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Original Paper

Analysis of the Decoupling Level and Water-Saving Targets: Economic Growth and Water Consumption in the Production-Living-Ecological Systems

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Abstract

Understanding the relationship between economic growth and water consumption aids in evaluating economic health and managing water resources. This study analyzes the decoupling level between economic growth and water consumption within the Production-Living-Ecological (PLE) systems, focusing on Guangdong Province, China. Using the Tapio decoupling model, this study identified various decoupling states and calculated target water-saving values for achieving decoupling. Results show Guangdong Province generally has an ideal level of decoupling, with production water consumption effectively controlled alongside economic growth. However, living and ecological water consumption remain closely linked to economic growth. The difficulty of achieving strong and weak decoupling is not significant, with required water savings less than 1%. Despite this, some cities have yet to achieve decoupling, indicating a need for targeted water-saving strategies. This study provides valuable insights for sustainable water resource management in Guangdong and similar regions.

Keywords

economic growth, water consumption, production-living-ecological systems, water-saving target, decoupling level

1. Introduction

The nexus between economic growth and water consumption has become a critical area of focus in the context of sustainable development (Wang et al., 2020). Water, as an essential resource, is central to economic activities, societal well-being, and ecological balance (Balata et al., 2022). However, the increasing pressure on water resources due to population growth, urbanization, and industrial expansion has led to a growing concern over the sustainability of current water use patterns, particularly in regions with high economic activity. Mastering the complex relationship between economic growth and water consumption is crucial for accurately assessing the economic health, and it is also an important step in identifying the balance point between economic development and water resource demands.

The relationship between economic growth and water consumption has become a significant topic in the fields of environmental economics and resource management, attracting extensive research attention in recent years (Wang et al., 2025). Current research mainly focuses on the following aspects (Barbier et al., 2024): i) Water resource stress and economic growth involve analyzing the degree of water scarcity and exploring the scientific use of water resources to ensure economic development (Barbier, 2024; Khan et al., 2017). ii) Quantifying the impact of water scarcity on economic growth involves taking into account factors such as water scarcity and climate change to analyze how water scarcity affects the growth prospects of the economy (Hao et al., 2019). iii) The dynamic relationship between economic growth and water consumption involves exploring the changes in water resource stress and their impact on promoting economic growth (Dolan et al., 2021). iv) The two-way causal relationship between water consumption and economic growth (Dinar, 2024; Lu et al., 2022). v) Socioeconomic factors of water consumption involve considering how various socioeconomic factors, such as population, changes in economic structure, technological progress, and environmental policies, impact economic development (Dolan et al., 2021). However, most current research focuses on the national or inter-provincial level and examines the total water consumption as the subject of study, with less attention given to different water consumption systems, such as production, domestic, and ecological water use systems.

The state of decoupling between economic growth and water consumption is an important indicator for evaluating the coordination between regional economic development and water resource utilization, and it is also one of the important methods for calculating potential water savings (Hu et al., 2023). The notion of decoupling, which posits the potential for economic progress to occur independently of environmental damage, has emerged as a critical approach in discussions on sustainable development. In particular, within the context of water resource management, decoupling indicates the feasibility of enhancing economic growth alongside a reduction in water consumption, thereby easing the burden on water supplies. For example, Lu et al. (2022) employed the Tapio model to examine strategies for diminishing the reliance of economic growth on water resources within regions facing scarcity, with a particular focus on water footprint and actual water usage.

Previous studies have employed various techniques to assess the decoupling status and its ramifications for the governance of water resources (Hu et al., 2023). Notably, the Tapio decoupling model has emerged as a distinguished tool, celebrated for its adeptness at elucidating the complex dynamics between economic growth and environmental stress, with a specific emphasis on water consumption. This model has been widely applied in the fields of environmental economics and resource utilization, offering a robust analytical framework for assessing decoupling states and calculating target values for water-saving initiatives.

Considering the aforementioned, this study delves into the decoupling level between economic growth and water consumption within the Production-Living-Ecological (PLE) systems, with a particular emphasis on Guangdong Province. By doing so, it aims to contribute to the understanding of how economic activities interact with water consumption patterns and to identify potential water-saving targets that could facilitate sustainable development.

2. Methodology

2.1 Tapio Decoupling Model

The Tapio decoupling model (Hu et al., 2023) is an analytical tool specifically designed to gain a deeper understanding of the interplay between economic development and environmental impacts. This model was first proposed by the Organisation for Economic Co-operation and Development and has quickly been applied in different areas, including but not limited to the assessment of environmental policies, sustainable management of resources, and optimization strategies for energy efficiency. As a powerful analytical tool, it helps to reveal the complex dynamic relationships between economic growth and environmental pressures, resource utilization, etc. The model enables independent analysis of different time periods, avoiding the limitations associated with selecting a specific base period. It not only examines changes in total quantities but also pays attention to the changes in relative quantities, thereby providing a more accurate measurement method for the level of decoupling. The Tapio decoupling model is one of the important tools in research fields such as environmental economics and resource utilization.

In this study, the Tapio decoupling model is utilized to reveal the level of decoupling between economic growth and water consumption within the PLE Systems. The model is designed as follows:

$$r = \frac{\Delta W}{\Delta GDP} = \frac{\frac{W_n - W_{n-1}}{W_{n-1}}}{\frac{GDP_n - GDP_{n-1}}{GDP_{n-1}}}$$

Where, r is the decoupling elasticity coefficient between economic growth and water consumption; W_n and W_{n-1} are the water consumption of the nth year and the (n-1)th year, respectively; GDP_n and GDP_{n-1} are the gross domestic product of the nth year and the (n-1)th year, respectively; ΔW and ΔGDP represent the rate of change in water consumption and gross domestic product between the nth year and the (n-1)th year , respectively.

In this study, the Tapio decoupling model is improved to avoid over-interpreting minor fluctuations in variables, i.e., a decoupling elasticity coefficient range from 0.8 to 1.2 is established to ascertain whether an ongoing correlation exists between economic growth and water resource consumption. When the elasticity coefficient falls within this range, we consider that there is still some connection between the two variables, but the connection varies depending on the direction of the variable's change (positive or negative). Specifically, if the variables show a positive change, we define it as a growth connection; conversely, if the variables exhibit a negative change, it is categorized as a recession connection.

Based on the decoupling elasticity coefficient and the direction of variable changes, the decoupling level between economic growth and water consumption in the PLE Systems is categorized more meticulously, i.e., three fundamental decoupling states and eight distinct levels of decoupling (Figure 1). These three basic states are: Decoupling (subdivided into strong decoupling, weak decoupling, and recessionary decoupling), Negative Decoupling (subdivided into strong negative decoupling, weak negative decoupling, and growth negative decoupling), and Connection (subdivided into growth link connection and recession connection). The state of decoupling is deemed the most desirable, with the state of coupling ranking second, whereas the state of negative decoupling is regarded as the least favorable. Specifically, the strong decoupling state is seen as the most ideal scenario, indicating that the growth in water resource consumption is not proportional to economic growth. Conversely, the negative decoupling state reveals that economic growth still largely depends on the increase in water resource consumption. The strong negative decoupling state is seen as the least ideal, implying that even a significant increase in water resource consumption fails to promote economic growth. Through this comprehensive classification approach, we can more precisely measure the interplay between economic growth and environmental variables.

2.2 The Water-saving Target Model

The water-saving target model is utilized to calculate the target water-saving values required to facilitate the decoupling of economic growth from water resource consumption. The target water-saving values are calculated based on the data from 2022 and 2023. Let TW_{2023} denote the target water consumption in the PLE Systems for the purpose of decoupling economic growth from water usage in 2023, while SW_{2023} indicates the water-saving target value for the same year. Based on the Tapio decoupling model, the water-saving target model is represented as follows:

(i) If $\Delta GDP > 0$, it is required $r \leq 0$ to ensure that economic growth is strongly decoupled from water consumption in the PLE Systems, i.e., $r = \frac{\Delta W}{\Delta GDP} = \frac{\frac{W_{2023} - W_{2022}}{W_{2022}}}{\frac{GDP_{2023} - GDP_{2022}}{GDP_{2022}}} \leq 0$. TW_{2023} should fall within the range $0 \leq TW_{2023} \leq W_{2023}$.

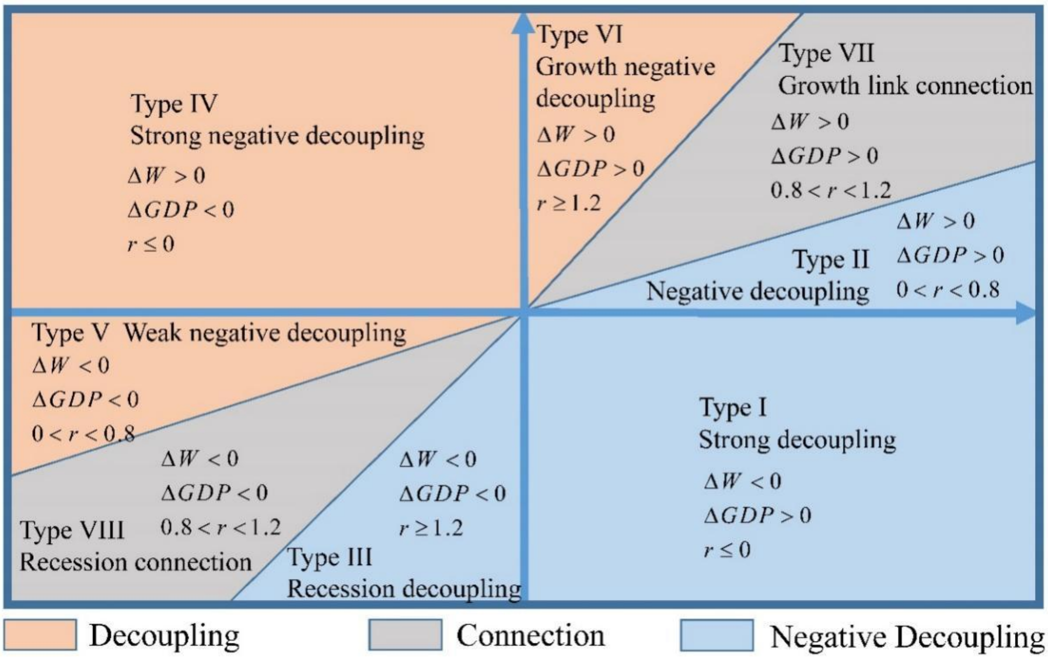


Figure 1. The Grade Classification for Three Fundamental Decoupling States and Eight Distinct Levels of Decoupling

(ii) If $\Delta GDP > 0$, it is required $0 < r < 0.8$ to ensure that economic growth is weakly decoupled from water consumption in the PLE Systems, i.e., TW_{2023} should fall within the range $W_{2022} \leq TW_{2023} \leq W_{2022} + 0.8W_{2022}\Delta GDP$.

(iii) If $\Delta GDP < 0$, it is required $r \geq 1.2$ to ensure that economic growth is recessionary decoupled from water consumption in the PLE Systems, TW_{2023} should fall within the range $0 \leq TW_{2023} \leq W_{2022} + 1.2W_{2022}\Delta GDP$.

From above, if $TW_{2023} \geq W_{2023}$, then $SW_{2023} = 0$; if $TW_{2023} < W_{2023}$, then $SW_{2023} \geq W_{2023} - TW_{2023}$. To facilitate the presentation of results, weak decoupling and recessionary decoupling are combined and referred to as weak decoupling in the following text.

3. Study Area and Data

3.1 Study Area

Guangdong Province, located on the southeast coast of China, is known for its thriving economy and complex water resource management. The province is characterized by a subtropical monsoon climate, with ample rainfall and relatively abundant water resources overall. The average annual precipitation in Guangdong reaches 1770.6mm, primarily concentrated during the flood season from April to September each year. However, a significant amount of rainfall is lost to the ocean in the form of floods, resulting in a reduced amount of actual usable water resources. The province has a substantial total volume of water resources, but the per capita share is relatively low, with a multi-year average of only 1458 m^3, which is below the national average. Guangdong uses only 6.6% of the country's water resources to meet the water needs of 8.9% of the national population and contributes 10.9% to the national economic output. While pursuing high-quality economic development, Guangdong Province is also committed to improving the efficiency of water resource use, steering water resource management towards a more rational direction. The water consumption in the PLE Systems and GDP data for Guangdong Province in the year 2023 are shown in Figure 2.

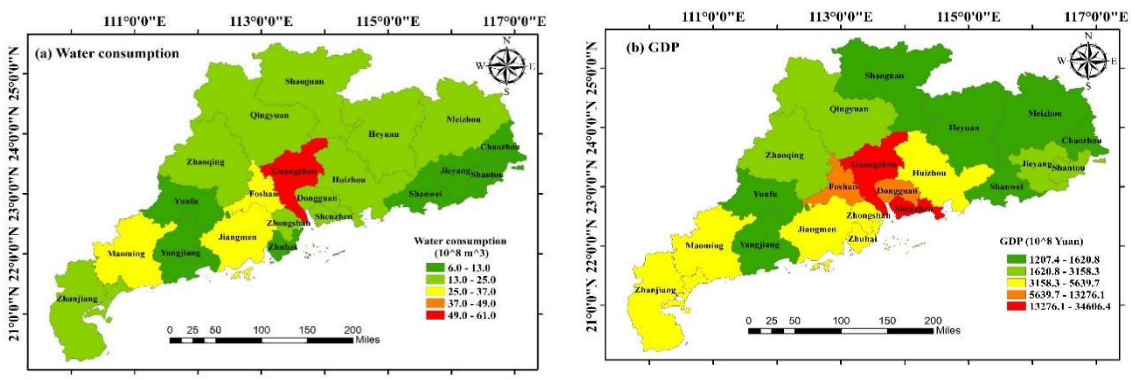


Figure 2. The Study Area (Guangdong Province) along with its PLE Water Consumption (a) and GDP (b) Data for the Year 2023

3.2 Data

This study focuses on Guangdong Province as the study area, and the data used primarily includes economic data and data on PLE water consumption. The economic data primarily relies on the GDP growth rates as published in the Guangdong Statistical Yearbooks for 2021, 2022 and 2023 by the Guangdong Provincial Bureau of Statistics (http://stats.gd.gov.cn/gdtjnj/index.html). The data on PLE water consumption is sourced from the Guangdong Province Water Resources Bulletins (http://slt.gd.gov.cn/szygb/), published by the Guangdong Provincial Department of Water Resources for the years 2021, 2022 and 2023.

4. Results and Discussion

4.1 Decoupling Status of Economic Growth and PLE Water Consumption

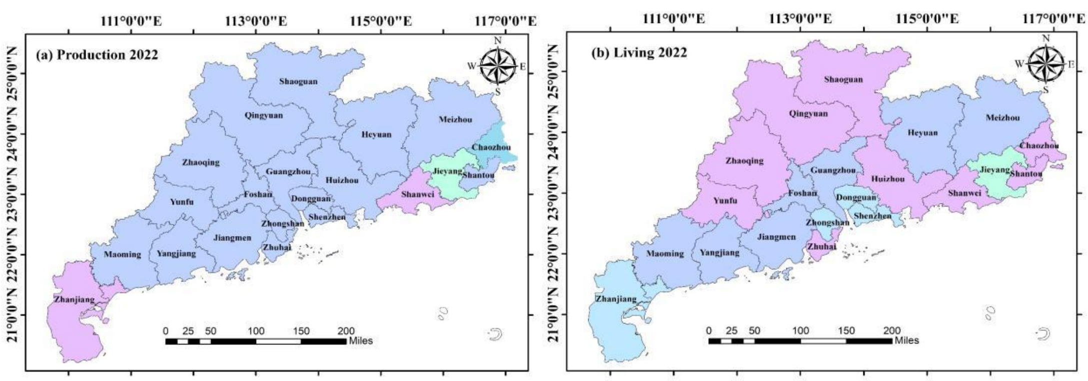
Decoupling status of economic growth and PLE water consumption in various cities of Guangdong Province in 2022 and 2023 are analyzed based on the Tapio decoupling model (Figure 3 and 4). The results demonstrate that there is generally an ideal level of decoupling between economic growth and PLE water consumption of Guangdong Province.

Generally, the water consumption for production and total have been effectively controlled with economic growth, but the relationship between living water consumption and ecological water consumption with economic growth remains relatively close. In 2022, among the 21 cities in Guangdong Province, there were 19 cities (17 of Type I, one of Type II, and one of Type III) where water consumption for production decoupled from economic growth, 12 cities (7 of Type I, 4 of Type II, and one of Type III) where water consumption for living decoupled from economic growth, 8 cities (5 of Type I, and three of Type II) where ecological water consumption decoupled from economic growth, and 18 cities (14 of Type I, three of Type II, and one of Type III) where total water consumption decoupled from economic growth. The cities where economic growth is negatively decoupled from water consumption for production, water consumption for living, ecological water consumption, and total water consumption are distributed as 2, 9, 12, and 3 cities, respectively, and all negative decoupling state are classified as Type VI. The year 2023 was similar to 2022.

4.2 Analyzing the Water-saving Targets

This study takes 2023 as the base year for the current situation, the water-saving target model is used to calculate water-saving targets for both strong and weak decoupling between economic growth and water consumption. The proportions of water savings to achieve strong and weak decoupling between economic growth and water consumption is shown in Table 1. The water-saving targets of achieving strong and weak decoupling between economic growth and water consumption are shown in Figure 5 and 6, respectively.

The difficulty of achieving strong and weak decoupling between economic growth and water consumption in Guangdong Province is generally not significant, but there are certain differences in various water consumption systems. The proportions of water savings to achieve strong and weak decoupling between economic growth and water consumption are both less than 1%. For strong decoupling, the proportions of water savings for production, living, ecology, and total are 0.97%, 0.27%, 0.31%, and 0.85%, respectively; while the proportions for weak decoupling are 0.24%, 0.07%, 0.23%, and 0.09%. Specifically, Economic growth still has a relatively strong relationship with production water consumption, followed by ecological water consumption, with living water consumption having the least.



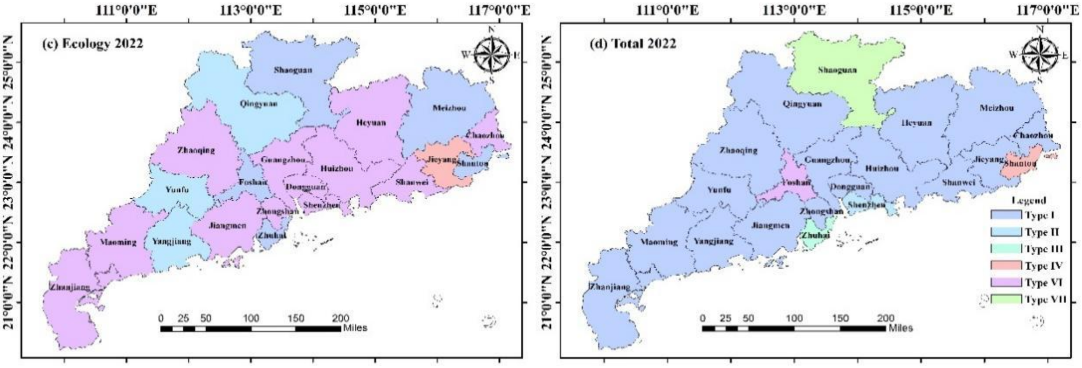


Figure 3. Decoupling Status of Economic Growth and PLE Water Consumption in Various Cities of Guangdong Province in 2022

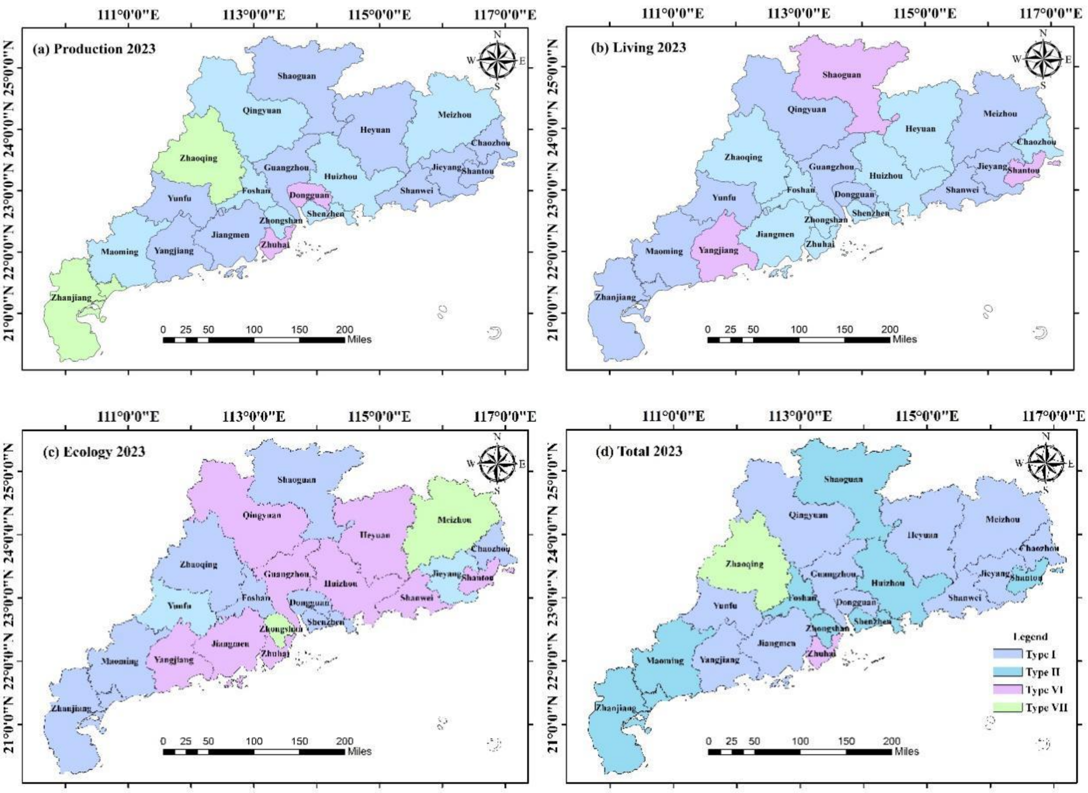


Figure 4. Decoupling Status of Economic Growth and PLE Water Consumption in Various Cities of Guangdong Province in 2023

The economic growth in Guangdong Province is generally decoupled from water consumption, but some cities have not yet achieved decoupling. Takes 2023 as the base year for the current situation, the cities where economic growth is not strong decoupled from water consumption for production, water consumption for living, ecological water consumption, and total water consumption are 11, 7, 11, and 10 cities, respectively (Table 1). Cities like Zhuhai, Dongguan, Zhanjiang, and Maoming face relatively high pressure to achieve strong decoupling between economic growth and production water consumption, with their water-saving targets are 0.25×10^8, 0.8×10^8, 0.65×10^8, and 0.5×10^8 m^3, respectively (Figure 5a). Their water-saving target proportions are all greater than 3% (Table 1). For living water consumption, Yangjiang, Shantou, and Shaoguan cities face relatively high pressure, with their water-saving targets are 0.2×10^8, 0.2×10^8, and 0.1×10^8 m^3, respectively (Figure 5b). Their water-saving target proportions are all greater than 5%. For ecological water consumption, Shanwei, Yangjiang, and Zhuhai cities face the highest pressure, with their water-saving targets are 0.23×10^8, 0.05×10^8, and 0.12×10^8 m^3, respectively (Figure 5c). Their water-saving target proportions are all greater than 50%; the proportions of Shantou, Huizhou are greater than 25%, and other cities below 14%. For total water consumption, cities face relatively less pressure; all cities have water-saving target ratios below 3%, except for Zhuhai (6.5%) and Zhaoqing (3.71%).

The economic growth in most cities within Guangdong Province shows a weak decoupling relationship with water consumption for living, and total. However, 11 cities have yet to achieve this level of decoupling (Table 1). For production water consumption, Dongguan, Zhanjiang, Zhaoqing, and Zhuhai need to save 0.54×10^8, 0.15×10^8, 0.15×10^8, and 0.13×10^8 m^3 of water consumption, respectively, to achieve weak decoupling (Figure 6a). The savings proportions for these cities are 4.11%, 0.71%, 1.01%, and 3.32%, respectively (Table 1). For living water consumption, Yangjiang, Shaoguan, and Shantou need to save 0.15×10^8, 0.09×10^8, and 0.03×10^8 m^3 of water consumption, respectively, to achieve weak decoupling (Figure 6b). For total water consumption, Zhuhai and Zhaoqing need to save 0.22×10^8 and 0.15×10^8 m^3 of water consumption, respectively, to achieve weak decoupling (Figure 6d). For ecological water consumption, Shanwei, Yangjiang, Zhuhai, Shantou, and Huizhou face the most significant pressure to achieve weak decoupling, and they need to reduce their water consumption by a range of 23% to 81%. Other 6 cities (Guangzhou, Heyuan, Meizhou, Zhongshan, Jiangmen, Qingyuan) face relatively less pressure, and they need to reduce their water consumption by less than 10%.

Table 1. The Proportions of Water Savings to Achieve Strong and Weak Decoupling between Economic Growth and Water Consumption

Cities	Strong decoupling				Weak decoupling			
	Production	Living	Ecology	Total	Production	Living	Ecology	Total
Guangzhou	0.00%	0.00%	8.33%	0.00%	0.00%	0.00%	3.93%	0.00%
Shenzhen	1.04%	3.41%	0.00%	1.38%	0.00%	0.00%	0.00%	0.00%
Zhuhai	6.17%	0.00%	52.17%	6.50%	3.32%	0.00%	50.72%	3.66%
Shantou	0.00%	5.71%	33.33%	0.51%	0.00%	2.55%	31.09%	0.00%
Foshan	1.36%	1.52%	0.00%	1.28%	0.00%	0.00%	0.00%	0.00%
Shaoguan	0.00%	5.26%	0.00%	0.06%	0.00%	1.78%	0.00%	0.00%
Heyuan	0.00%	0.00%	9.09%	0.00%	0.00%	0.00%	6.18%	0.00%

Meizhou	1.90%	0.00%	5.88%	0.00%	0.00%	0.00%	0.99%	0.00%
Huizhou	0.61%	2.50%	26.32%	1.54%	0.00%	0.00%	23.01%	0.00%
Shanwei	0.00%	0.00%	82.14%	0.00%	0.00%	0.00%	81.43%	0.00%
Dongguan	6.06%	0.00%	0.00%	0.00%	4.11%	0.00%	0.00%	0.00%
Zhongshan	1.85%	2.78%	4.55%	2.55%	0.00%	0.00%	0.27%	0.00%
Jiangmen	0.00%	0.00%	13.53%	0.00%	0.00%	0.00%	9.72%	0.00%
Yangjiang	0.00%	11.76%	71.43%	0.00%	0.00%	9.08%	70.56%	0.00%
Zhanjiang	3.04%	0.00%	0.00%	2.17%	0.71%	0.00%	0.00%	0.00%
Maoming	2.26%	0.00%	0.00%	1.50%	0.00%	0.00%	0.00%	0.00%
Zhaoqing	3.85%	0.00%	0.00%	3.71%	1.01%	0.00%	0.00%	0.86%
Qingyuan	0.55%	0.00%	12.50%	0.00%	0.00%	0.00%	9.35%	0.00%
Chaozhou	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Jieyang	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Yunfu	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	0.97%	0.27%	0.31%	0.85%	0.24%	0.07%	0.23%	0.09%

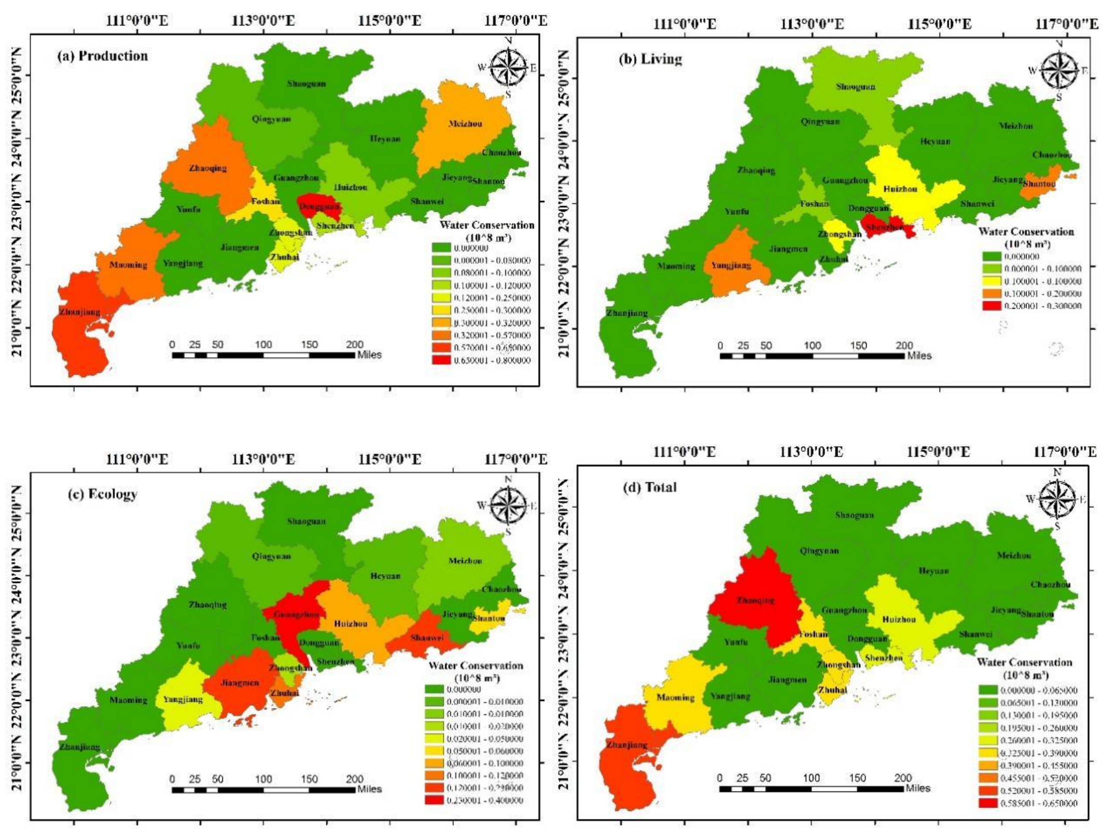


Figure 5. The Water-saving Targets of Achieving Strong Decoupling between Economic Growth and Water Consumption

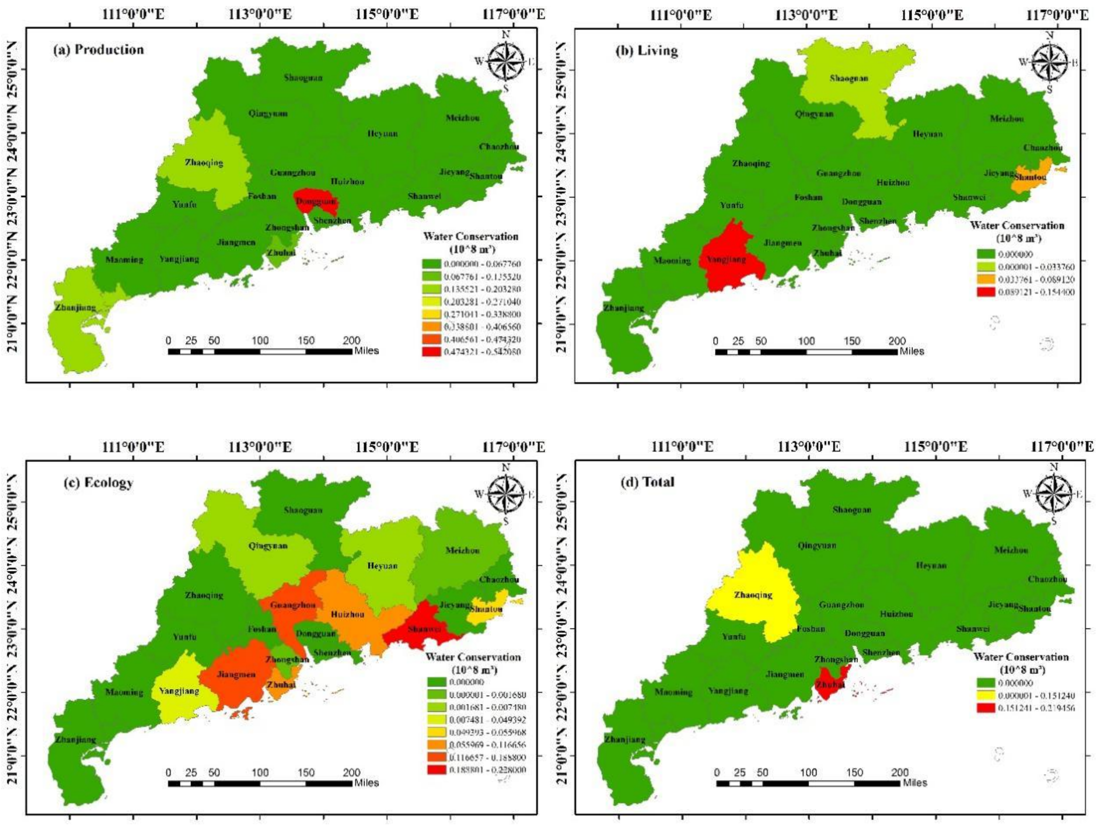


Figure 6. The Water-saving Targets of Achieving Weak Decoupling between Economic Growth and Water Consumption

5. Conclusions

This study provides a comprehensive analysis of the decoupling level between economic growth and water consumption within the Production-Living-Ecological (PLE) systems, with a particular focus on Guangdong Province in China. Utilizing the Tapio decoupling model, this study has delineated the intricate relationship between these two variables and identified various decoupling states. What's more, the water-saving target model was employed to calculate the target water-saving values for achieving decoupling. The research indicate that:

(i) Guangdong Province generally exhibits an ideal level of decoupling between economic growth and PLE water consumption. The production water consumption is effectively controlled in conjunction with economic growth. However, the relationship between living and ecological water consumption and economic growth remains closely linked.

(ii) The difficulty of achieving strong and weak decoupling in Guangdong Province is generally not significant, with water savings required for both strong and weak decoupling being less than 1%. Notably, the proportion of water savings needed for strong decoupling in production, living, ecology, and total water consumption are 0.97%, 0.27%, 0.31%, and 0.85%, respectively. For weak decoupling, these proportions are even lower, indicating a relatively easier path to achieving decoupling targets.

(iii) Despite the overall positive decoupling trend, some cities within Guangdong Province have yet to achieve decoupling, highlighting the need for targeted water-saving strategies. Cities like Zhuhai, Dongguan, Zhanjiang, and Maoming face higher pressure to achieve strong decoupling between economic growth and production water consumption, with significant water-saving targets required. Similarly, for living and ecological water consumption, certain cities face considerable pressure to reduce water consumption to meet weak decoupling targets.

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