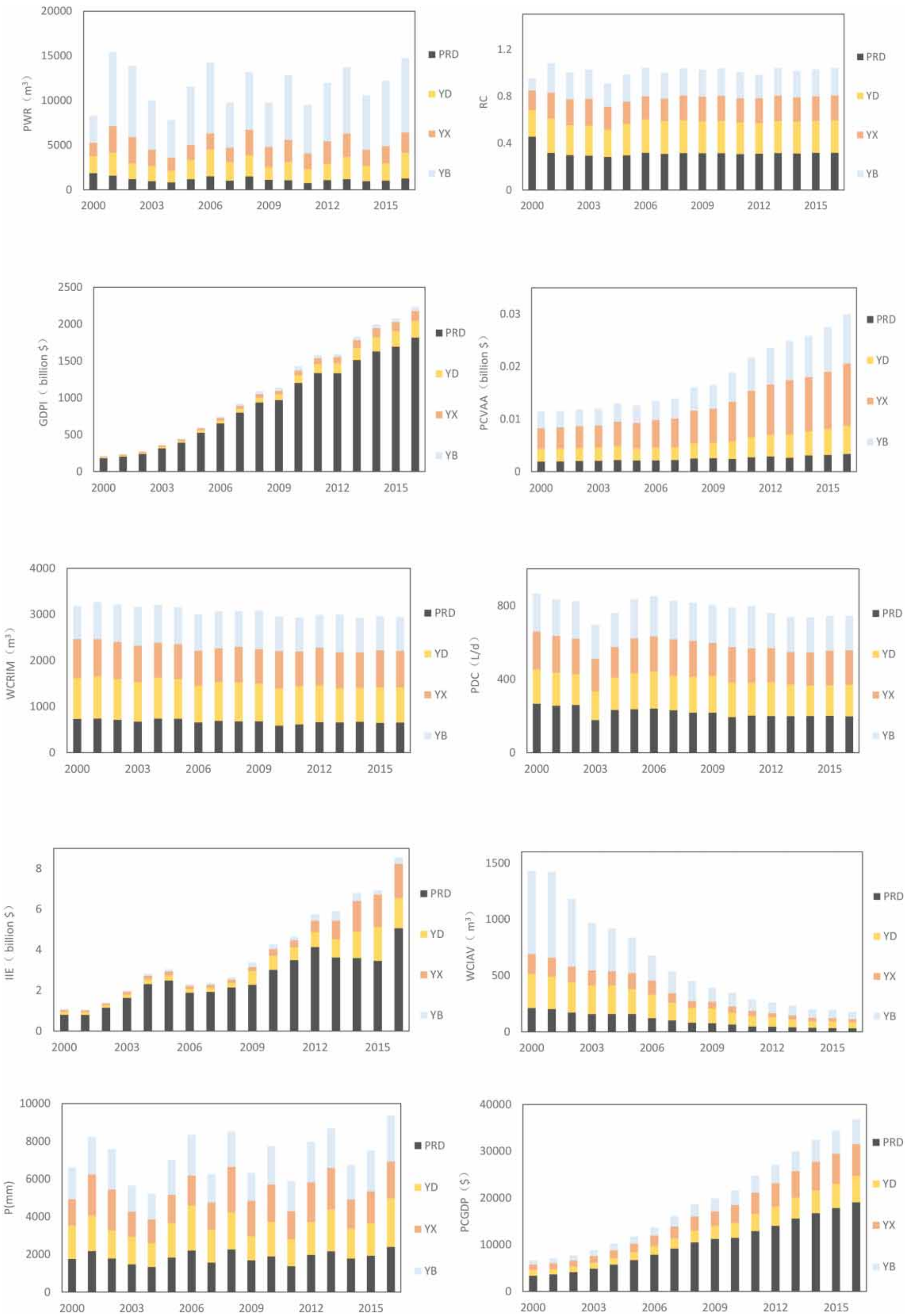

Fig. 4. Values of explanatory variables in the MLR models.

of the data set cannot provide a clear answer to these questions. Instead formal methods are needed to identify and isolate the contributions of each influencing factor. The multiple linear regression (MLR) models described in the following sections were designed to accomplish this objective.

The MLR models were fitted to historical WUE for Guangdong province and the four sub-regions. The Theil indexes of several possible influencing factors (Table 1), including precipitation, per capital water resources, per capital GDP, industrial value, industrial added value, population, per capital residential water consumption, and invest in education, are considered as independent variables, whereas the Theil index of WUE is considered as a dependent variable in the analysis, covering natural and socioeconomic aspects of influencing factors. The possible influencing factors in Table 1 were chosen as candidates for inclusion in the various models based on previous studies on water use.

Theil index

The Theil index measures the inequality and difference according to the concepts of information quantity and entropy (Ausloos *et al.*, 2019). It decomposes the overall difference into within sub-region difference and between sub-region difference, and has wide applications in the decomposition and analysis of difference and inequality. The Theil index has been applied to assess the inequality in water supply (Malakar *et al.*, 2018), the cross-scale water resource vulnerability (Chen *et al.*, 2016) and so on, and it is demonstrated as a useful quantitative evaluation method of water resources management.

Taking the regional difference of WUE for instance, the Theil index is calculated as follows (Malakar *et al.*, 2018):

$$T_b = \sum_{k=1}^{K} y_k \cdot ln\left(y_k \Big/ \frac{n_k}{n} \right) \tag{1}$$

$$T_w = \sum_{k=1}^{K} y_k \sum_{i=1}^{n_k} \frac{y_i}{y_k} ln\left(\frac{\frac{y_i}{y_k}}{\frac{1}{n_k}} \right) \tag{2}$$

$$T = T_b + T_w \tag{3}$$

where K is the number of sub-regions, n_k is the number of cities in a sub-region k, n is the total number of cities, y_i and y_k are the WUE of city i and sub-region k, respectively, T_b is the within sub-region of Theil index and T_w is the between sub-region of Theil index.

In the current study, Guangdong province is divided into four sub-regions, and Theil indexes of WUE and TWU from 2000 to 2016 were calculated according to Equations (1)–(3).

Multiple linear regression

The multiple linear regression analysis, as a way of dealing with the statistical correlation relationships among various variables, is usually used to detect the correlation relationship between a dependent variable and some independent variables (Adamowski *et al.*, 2012). It has been widely used in water demand forecasting and water supply system planning (Haque *et al*., 2017; Cabral *et al*., 2019). In the current study, the MLR models are used to quantify the impacts of the independent variables on WUE of Guangdong province and the four sub-regions. A linear equation involving explanatory variables is fitted to the observed data presented in the MLR model. Multiple linear regression coefficients are chosen for the independent variables to estimate the corresponding dependent variable, according to the least square errors. In this study, five MLR models were developed to detect the possible driving forces behind the WUE at sub-region and provincial levels.

The MLR equation is shown as (Marchionni *et al*., 2016):

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i \; i = 1, 2, \ldots, \mathrm{n} \tag{4}$$

where Y is dependent variable, X_i is independent variable, β_i is linear regression coefficient, and n is the total number of independent variables.

In the current study, Y represents the Theil index (T) of WUE for the whole province and the four sub-regions, $X_i(i = 1, 2, \ldots, 11)$, representing the T of each possible influencing factor shown in Table 1, is the explanatory variable. The MLR models were fitted using all yearly data from 2000 to 2016 for WUE and the possible influencing factors.

Results and discussion

Regional differences of TWU and WUE indicated by the Theil index

Theil indexes of TWU and WUE for Guangdong province and the four sub-regions were calculated according to Equations (1)–(3). As shown in Figure 5(a), the Theil index of TWU for the whole province had a slight increase during 2000–2004 and decreased steadily after then, indicating that the regional difference of TWU has had a predominantly decreasing trend over recent decades. The WUE of the whole province exhibited both periods of increase and decrease, and followed a predominantly increasing trend over the period 2000–2016, suggesting that the regional difference of WUE has been enlarged in Guangdong province in recent years, which is the opposite to that of TWU. Additionally, WUE has a higher value of Theil index than that of TWU for each year, indicating that more regional difference occurs for WUE when compared to TWU in Guangdong province during this period.

Theil indexes of TWU and WUE for the whole province (Figure 5(a)) consist of two parts: Theil index within sub-regions and Theil index between sub-regions. The two parts of Theil indexes are shown in Figure 5(b)–5(f), respectively. Similar to the whole province, the Theil index value of WUE was higher than that of TWU in all sub-regions except YB, in which the Theil index value of WUE has almost the same curve as TWU (Figure 5(d)), and they both remain at the lowest level with very little net change over the study period when compared to other sub-regions. It can be inferred that both regional difference of TWU and WUE in YB are insignificant and they contributed little to the regional difference of TWU and WUE for the whole province. Out of all the four sub-regions, the PRD had the highest Theil index value of both WUE and TWU over the study period (Figure 5(e)), indicating that the regional difference of WUE and TWU in the PRD was more significant than other sub-regions in Guangdong province. The Theil index values of both WUE and TWU in YD (Figure 5(b)) and YX

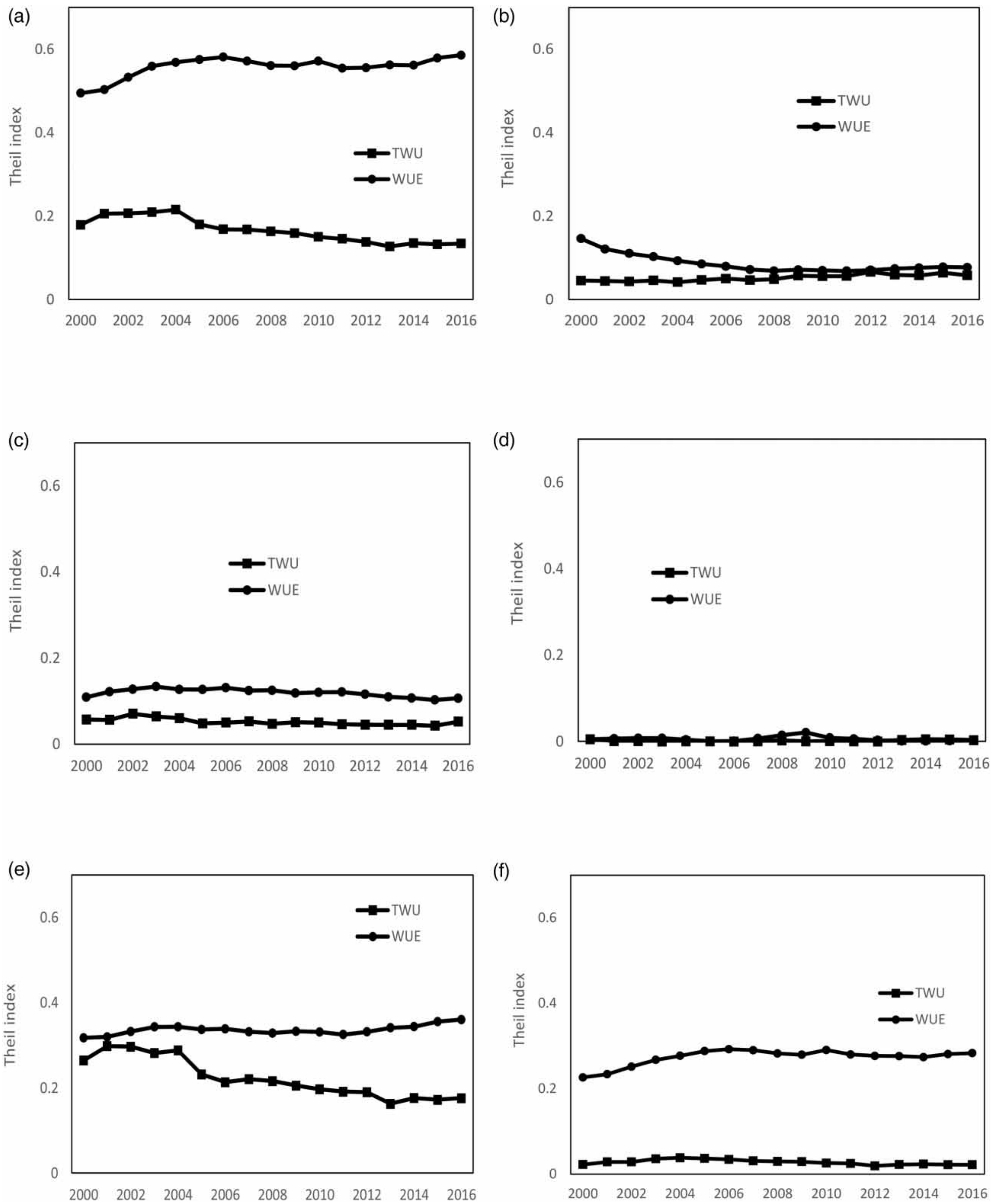

Fig. 5. Theil indexes of TWU and WUE for Guangdong province and the four sub-regions. (a) Whole province, (b) YD, (c) YX, (d) YB, (e) PRD, (f) Between.

(Figure 5(c)) are all below 0.2, while in the PRD, most of the Theil index values are above 0.2, particularly for WUE. In addition, the curves of WUE and TWU in the PRD are very similar to that of the whole province, suggesting that regional differences of WUE and TWU in the PRD played a dominant role in the whole province.

With regard to the Theil index between sub-regions (Figure 5(f)), it has a similar changing trend with the Theil index of the whole province. TWU had little change while WUE had a slight increase over recent years. Compared to the Theil index of TWU within the whole province, the Theil index of TWU between sub-regions of the whole province only accounted for a small proportion (Figure 6(a)) and therefore played a weak role in the regional difference of TWU in Guangdong province. This is different from the Theil index of WUE, in which the contribution rates of the Theil index within the whole province are larger than those of the Theil index between sub-regions before 2004 and after 2012 (Figure 6(b)), indicating that both the differences within the whole province and between sub-regions contributed greatly to the difference of WUE in the whole province.

Possible driving forces behind such regional differences of water use

Given that total water use and water use structure (i.e. the proportion of domestic, productive and ecological water use) were stable during 2000–2016 (Figure 2(a)) and the influencing factor is simple, while the change of WUE and its influencing factors are complex, a concise and qualitative analysis of possible driving forces is given for TWU, and the MLR analysis of driving forces is given for WUE.

TWU in Guangdong province was initially driven by the socioeconomic development and was strictly limited by the 'Three Red Lines' implemented by the Chinese central government since 2012. A total amount of water resources is given for the whole province and TWU should not exceed such a given amount. Therefore, although the whole province has experienced a growing population and rapidly developing economy in recent decades, the TWU of each year was stable and has even decreased since 2012. The performances of the MLR models for WUE were evaluated using Matlab 2012a. Five separate models corresponding to the whole province and the four sub-regions were developed considering the same time step and explanatory variables associated with

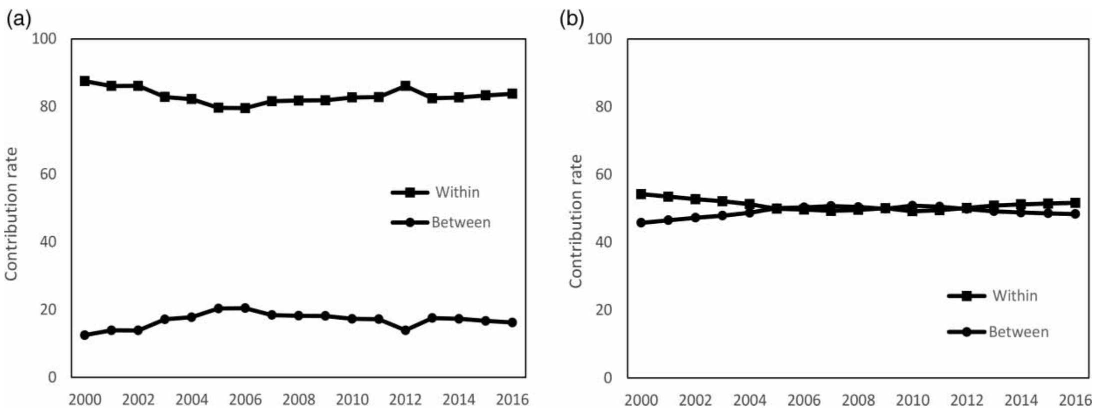

Fig. 6. Contributions of the within- and between-group differences to the total difference of TWU and WUE. (a) TWU, (b) WUE.

WUE. Analysis of the results demonstrate the variation of factors that influence WUE in the whole province and its four sub-regions.

Performance evaluations of the five MLR models

The performances of the five MLR models were evaluated using the coefficient of determination (R^2), standard deviation (SD), and *F* value, since the three parameters are dimensionless and usually not affected by scale of unit differences between the dependent variables. They could provide general indications of model performance. Figure 7 shows the SD, R^2 and F value for the five models. Out of all the five models, the MLR model for the YD had the highest R^2 of 0.99 indicating that 99% of the variability of the difference of WUE was explained by the linear relationship with the explanatory variables. The MLR model for the YB, on the other hand, had the lowest R^2 of 0.75 because only two explanatory variables were significant in the model. For SD and F values, the MLR model for the YD has the highest F value whereas the lowest SD compared to the other four models. All the models are significant in terms of F value at 0.01 significance level. The SD of four models is less than 1, although the MLR model for the whole province has a larger SD greater than 1. Overall, the three parameters demonstrate that the five MLR models had good performance and could be used to reveal the relationship between the differences of WUE and the possible influencing factors.

Significant variables identified in the model

Significant variables with *p*-values below 0.05 were kept in the MLR models. Equations (5)–(9) show the MLR models with only significant variables ranked. The results of the MLR models show the

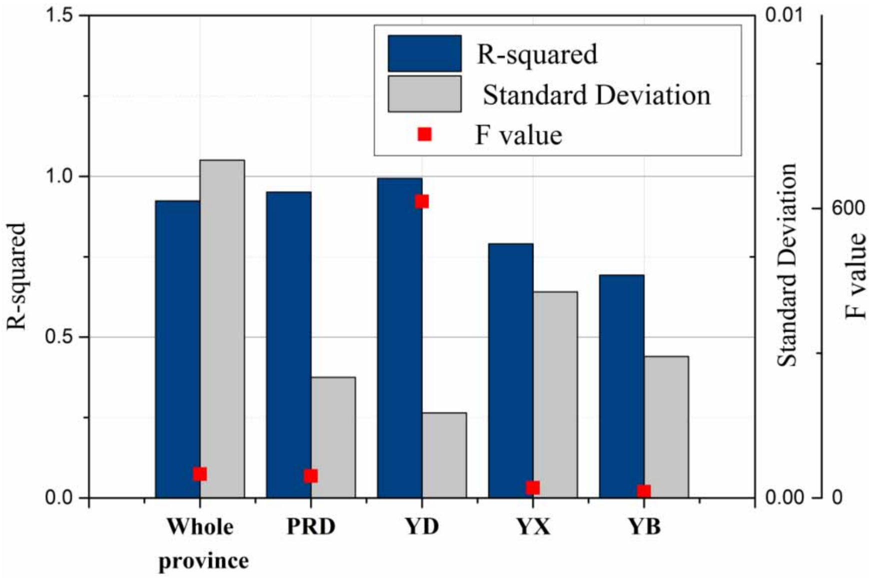

Fig. 7. Performance of the five MLR models.

differences of main factors influencing WUE for the whole province and the four sub-regions (Figure 8).

$$T_{WUE} = 0.55 + 0.85T_{PCGDP} - 0.09T_{IIE} - 0.73T_P + 0.59T_{WCRIM} \quad (5)$$

As shown in Equation (5) and Figure 8(a), the difference of WUE for the whole province was highly influenced by *T* of per capita GDP (a*PCGDP*), invest in education (*IIE*), precipitation (*P*) and water consumption of real irrigation per mu (*WCRIM*). An increase of one unit of *T* of *PCGDP* in the

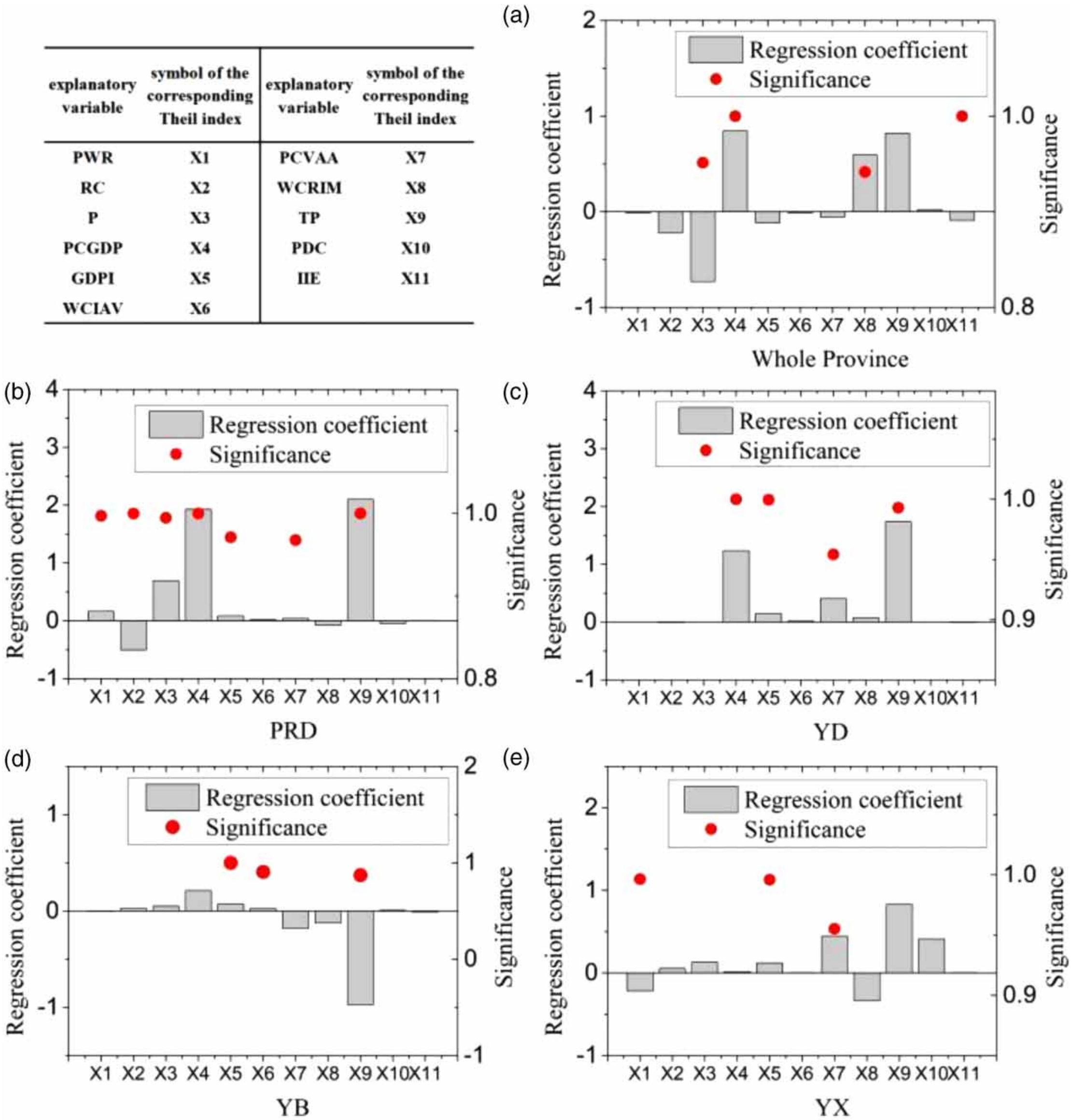

Fig. 8. Significant variables and their regression coefficients for each MLR model.

model yields 0.85 units of *T* of WUE per year. An increase of one unit of *T* of *IIE*, however, leads to a decrease of 0.09 units of *T* of WUE. An increase of one unit of *T* of *P* decreases 0.73 units of *T* of WUE per year, and finally, an increase of one unit of *T* of *WCRIM* increases 0.59 units of *T* of WUE per year. It is clear that *PCGDP* and *WCRIM* have positive correlations with WUE whereas *IIE* and *P* do not. This is reasonable, as both *PCGDP* and *WCRIM* are the two important indicators of WUE, and the higher differences of the two indicators, the more difference of WUE would be. However, *IIE* and *P* are associated with comprehensive quality of human resources and water resources, respectively, and the increases of *T* of *IIE* and *P* within the whole province contribute to the even distribution of economy development and utilization of water resources and therefore decrease *T* of *PCGDP*. As for the whole province, it suggests that emphasis should be placed on improving the economy level in less developed areas and enhancing the balanced development of agriculture, including the adjustment of planting structure and introduction of advanced irrigation technology.

$$T_{WUE} = -0.06 + 0.16T_{PWR} - 0.50T_{RC} + 0.70T_{P} + 1.93T_{PCGDP} + 0.09T_{GDPI} + 0.04T_{PCVAA} + 2.1T_{TP} \quad (6)$$

The MLR model for the PRD, Equation (6) as well as Figure 8(b), indicated that *T* of per capita water resources (*PWR*), runoff coefficient (*RC*), *P*, *PCGDP*, GDP of industry (*GDPI*), per capita value-added by agricultural (*PCVAA*) and total population (*TP*) were statistically significant. However, *T* of *WCRIM* and *IIE* were not significant. The MLR model shows that an increase of one unit of *T* of *RC* yields a decrease of 0.5 units of *T* of WUE per year. An increase of one unit of *T* of *PWR* leads to an increase of 0.16 units of *T* of WUE per year while an increase of one unit of *T* of *P* leads to an increase of 0.7 units of *T* of WUE per year. Moreover, an increase of one unit of *T* of *PCGDP*, *GDPI*, *PCVAA* and *TP* leads to an increase of 1.93, 0.09, 0.04 and 2.1 units of *T* of WUE per year, respectively. Among the seven significant variables, besides some indicators of WUE (*T* of *PCGDP*, *GDPI*, *PCVAA*), *T* of *PWR* and *T* of *P*, indicators of amount of water resources as well as *T* of *TP*, also have positive correlation with *T* of WUE. This is different from that of the whole province. Because the PRD is economically developed with a dense population, total water use is mainly made up of industrial, tertiary and domestic water consumption. The higher variability of water resources could impact the water use of some industries and the increases in *T* of PWR and *T* of *P*, then increase *T* of WUE to some extent. Additionally, *T* of *TP* has a positive correlation coefficient whereas *T* of *RC* has a negative coefficient. Because *TP* determines the domestic water consumption, and increase of *T* of *TP*, therefore the variability of domestic water consumption increases and finally increases *T* of WUE. As for *RC*, the increase of *T* of *RC* represents the increase in the uneven distribution of water resources, contributes to the even utilization of water resources and therefore decreases *T* of WUE. This indicates that it is necessary for the PRD to adopt a spatial equilibrium layout of industry and population in urban planning and achieve a more balanced socioeconomic development:

$$T_{WUE} = -0.07 + 1.24T_{PCGDP} + 0.15T_{GDPI} + 0.41T_{PCVAA} + 1.74T_{TP} \quad (7)$$

As shown in Equation (7) and Figure 8(c), the difference of WUE for the YD was more sensitive to *T* of *PCGDP*, *GDPI*, *PCVAA* and *TP*. The explanatory variable *T* of *PCGDP* indicated that an increase of one unit of *T* of *PCGDP* yields an increase of 1.24 units of *T* of WUE per year. As for *GDPI*, an increase of one unit of *T* of *GDPI* contributes to an increase of 0.15 units of *T* of WUE per year.

An increase of one unit of *T* of *PCVAA* leads to an increase of 0.41 units of *T* of *GDPI* per year, whereas an increase of one unit of *T* of *TP* leads to an increase of 1.74 units of *T* of WUE per year. It is demonstrated that the indicators of WUE as well as *TP* have significant impacts on the WUE for the YD. This is similar to that of the PRD, in which the increases in the regional differences of indicators of WUE and *TP* increase the regional differences of GDP as well as industrial and domestic water consumptions and consequently enlarge the regional difference of WUE. As for the YD, it has a dense population but a less developed economy. Given this, improving the comprehensive quality of human resources, spatial equilibrium layout of population and balancing regional economy development would contribute to weakening the regional WUE of the YD:

$$T_{WUE} = 0.11 - 0.22T_{PWR} + 0.12T_{GDPI} + 0.45T_{PCVAA} \tag{8}$$

For the MLR model of the YX (Equation (8)), the significant explanatory variables were *T* of *PWR*, *GDPI* and *PCVAA*. As shown in Equation (8) and Figure 8(d), an increase of one unit of *T* of *PWR* yields a decrease of 0.22 units of *T* of WUE per year whereas an increase of one unit of *T* of *GDPI* leads to an increase of 0.12 of *T* of WUE per year. As for *PCVAA*, an increase of one unit of *T* of *PCVAA* leads to an increase of 0.45 of *T* of WUE per year. Different from the PRD, *T* of *PWR* has a negative coefficient with *T* of WUE. Similarly, increase in the regional differences of *GDPI* and *PCVAA*, the two indicators of WUE, enhances the regional difference of WUE. This indicates that, as for the YX, more attention should be placed on balancing the regional economy development, particularly for the benefits of agricultural production:

$$T_{WUE} = 0.07T_{GDPI} + 0.03T_{WCIAV} \tag{9}$$

T of *GDPI* and water consumption per 10,000 yuan of value-added by industry (*WCIAV*) were the significant explanatory variables of the MLR model for the YB, whereas the other explanatory variables were not. As shown in Equation (9) and Figure 8(e), as the *T* of *GDPI* in the YB increases by an increment of one, *T* of WUE increases by 0.07 per year. For *WCIAV*, an increase of one unit of *T* of *WCIAV* contributes to an increase of 0.03 units of *T* of WUE per year. It can be seen that, compared to the other three sub-regions and the whole province, the significant explanatory variables are fewer and only represent the indicators of WUE. As for the YB, it suggests that balancing agriculture water use efficiency is vital and should be improved.

Overall, the results of the MLR models indicate that the significant explanatory variables vary for different sub-regions and the whole province, and have different impacts on the regional differences of WUE. The PRD has the most significant explanatory variables whereas the YB has the least. The PRD aggregates several metropolises with dense populations and the most developed economy of the whole province, the developed economy involves many industries and the production process is more complex. Therefore, its WUE is sensitive to more explanatory variables compared to other sub-regions. As for the YB, it has a less developed economy with sparse population and the industrial water use is simpler, the regional difference of WUE is only dominated by the regional difference in *GDPI* and *WCIAV*. Basically, per capita domestic water consumption (*PDC*), *RC* and *WCRIM* did not influence WUE in most of the models, because these three factors in the province did not fluctuate greatly over the years (Figure 4). However, *TGDPI* was the significant explanatory variable in most of the models, followed by *TPCGDP* and *TPCVAA*. This could be because the three factors had direct impacts on the regional *GDP* and TWU, which determines the regional WUE. Additionally, *TPWR* shows positive correlation with *TWUE* in the model for PRD, whereas it is not the case in the model for YX. The results of the analysis can be used by decision makers as tools to work out balanced regional WUE strategies for the whole province.

Conclusions

In the current study, both Theil indexes of TWU and WUE were calculated to explore the regional difference of water use of Guangdong, a province with significantly unbalanced socioeconomic development in China. The MLR models were evaluated and used to fit historical water use data for the whole province and the four sub-regions.

Results for regional differences of TWU and WUE demonstrated that, as for the whole province, both the Theil indexes of TWU and WUE had fluctuations. The Theil index of TWU showed a decreasing trend whereas the Theil index of WUE increased in recent decades, suggesting that Guangdong province has experienced an enlarging regional difference of WUE, although the regional difference of TWU has been gradually weakened. The higher values of Theil index for WUE than that of TWU indicates that more regional difference occurs for WUE than that of TWU in the whole province. The regional differences of WUE and TWU in the PRD were significant and played a predominant role in the regional difference of water use in the whole province. Different from TWU, in which the Theil index between sub-regions of the whole province only accounted for a small proportion, the differences of WUE within the whole province and between sub-regions almost have an equal role in the whole province, suggesting that inter-sub-regional exchange of water resources exploitation as well as industrial adjustment within sub-regions should be encouraged to achieve a more balanced water use in the whole province for long-term development.

The MLR models for the whole province and its four sub-regions showed good performances to fit the Theil index of TWU with Theil indexes of the possible influencing factors. The results of the MLR models indicated that the significant explanatory variables impacting the regional difference of WUE vary both at sub-regional and the whole provincial scales, which was closely related to the regional economy development level and population. For instance, the PRD had the most significant explanatory variables whereas the YB had the least. Taken together, *TGDPI*, *TPCGDP* and *TPCVAA* were the three significant explanatory variables with positive regression coefficients in most of the models and the increases in the regional difference of the three variables help to enlarge the regional differences of WUE.

This study is novel in quantifying the regional differences of water use and identifying the possible driving forces behind such differences, according to a large water use dataset of Guangdong province, a typical province with distinctly unbalanced development of social economy in China. Future regional differences of water use should aim to include better indicators of natural and human activities as possible influencing factors of WUE at varied time scales (monthly and seasonal, etc.), which were not available for this study.

Understanding the regional differences of water use and the possible driving forces can help inform planning for the layout of water supply system, such as that of Guangdong province in the future. Further, development of the MLR models will enhance better forecasting of regional water use under changing conditions of available water resources, population and economy.

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Data availability statement

All relevant data are included in the paper or its Supplementary Information.

References

Adamowski, J., Chan, H. F., Prasher, S. O., Ozga-Zielinski, B. & Sliusarieva, A. (2012). Comparison of multiple linear and non-linear regression, auto-regressive integrated moving average, artificial neural network, and wavelet artificial neural network methods for urban water demand forecasting in Montreal, Canada. *Water Resources Research 48*. doi:10.1029/2010WR009945.

Ausloos, M., Nedic, O. & Dekanski, A. (2019). Seasonal entropy, diversity and inequality measures of submitted and accepted papers distributions in peer-reviewed journals. *Entropy 21*(6). doi:10.3390/e21060564.

Cabral, M., Loureiro, D., Amado, C., Mamade, A. & Covas, D. (2019). Demand scenario planning approach using regression techniques and application to network sectors in Portugal. *Water Policy 21*(2), 394–411.

Chen, J. X., Xia, J., Zhao, Z. F., Hong, S., Liu, H. & Zhao, F. (2016). Using the RESC model and diversity indexes to assess the cross-scale water resource vulnerability and spatial heterogeneity in the Huai River Basin, China. *Water 8*(10), 431.

Cole, M. J., Bailey, R. M., Cullis, J. D. S. & New, M. G. (2018). Water for sustainable development in the Berg Water Management Area, South Africa. *South African Journal of Science 114*(3–4), 1–10.

Deng, G. Y., Li, L. & Song, Y. N. (2016). Provincial water use efficiency measurement and factor analysis in China: based on SBM-DEA model. *Ecological Indicators 69*, 12–18.

Duncan, A. E., DeVries, N. & Nyarko, K. B. (2019). The effectiveness of water resources management in Pra Basin. *Water Policy 21*(4), 787–805.

Feng, K. S., Hubacek, K., Pfister, S., Yu, Y. & Sun, L. (2014). Virtual scarce water in China. *Environmental Science & Technology 48*(14), 7704–7713.

Guo, B., Yang, F., Fan, Y. W., Han, F., Jiang, L., He, T. L., Zhang, H. & Chen, S. T. (2019). An improved gridded water resource distribution for China based on second-order basin data. *Geomatics Natural Hazards & Risk 10*(1), 368–384.

Haque, M. M., DeSouza, A. & Rahman, A. (2017). Water demand modelling using independent component regression technique. *Water Resources Management 31*(1), 299–312.

He, Y. H., Chen, X. H., Ye, C. Q. & Cheng, L. (2015). Classification-based spatiotemporal variations of pan evaporation across the Guangdong Province, South China. *Water Resources Management 29*, 901–912.

He, Y. H., Wang, Y. L. & Chen, X. H. (2019). Spatial patterns and regional differences of inequality in water resources exploitation in China. *Journal of Cleaner Production 227*, 835–848.

Her, Y., Yoo, S. H., Cho, J., Hwang, S., Jeong, J. & Seong, C. (2019). Uncertainty in hydrological analysis of climate change: multi-parameter vs. multi-GCM ensemble predictions. *Scientific Reports 9*, 4974. doi:10.1038/s41598-019-41334-7.

Hong, S., Xia, J., Chen, J. X., Wan, L., Ning, L. & Shi, W. (2017). Multi-object approach and its application to adaptive water management under climate change. *Journal of Geographical Sciences 27*(3), 259–274.

Hsieh, J. C., Ma, L. H. & Chiu, Y. H. (2019). Assessing China's use efficiency of water resources from the resampling super data envelopment analysis approach. *Water 11*(5), 1069. doi:10.3390/w11051069.

Khatri, K. B., Strong, C., Kochanski, A. K., Miller, C. & Hasenyager, C. (2018). Water resources criticality due to future climate change and population growth: case of river basins in Utah, USA. *Journal of Water Resources Planning and Management 14*(8), 04018041. doi:10.1061/(ASCE)WR.1943-5452.0000959.

Liao, F. H. & Wei, Y. D. (2015). Space, scale, and regional inequality in provincial China: a spatial filtering approach. *Applied Geography 61*, 94–104.

Malakar, K., Mishra, T. & Patwardhan, A. (2018). Inequality in water supply in India: an assessment using the Gini and Theil indices. *Environment, Development and Sustainability 20*, 841–864.

Marchionni, V., Cabral, M., Amado, C. & Covas, D. (2016). Estimating water supply infrastructure cost using regression techniques. *Journal of Water Resources Planning and Management 142*(4), 04016003. doi:10.1061/(ASCE)WR.1943-5452.0000627.

Papadopoulou, M. P., Charchousi, D., Tsoukala, V. K., Giannakopoulos, C. & Petrakis, M. (2016). Water footprint assessment considering climate change effects on future agricultural production in Mediterranean region. *Desalination and Water Treatmen t 57*(5), 2232–2242.

Qian, Q. L. & Chen, Y. B. (2012). Analysis of county economic development disparity in guangdong Province based on BP artificial neural network. *Advances in Electronic Commerce, Web Application and Communication 148*, 151–146.

Song, M. L., Wang, R. & Zeng, X. Q. (2018). Water resources utilization efficiency and influence factors under environmental restrictions. *Journal of Cleaner Production 184*, 611–621.

Sun, S. A., Fu, G. T., Bao, C. & Fang, C. L. (2019). Identifying hydro-climatic and socioeconomic forces of water scarcity through structural decomposition analysis: a case study of Beijing city. *Science of the Total Environment 687*, 590–600.

Sun, S., Fang, C. L. & Lv, J. J. (2017). Spatial inequality of water footprint in China: a detailed decomposition of inequality from water use types and drivers. *Journal of Hydrology 553*, 398–407.

Tan, Y. & Liu, X. C. (2017). Water shortage and inequality in arid Minqin oasis of northwest China: adaptive policies and farmers' perceptions. *Local Environment 22*(8), 934–951.

Wang, H. Y. (2019). Irrigation efficiency and water withdrawal in US agriculture. *Water Policy 21*(4), 768–786.

Wang, K. & Davies, E. G. R. (2018). Municipal water planning and management with an end-use based simulation model. *Environmental Modelling & Software 101*, 204–217.

Xu, C. Y. & Singh, V. P. (2004). Review on regional water resources assessment models under stationary and changing climate. *Water Resources Management 18*(6), 591–612.

Yuan, Y. & Wu, F. L. (2013). Regional social inequalities and social deprivation in Guangdong Province, China. *Growth Change 44*(1), 149–167.

Zhang, Y., Tong, D. & Liang, X. F. (2018). New perspective on regional inequality: theory and evidence from Guangdong. *China. Journal of Urban Planning and Development 144*(1), 04018002. doi:10.1061/(ASCE)UP.1943-5444.0000427.

Zhao, X., Liu, J. G., Liu, Q. Y., Tillotson, M. R., Guan, D. B. & Hubacek, K. (2014). Physical and virtual water transfers for regional water stress alleviation in China. *PNAS 112*(4), 1031–1035.

Zhao, L. S., Sun, C. Z. & Liu, F. C. (2017). Interprovincial two-stage water resource utilization efficiency under environmental constraint and spatial spillover effects in China. *Journal of Cleaner Production 164*, 715–725.

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