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Temporal-spatial variation characteristics of utilization efficiency of water resources in Changbai Mountain area

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ABSTRACT

Changbai Mountain area is an important water source in Jilin Province, China. In recent years, due to the accelerated development, over-exploitation and ecological environment destruction of the region, the water resource problem of the region is becoming more and more prominent. Effectively solving water resources problems and achieving sustainable utilization of water resources have become important issues for regional development. Using Changbai Mountain area as the study area, the water utilization efficiency of Changbai Mountain area from 2009 to 2018 was measured and analyzed using data envelopment analysis (DEA-Malmquist) index model. The results show that in 2009–2018, the overall water utilization efficiency of 19 cities and counties in this area is at a moderate to low level, where the overall efficiency is 0.772, the pure technical efficiency is 0.853, and the scale efficiency is 0.891. The percentage of cities and counties that reached DEA effective in each year from 2009–2018 was 32%, 36%, 53%, 63%, 58%, 58%, 58%, 63%, 47%, and 32%, respectively. From 2009 to 2018, the total factor index of water resources utilization efficiency in Changbai Mountain area overall showing a downward trend in volatility, with an overall decreasing trend of 13.4%. There are uneven and unbalanced problems in water resources utilization efficiency in Changbai Mountain area. And improving the pure technical efficiency is the key to solving the problem of water resource utilization efficiency.

Keywords: Water resources; Utilization efficiency; Temporal-spatial variation; DEA-Malmquist index model; Changbai Mountain area

1. Introduction

With population growth and rapid economic development, the contradiction between water resources and human development has become increasingly apparent [1]. Humans have carried out large-scale development of water resources for their own needs. In the process of development, they are more satisfied with their own needs and ignore the development law of water resources themselves, resulting in a series of water resources problems [1]. The sustainable utilization of water resources has become the key to solving the current water resources problems [2]. As a developing country with a large population base, China's per capita water resources are lower than the global average, and the spatial distribution of water resources is uneven [2]. Therefore, improving the utilization efficiency of water resources has become an effective way to solve the contradiction between water resources and social development [3].

At present, many scholars at home and abroad have carried out research on the utilization efficiency of water resources. Relevant scholars have used the data envelopment analysis (DEA) method in combination with other models (such as the Malmquist index and the Tobit model) to measure and analyze the efficiency of water resources use, and found that changing production factors can effectively

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improve the efficiency of water resources use [3–7]. Hao et al. [8] used stochastic frontier analysis (SFA) and projection pursuit model to study and analyze the energy efficiency of the Silk Road Economic Belt Region, and found that both import trade and foreign direct investment (FDI) significantly improved the utilization of energy efficiency in the region; Lu and Xu [9] used the DEA-Malmquist index method to dynamically measure the water resource utilization efficiency of the Yangtze River Economic Belt in different time series, and the results show that the total factor productivity index has a certain dependence on technological changes; The analysis methods and models commonly used in the research of water resource utilization efficiency mainly include SFA [10–12], analytic hierarchy process (AHP) [13,14], and artificial neural network analysis [15–17] and the DEA-SBM model [18], etc. Among the above methods, the DEA method does not need to consider the functional relationship between each input and output, and has the characteristics of no need to estimate parameters in advance and simple calculation method. However, this method is susceptible to the interference of human factors in the selection of indicators, resulting in one-sided selection of indicators [19–21]. The super-efficiency slack based model (SBM) model is also one of the commonly used methods for measuring water resource efficiency. This method effectively avoids the deviation problem caused by the radial and angle of the traditional DEA method, but this method cannot distinguish the difference between the effective decision-making units with an efficiency value of 1 [22,23]. Because the DEA model can only analyze the static efficiency of each decision-making unit at the same time point, and cannot analyze long-term series data, the research results lack dynamic analysis. The Malmquist index model can reflect the dynamic relationship between the two by measuring the input and output indicators in different periods [9]. Some scholars have used the DEA-Malmquist index method to measure the resource utilization efficiency, but most of them are analyzed from the time series. Rare scholars have evaluated and measured utilization efficiency of water resources from different scales such as static and dynamic, time and space.

The Changbai Mountain area is an important ecological barrier in Northeast China and one of the sources of water resources in Jilin Province. In recent years, due to the accelerated development of the region, the unreasonable allocation of water resources, the destruction of the ecological environment and other reasons, the water resources problem in the region has become increasingly serious. Among them, the phenomenon of low freshwater utilization efficiency and waste in production and life has accelerated the deterioration of water resources [24]. Therefore, how to rationally allocate limited water resources and improve the efficiency of water resources utilization has become an urgent problem to be solved in my country at this stage [25]. In response to the above problems, this study couples the DEA model and the Malmquist production index model to evaluate the water utilization efficiency of the region by selecting the input and output indicators of 19 cities and counties in the Changbai Mountains region, and applying the DEA C^2R model and BC^2 model and carry out static analysis of time series and space series on the evaluation results; according to the temporal and spatial differentiation of static water resource use efficiency in the region, the Malmquist total factor productivity index method is used to analyze the dynamic change of water resource use efficiency in Changbai Mountain area. The research results not only provide a reference for improving the efficiency of water resources utilization in the Changbai Mountains, but also provide sustainable development advice for the rational development and utilization of water resources by the relevant departments of the Jilin Provincial Government.

2. Materials and methods

2.1. Overview of the study area

The total area of Changbai Mountain (125°10′E-131°18′E, 40°52′N-44°30′N) is about 76,400 km^2, accounting for 39.42% of the total area of Jilin Province. The study area is bordered by Russia and North Korea in the east, Liaoning Province in the south, Jilin City and Liaoyuan City in Jilin Province in the west, and Heilongjiang Province in the north [26]. The actual zoning of the study area is shown in Fig. 1. The Changbai Mountain area is rich in forest resources and has a humid and rainy climate. The area is a humid area with abundant water resources and dense and complex river networks. Changbai Mountain is the main source of rivers in Jilin Province. Surface water accounts for 45.5% of the province's groundwater and is one of the main sources of Jilin Province's water system. The population of Changbai Mountain area is 4.9245 million, accounting for 18.83% of the total population of Jilin Province. The population density is 65 people/km^2, which is far lower than the population density of 140 people/km^2 in Jilin Province. Among the study areas, Meihekou City has the largest population with 594,300 people, and the lowest Changbai Korean Autonomous County with only 79,000 people. To sum up, it can be seen that the population of the study area is relatively small, the economic development is relatively slow, and the population density and GDP density are both lower than the provincial average. The spatial distribution of water resources in the Changbai Mountains is relatively uneven (Table 1).

2.2. Data sources

Considering the availability of data and the characteristics of the data envelopment analysis method, the evaluation index of water resource utilization efficiency established by other scholars [27–30] was used. Combined with the characteristics of the Changbai Mountains, this paper selects the Changbai Mountains. The total water consumption, power machinery for irrigation and drainage, and total expenditure on agriculture of the 19 cities (counties) in the region from 2009 to 2018 are the input indicators, and total output value of agriculture, the total output value of industry above the scale and the per capita GDP are used as output indicators. Total output value of agriculture, the total output value of industry above the scale and the per capita GDP are used as output indicators represent economic output, while the total water consumption, power machinery for irrigation and drainage, and total expenditure

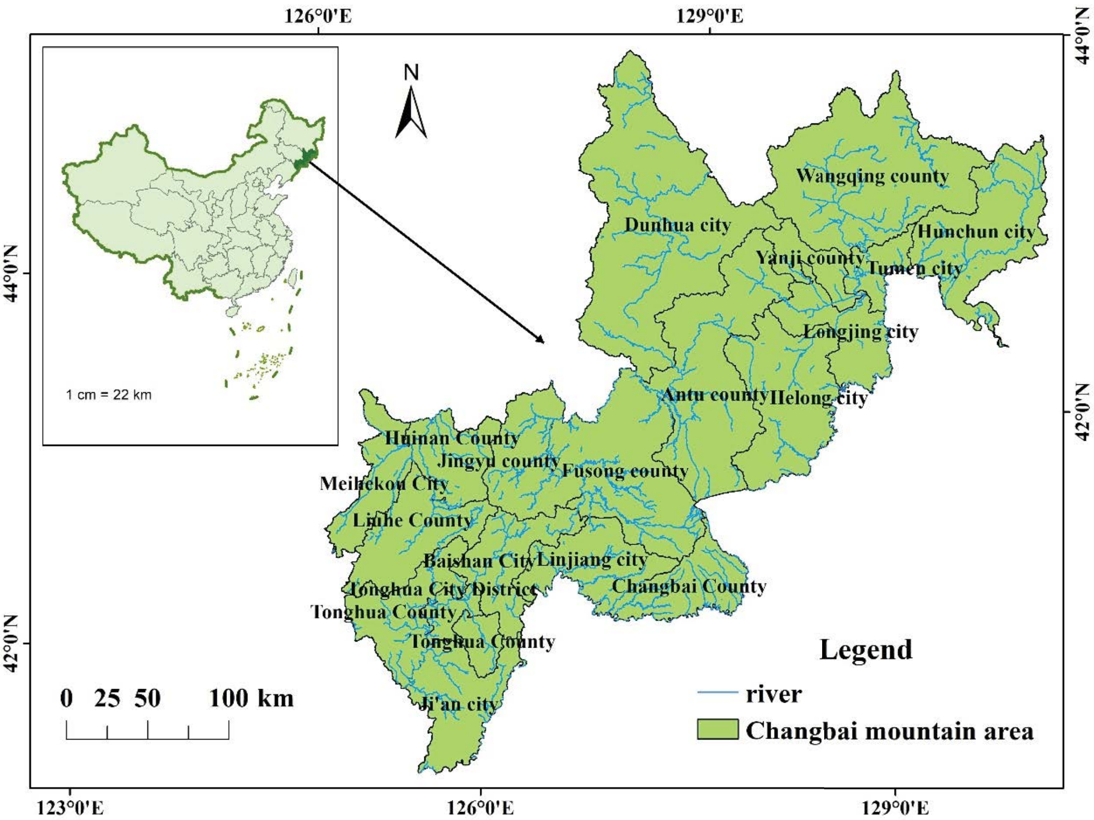

Fig. 1. Location and administrative division of Changbai Mountain.

Table 1
Spatial distribution of water resources in various administrative divisions in Changbai Mountains Unit: billion m³

Administrative division	Tonghua City	Baishan City	Yanbian (Korean) Nationality Autonomous Prefecture
Annual precipitation	134.66	132.40	308.81
Surface water resources	64.05	73.20	141.58
Groundwater resources	10.60	14.58	26.64
Repeated calculation	9.65	14.20	25.66
Total water resources	65.00	73.58	142.56

on agriculture represent the input of natural factors, social resources, and economic factors, respectively. The specific information and sources of the data are shown in Table 2.

2.3. Research methods

Data envelopment analysis (DEA model for short) is a non-parametric statistical evaluation model to calculate the relative efficiency between indicators of the same type [7–9]. The C²R module and the BC² module in the DEA model are used to evaluate the relative effectiveness and scale returns of decision-making units under the condition of multi-factor input and output. By combining the C²R model and the BC² model, the comprehensive efficiency, pure technical efficiency and scale efficiency of each decision-making unit can be evaluated. According to the relative efficiency value, the decision-making units are divided into two categories: relatively effective (θ ≥ 1) and relatively ineffective (θ < 1). Assuming that there are n independent decision-making units (DMUs), each DMU consumes m items of input to obtain s items of output, and x_{ij} and y_{rj} represent the ith input and rth output of the jth DMU, respectively. The inefficiencies of decision-making units caused by management inefficiencies are called slack variables. Its model is as follows:

$$\min\left[\theta - \varepsilon\left(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+\right)\right]$$

Table 2
Input–output indicators and data sources

Data type	Indicator name	Data source
Input indicator	Total water consumption, billion/m³	Jilin Water Resources Bulletin (http://slt.jl.gov.cn/zwgk/szygb/)
	Power machinery for irrigation and drainage, pcs	
	Total expenditure on agriculture, CNY 10000	Jilin Statistical Yearbook (http://tjj.jl.gov.cn/tjsj/tjnj/)
Output indicator	Total output value of agriculture, CNY 10000	
	Total output value of industry above the scale, CNY 10000	
	GDP per capita, CNY Yuan	China Statistical Yearbook (http://www.stats.gov.cn/tjsj/ndsj/)

$$s.t.\begin{cases} \sum_{j=1}^{n}\lambda_j X_{ij} + S_i^- = \theta X_{io} \\ \sum_{j=1}^{n}\lambda_{rj} X_i - S_r^+ = X_{ro} \\ \sum_{j=1}^{n}\lambda_j = 1 \\ \lambda_j \geq 0;\ S_i^-, S_r^+ \geq 0;\ j=1,2,...,n;\ i=1,2,...m;\ r=1,2,...s \end{cases} \quad (1)$$

where θ is the comprehensive efficiency evaluation index, ε is an infinitesimal quantity, s^- and s^+ are slack variables, and λ_j is the total variable of DMU_j. The biggest advantage of this method is that it does not need to consider the functional relationship between input and output indicators, but there is also the problem of "falsely high" relative efficiency evaluation results due to the influence of slack variables [31].

Swedish economist Sten Malmquist established the earliest Malmquist index in 1953 in order to construct the consumption quantity index. Then Fare et al. combined the data envelopment analysis method with the Malmquist index, and established the Malmquist productivity index from period t to period $t + 1$, which was expressed as technological change, technological efficiency change and total factor change, and the total factor productivity (TFP) index is:

$$N\left(m^{t+1}, n^{t+1}, m^t, n^t\right) = \left[\frac{F^t\left(m^{t+1}, n^{t+1}\right)}{F^t\left(m^t, n^t\right)} \times \frac{F^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F^{t+1}\left(m^t, n^t\right)}\right]^{\frac{1}{2}} \quad (2)$$

Among them, $F^t(m^t, n^t)$, $F^t(m^{t+1}, n^{t+1})$ respectively represent the distance function of decision-making units in t period and $t + 1$ period based on the technology of t period (that is, the data of t period); $F^t(m^t, n^t)$, $F^t(m^{t+1}, n^{t+1})$ respectively represent the decision-making in $t + 1$ period and $t + 1$ period with the technology of t +1 period (that is, the data of t period) as reference. The distance function of the unit. Write $N = N(m^{t+1}, n^{t+1}, m^t, n^t)$, then the meaning of N is: when $N > 1$, the productivity of the evaluation unit is improved; when $N = 1$, the productivity remains unchanged; $N < 1$ when, productivity declines, but it does not mean that both overall efficiency and technical efficiency decline. Technical efficiency change (Effch) can be further decomposed into pure technical efficiency change (Pech) and scale efficiency change (Sech). Its decomposition model is as follows:

$$N\left(m^{t+1}, n^{t+1}, m^t, n^t\right) = \text{Effch} \times \text{Techch} = \text{Pech} \times \text{Sech} \times \text{Techch}$$

$$\begin{cases} \text{Effch} = \dfrac{F_a^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F_a^t\left(m^t, n^t\right)} \\ \text{Techch} = \left(\dfrac{F_a^t\left(m^{t+1}, n^{t+1}\right)}{F_a^{t+1}\left(m^{t+1}, n^{t+1}\right)} \times \dfrac{F_a^t\left(m^t, n^t\right)}{F_b^{t+1}\left(m^t, n^t\right)}\right)^{\frac{1}{2}} \\ \text{Pech} = \dfrac{F_b^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F_b^t\left(m^t, n^t\right)} \\ \text{Sech} = \left(\dfrac{F_a^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F_b^{t+1}\left(m^{t+1}, n^{t+1}\right)} \times \dfrac{F_b^t\left(m^t, n^t\right)}{F_a^t\left(m^t, n^t\right)}\right) \end{cases}$$

$$N\left(m^{t+1}, n^{t+1}, m^t, n^t\right) = \frac{F_b^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F_b^t\left(m^t, n^t\right)} \times \left(\frac{F_a^{t+1}\left(m^{t+1}, n^{t+1}\right)}{F_b^{t+1}\left(m^{t+1}, n^{t+1}\right)} \times \frac{F_b^t\left(m^t, n^t\right)}{F_a^t\left(m^t, n^t\right)}\right) \times \left(\frac{F_a^t\left(m^{t+1}, n^{t+1}\right)}{F_a^{t+1}\left(m^{t+1}, n^{t+1}\right)} \times \frac{F_a^t\left(m^t, n^t\right)}{F_b^{t+1}\left(m^t, n^t\right)}\right)^{\frac{1}{2}} \quad (3)$$

When N is less than 1 in $N = N(m^{t+1}, n^{t+1}, m^t, n^t)$, the productivity decreases, when N is greater than 1, the productivity increases; when Effch is less than 1, the decision-making target is at $t + 1$ and $t + 1$. The distance of the frontier surface is farther than the distance of the frontier surface of the t and t periods, which means that the relative efficiency is improved. When Effch is greater than 1, the opposite is true; if Pech is less than 1, it means that the efficiency decreases due to the regression of management, and the opposite is when Pech is greater than 1; If Sech is less than 1, it means that the input–output ratio of the decision-making target is close to the worst scale, and the opposite is true when Sech is greater than 1; if Techch is less than 1, it means technological regression, and Techch greater than 1 means technological progress.

3. Results and analysis

In this paper, the relative water resources utilization efficiency of 19 cities and counties in Changbai Mountain area from 2009 to 2018 was measured and evaluated statically using the DEA method. Secondly, the static efficiency is decomposed by the Malmquist index method, and the water resource utilization efficiency is dynamically analyzed from different time series and spatial differentiation. Combining dynamic and static to achieve a comprehensive evaluation and analysis of water resources utilization efficiency in the region.

3.1. Static utilization efficiency evaluation

3.1.1. DEA evaluation based on time series

Firstly, the relative efficiency of each region of Changbai Mountain was calculated by taking each year as the study period and doing data analysis for each year. ArcGIS 10.8 software was also used to display the output results to the spatial cross section of the area.

According to the year-by-year analysis of the output results, it can be seen that in 2009, the cities and counties in Changbai Mountain area that reached DEA validity for water utilization efficiency were Tonghua City District, Tonghua County, Fusong County, Tyumen City, Hunchun City and Halong City, while the pure technical efficiency of Huinan County, Yanji City, Dunhua City and Longjing City reached validity, but the DEA was invalid due to the low scale efficiency, indicating that in 2009, these cities and counties failed to take into account the development of scale efficiency in the development process. Process failed to take into account the development of scale efficiency, and there was input redundancy; the cities and counties that reached DEA validity in 2010 in Changbai Mountain area were Tonghua City District and Tonghua County, Baishan City District, Changbai County, Tyumen City, Hunchun City, and Halong City. Although the comprehensive efficiency of Yanji City is lower than 1 and the pure technical efficiency has reached effective, the scale efficiency is relatively low at 0.892, resulting in a comprehensive efficiency of only 0.897, and the scale efficiency and pure technical efficiency of other regions have not reached effective; a total of 10 regions have reached effective DEA in 2011. Compared with 2009 and 2010, the efficiency has improved. Affected by the lower scale efficiency, Meihekou City failed to reach DEA effective. The remaining eight regions failed to reach DEA validity for pure technical efficiency, comprehensive efficiency, and scale efficiency; while in 2012, 12 out of 19 cities reached DEA validity, Meihekou City and Yanji City only reached DEA validity for pure technical efficiency, and scale efficiency was too low, resulting in comprehensive efficiency not reaching validity. In 2013, the cities and counties in Changbai Mountain region that reached DEA validity were Tonghua City District and Tonghua County, Baishan City District, Fusong County, Jingyu County, Linjiang City, Changbai County, Dunhua City, Hunchun City, Halong City and Antu County, while other regions did not reach DEA validity; in 2014, the cities and counties in Changbai Mountain region that reached DEA validity were cities and counties were Tonghua City District and Tonghua County, Baishan City District, Fusong County, Jingyu County, Linjiang City, Changbai County, Tyumen City, Dunhua City, Hunchun City, and Halong City. The pure technical efficiency of Longjing City reached effective, but the scale efficiency was only 0.804, thus leading to low overall efficiency. The scale efficiency and pure technical efficiency in other regions did not reach effective; in 2015, as in 2014, Longjing City was affected by scale efficiency, resulting in not reaching effective overall efficiency, and the scale efficiency and pure technical efficiency in other regions did not reach effective. Four regions, Huinan County, Liuhe County, Meihekou City, and Wangqing County, had the lowest water utilization efficiency, with all comprehensive efficiencies below 50%; a total of 12 regions reached DEA validity in 2016. Longjing City is still affected by scale efficiency, resulting in failure to achieve effective comprehensive efficiency, while four regions, namely Huinan County, Liuhe County, Meihekou City, and Wangqing County, still have the lowest water resources utilization efficiency and are affected by too low technical efficiency, with comprehensive efficiency below 50%; the cities and counties in Changbai Mountain region that reached DEA effective in 2017 are Huinan County, Liuhe County, Meihekou City, Ji'an City, Tyumen City, Dunhua City, Hunchun City, Halong City, Wangqing County, a total of nine areas, while Tonghua City District and Tonghua County, which reached DEA validity in 2009–2016, did not reach DEA validity in 2017. Four regions, Fusong County, Jingyu County, Linjiang City, and Changbai County, did not reach effective comprehensive efficiency, scale efficiency, and pure technical efficiency; the cities and counties in Changbai Mountain region that reached DEA effective in 2018 were Liuhe County, Meihekou City, Ji'an City, Tyumen City, Heilong City, and Wangqing County. Only pure technical efficiency reached validity in Dunhua City, Huinan County, and Changbai County, and the comprehensive efficiency failed to reach validity due to the influence of low scale efficiency. The main reason why the other regions failed to achieve effective comprehensive efficiency was that the pure technical efficiency was too low, and although the scale efficiency all reached above 0.9, the pure technical efficiency was around 0.5, thus limiting the overall efficiency (Fig. 2).

3.1.2. DEA evaluation based on spatial sequence

In order to comprehensively analyze the water utilization efficiency of Changbai Mountain area, the spatial panel data analysis of Changbai Mountain area was carried out by combining each region with each year and calculating the static efficiency of each region in each year (Fig. 3).

The results of the input–output slack analysis of 19 cities and counties in Changbai Mountain area are shown in Tables 4 and 5. The output results show that there is still output slack in the total industrial output value above the scale in Liuhe County, Meihekou City, Ji'an City, Linjiang City, Wangqing County and Antu County. This indicates that the efficiency of industrial water utilization in these areas needs to be improved, and Linjiang City has a slack amount of 137,517,277,000 yuan in the total output value of agriculture, forestry, animal husbandry and fishery. Slack exists in Liuhe and Jingyu counties as well as Wangqing

Table 3
Static efficiency of panel data for 19 cities and counties in Changbai Mountain area

Relative efficiency	Comprehensive efficiency	Technical efficiency	Scale efficiency	Gain of scale
Tonghua City District	1.000	1.000	1.000	–
Tonghua County	1.000	1.00	1.000	–
Huinan County	0.938	1.000	0.938	drs
Liuhe County	0.271	0.396	0.685	irs
Meihekou City	0.244	0.278	0.879	irs
Ji'an City	0.601	0.619	0.971	drs
Baishan City	1.000	1.000	1.000	–
Fusong County	1.000	1.000	1.000	–
Jingyu County	0.708	0.763	0.928	irs
Linjiang City	0.897	0.973	0.922	drs
Changbai County	1.000	1.000	1.000	–
Yanji County	0.897	1.000	0.897	drs
Tyumen City	1.000	1.000	1.000	–
Dunhua City	0.581	1.000	0.581	drs
Hunchun City	1.000	1.000	1.000	–
Longjing City	0.661	1.000	0.661	irs
Halong City	1.000	1.000	1.000	–
Wangqing County	0.338	0.455	0.743	irs
Antu County	0.533	0.731	0.728	irs
Average	0.772	0.853	0.891	–

Note: "–" indicates constant returns to scale, "irs" indicates increasing returns to scale, and "drs" indicates decreasing returns to scale.

and Antu counties in terms of gross output value per inhabitant. And there is slack in total water consumption in Liuhe County and Meihekou City, and slack in power machinery for drainage and irrigation in Liuhe County, Meihekou City and Ji'an City, and in Jingyu County and Linjiang City.

In summary, the overall utilization efficiency of water resources in Changbai Mountain area from 2009–2018 was moderately low, with a mean value of 0.772 for comprehensive efficiency, 0.853 for pure technical efficiency, and 0.891 for scale efficiency, and the percentages of cities and counties that reached DEA effective in each year were 32%, 36%, 53%, 63%, 58%, 58%, 58%, 63%, 58%, 63%, 47%, and 32%. In terms of the average value, there is still much room for improvement in water utilization efficiency in Changbai Mountain area in these 10 y. From the decomposition of the integrated efficiency, it is mainly the low pure technical efficiency that leads to the low integrated efficiency. The integrated efficiency of this decade shows wave-like fluctuations, increasing and decreasing three times before and after. During the study period, there was little change in scale efficiency, which was mainly influenced by pure technical efficiency. Therefore, it can be judged that the comprehensive efficiency is mainly influenced by pure technical efficiency, and the role of technology and management in water resources utilization in Changbai Mountain area is neglected, resulting in constant fluctuations in pure technical efficiency. Among the 19 cities and counties, the regions that reached both pure technical efficiency and scale efficiency effectively from 2009 to 2018 are Tonghua City District, Tonghua County, Baishan City District, Fusong County, Changbai County, Hunchun City, and Halong City, a total of seven regions, while the other regions failed to reach DEA effectiveness, and the three regions of Liuhe County, Meihekou City, and Wangqing County have an integrated efficiency below 0.5, while the other regions are affected by too low pure technical efficiency due to The combined efficiency of other regions is between 0.5 and 1.0 due to the influence of low pure technical efficiency. This shows that there is an imbalance in the utilization efficiency of water resources in Changbai Mountain area. From the analysis of input and output slack variables in each region, it can be seen that the inefficient cities and counties are mainly affected by the output slack, so the efficiency of water resources utilization can be improved by adjusting the resource allocation. In addition, water resources should be reasonably allocated among regions and developed in an integrated manner. In the distribution of water resources, the areas with higher water utilization efficiency centered on Baishan City should be shifted to the northern and western regions of Changbai Mountain area. As a non-renewable and scarce resource, water resources should be used rationally, economically and repeatedly.

3.2. Dynamic utilization efficiency evaluation

Malmquist productivity index (TFPCH) as a whole can be divided into technical efficiency change and technical change, which in turn can be decomposed into pure technical efficiency change and scale efficiency change. Effch, Techch, Pech, Sech, and TFPCH denote technical efficiency change, technical change, pure technical efficiency change, and scale efficiency change, respectively, and Malmquist productivity index. Malmquist productivity index analysis was performed on the panel data of 19 cities and counties in Changbai Mountain area, and the evaluation results of total factor productivity index and its decomposition were obtained for 19 cities and counties by year and by city and county.

3.2.1. Malmquist index evaluation based on time series

According to Table 6, the mean value of total factor productivity index in Changbai Mountain area is 0.866, which indicates that overall total factor productivity in Changbai Mountain area is a decreasing process, decreasing by 13.4%. In addition the mean value of technical efficiency change is 1.055, the mean value of technical change is 0.820, the mean value of pure technical efficiency change is 1.028 and the mean value of scale efficiency change is 1.026.The overall technical efficiency change is in an upward process, with an average increase of 5.5% from 2009 to 2018, of which the change brought by pure technical efficiency is 2.8% and the change brought by scale efficiency is 2.6%. The reason for the decrease in the total factor productivity index is the 18.0% decrease in technical changes, which indicates that the total factor productivity index in Changbai Mountain area is mainly influenced by technical changes.

From 2009 to 2010, 2012 to 2014, and from 2016 to 2018, the TFP index was less than 1, while the TFP index in other years was greater than 1. The change trend of TFP index and T_c value in Changbai Mountain area was consistent, which means that technological progress in Changbai Mountain area can effectively promote. The output efficiency of the economy under the condition of water resources, and increasing the investment in science and technology is conducive to promoting the efficiency of water resources utilization in the region. The E_c values in 2009–2010, 2012–2013 and 2014–2018 were all greater than 1, indicating that the technical efficiency in these years showed an upward trend; while the E_c values in 2010–2012 and 2013–2014 were all less than 1, indicating that due to the water in these years. Resource management strength and scale system are not perfect, resulting in a downward trend in technical efficiency; the average E_c from 2009 to 2018 is greater than 1, indicating that the overall technical efficiency of Changbai Mountain has improved in the past 10 y. Although the E_c value was greater than 1 in 2014–2015 and 2016–2017, the Sec value was less than 1, indicating that scale efficiency is not the main factor promoting technical efficiency in this region. The total factor productivity index fluctuated greatly from 0.171 to 1.871 in 2009–2012 and peaked in 2012. During this period, the fluctuations of technological changes were also relatively large, indicating that total factor productivity was mainly affected by technological changes during this period.

3.2.2. Malmquist index evaluation based on spatial sequence

According to Table 7, the total factor productivity of four regions, namely, Jingyu County, Linjiang City, Halong City, and Antu County, all reach above 1, while the total factor index of other regions is below 1. Combining the values of technical efficiency change and technical change, we can find that the change of total factor index is mainly affected by

Table 4
Input slack in 19 cities and counties in Changbai Mountain area

Indicators	Total water consumption (billion/m^3)	Drainage and irrigation power machinery (pcs)	Total expenditure on agriculture, forestry and water affairs (CNY 10000)
Tonghua City District	0	0	0
Tonghua County	0	0	0
Huinan County	0	0	0
Liuhe County	0.093	168.426	0
Meihekou City	0.121	1,106.67	0
Ji’an City	0	2,243.469	0
Baishan City	0	0	0
Fusong County	0	0	0
Jingyu County	0	186.868	0
Linjiang City	0	257.84	0
Changbai County	0	0	0
Yanji County	0	0	0
Tyumen City	0	0	0
Dunhua City	0	0	0
Hunchun City	0	0	0
Longjing City	0	0	0
Halong City	0	0	0
Wangqing County	0	0	0
Antu County	0.195	0	0
Average	0.022	208.593	0

Table 5
Output slack in 19 cities and counties in Changbai Mountain area

Indicators	Total output value of agriculture, forestry, animal husbandry and fishery (CNY 10000)	Total industrial output value above the scale (CNY 10000)	Per capita G·N·P (CNY)
Tonghua City District	0	0	0
Tonghua County	0	0	0
Huinan County	0	0	0
Liuhe County	0	1,169,813.484	7,504.126
Meihekou City	0	1,050,362.43	0
Ji'an City	0	898,279.442	0
Baishan City	0	1	0
Fusong County	0	1	0
Jingyu County	0	0.763	1,801.037
Linjiang City	137,517.277	61,062.782	0
Changbai County	0	0	0
Yanji County	0	0	0
Tyumen City	0	0	0
Dunhua City	0	0	0
Hunchun City	0	0	0
Longjing City	0	0	0
Halong City	0	0	0
Wangqing County	0	896,342.639	11,583.631
Antu County	0	224,681.31	5,831.029
Average	7,237.751	226,344.32	1,406.307

Table 6
Changbai Mountain area 2009–2018 total factor production index change

Indicators	Effch	Techch	Pech	Sech	TFPCH
2009–2010	1.628	0.105	1.296	1.257	0.171
2010–2011	0.941	1.730	1.023	0.919	1.627
2011–2012	0.655	2.859	0.709	0.923	1.871
2012–2013	1.446	0.561	1.310	1.104	0.812
2013–2014	0.825	1.168	0.796	1.037	0.963
2014–2015	1.124	0.962	1.137	0.988	1.081
2015–2016	1.090	1.235	1.066	1.022	1.346
2016–2017	1.094	0.823	1.112	0.984	0.901
2017–2018	1.011	0.506	0.971	1.041	0.511
Average	1.055	0.820	1.028	1.026	0.866

technical change, for example, the technical efficiency change of Tonghua City District, Tonghua County, Huinan County, Liuhe County, Meihekou City, Tyumen City, and Longjing City In addition, there are still some cities and counties that are mainly influenced by technical efficiency changes, such as Wangqing County. The above results indicate that many regions have failed to achieve progress in water utilization technology and management improvement in the process of water utilization. In addition, the all-importance index of each region has a maximum of 1.332 and a minimum of

Table 7
Total factor production index and its decomposition by cities and counties in Changbai Mountain area

Indicators	Effch	Techch	Pech	Sech	TFPCH
Tonghua City District	1.036	0.688	0.991	1.046	0.713
Tonghua County	1.056	0.679	1.014	1.041	0.717
Huinan County	1.040	0.672	1.019	1.021	0.699
Liuhe County	1.037	0.719	1.011	1.026	0.746
Meihekou City	1.002	0.749	1.004	0.998	0.750
Ji'an City	0.992	0.739	0.992	1.000	0.733
Baishan City	0.992	0.803	0.992	0.999	0.797
Fusong County	1.000	0.842	1.000	1.000	0.842
Jingyu County	1.486	0.856	1.210	1.228	1.271
Linjiang City	1.364	0.909	1.184	1.152	1.241
Changbai County	0.988	0.814	1.000	0.988	0.804
Yanji County	0.999	0.793	1.000	0.999	0.793
Tyumen City	1.004	0.752	1.000	1.004	0.756
Dunhua City	1.000	0.819	1.000	1.000	0.819
Hunchun City	1.000	0.870	1.000	1.000	0.870
Longjing City	1.000	0.862	1.000	1.000	0.862
Halong City	1.000	1.057	1.000	1.000	1.057
Wangqing County	0.989	1.008	0.989	1.000	0.997
Antu County	1.196	1.114	1.169	1.023	1.332
Average	1.055	0.820	1.028	1.026	0.866

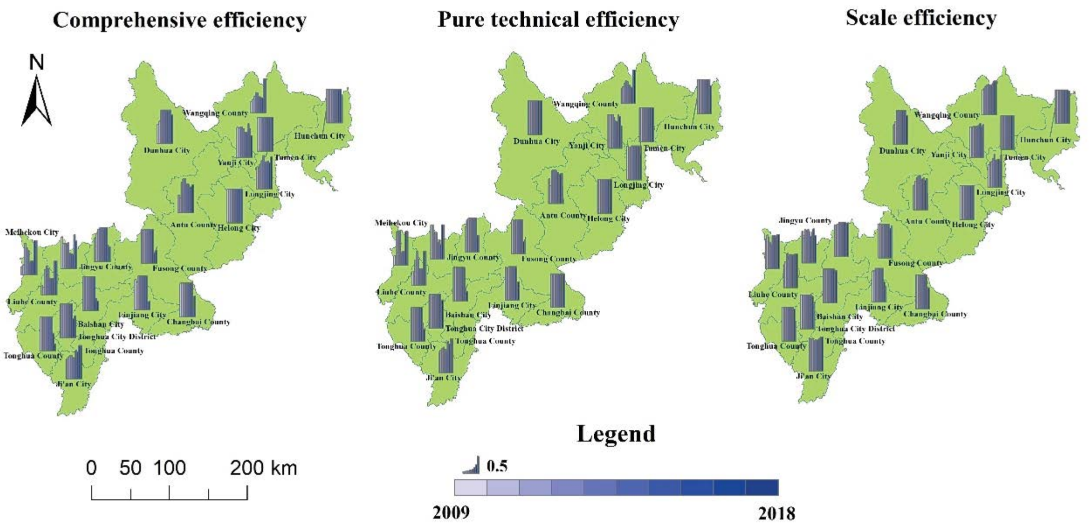

Fig. 2. Relative efficiency of time series in Changbai Mountain area.

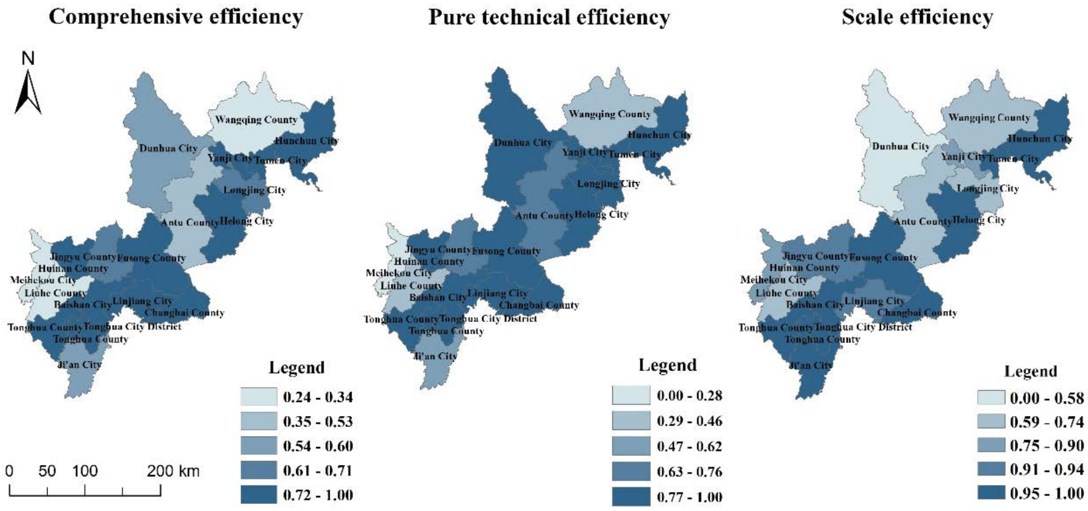

Fig. 3. Relative efficiency of spatial sequences in Changbai Mountain area.

0.699, with a difference of 0.633, indicating that there are large spatial differences in water utilization efficiency among cities and counties in the Changbai Mountain region.

4. Discussion

4.1. Discussion of the study results

In this paper, the DEA-Malmquist index model is used to measure and analyze the water resource utilization efficiency in the Changbai Mountains in the past 10 y. The change process from increasing to decreasing (Fig. 4), in which the comprehensive efficiency, pure technical efficiency and scale efficiency reached their peaks in 2012, 2012 and 2013 respectively; the relative change value of the comprehensive efficiency in 10 y was 0.195, and the pure technical efficiency The relative change value of 0.173, while the relative change of scale efficiency is small, only 0.090.

From 2009 to 2018, the total factor index of water resource utilization efficiency in the Changbai Mountains showed two fluctuations of first increase and then decrease on the whole. A maximum value of 1.871 in 2011–2012 and a minimum value of 0.511 in 2017–2018. Liao and Dong [32] pointed out that technology is the dominant factor restricting water resource utilization efficiency in 12 western provinces based on DEA and Malmquist index, the change of total factor production index in Changbai Mountain area is in decline, which is mainly affected by the change of technical efficiency. It can be seen that the results of this study are consistent with this study. In their research on water resource utilization efficiency in Jilin Province, Qiao and Jing [33] found that technological change is the main reason for the size of the total factor productivity index, which is consistent with the results of this paper; Lu and Xu [9] The research on water use efficiency pointed out that the total factor productivity index has a heavy dependence

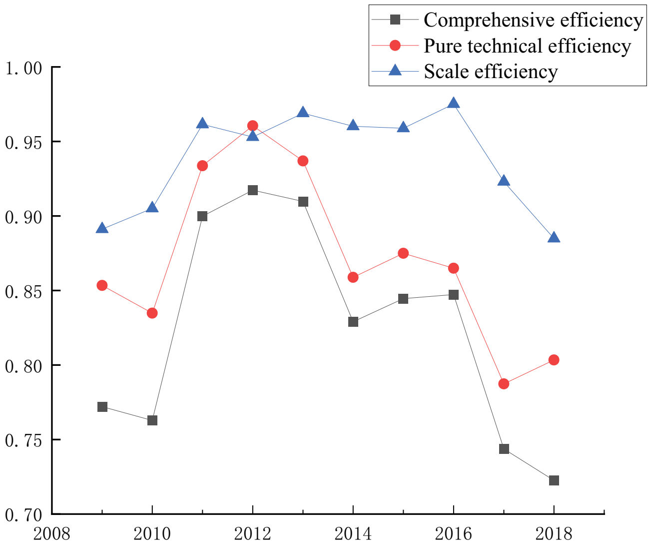

Fig. 4. Trend change of water utilization efficiency in Changbai Mountain area.

on technological changes. In the decomposition of technological change, pure technical efficiency brings the greatest change. From this, the same conclusion can be drawn: the change of the total factor index is consistent with the change of technical efficiency, and there is a lack of technical management in the utilization of water resources in the Changbai Mountains. Only Jingyu County, Linjiang City, Halong City, and Antu County have a TFP index greater than 1 in each region. Different from the results of DEA efficiency analysis, although Jingyu County, Linjiang City, and Antu County did not achieve DEA efficiency, the total factor productivity index of these three regions was greater than 1, indicating that water resource utilization efficiency was in a stage of continuous improvement. The total factor production index in other regions failed to reach 1 or above, indicating that there is still much room for improvement.

In the utilization of water resources in the Changbai Mountains, due to the neglect of the role of technology and management in the utilization of water resources, the pure technical efficiency is constantly fluctuating. Through the process and results of the evaluation of sustainable utilization of water resources, it can be seen that in the process of water resources utilization in the region, there are still unreasonable water resources utilization structure, high proportion of agricultural water use, severe water ecological environment, regional water resources distribution and economic development. Unbalanced distribution of water demand. And it is necessary to further adjust the regional industrial structure and agricultural internal structure to promote the sustainable utilization of regional water resources. From this, it can be seen that the results of dynamic efficiency analysis and static efficiency analysis are the same, both of which are affected by technology, which once again proves the lack of technical management in water resources utilization in Changbai Mountain.

The DEA-Malmquist index model was used in this study. The method has a complete system and clear steps. It can be widely used as a theoretical reference for other studies on resource utilization efficiency [34,35]. It has global significance. The new perspective and research system of this paper can provide a research basis for other regions with water scarcity and low utilization efficiency.

4.2. Deficiencies and prospects

Since the research on the resource efficiency calculation model is not deep enough, there are still some parts that need to be improved in this research. Due to the availability of data, when selecting input–output indicators, the total expenditure on agriculture, forestry and water affairs is used to replace the total water consumption of agriculture, forestry and water affairs, resulting in an inaccurate output structure of the model, but the output structure still has a certain reference value. In addition, this paper selects 10 y of data from 2009 for research, but the Malmquist production index model generally uses data of longer time series for measurement and research. Due to the small-time span of research years, the research results may have certain limitations. More issues to be discussed are as follows:

- There are many research objects, and the required data years are long, which puts forward higher requirements for data acquisition. The Changbai Mountain area needs to obtain data from the statistical yearbook of Jilin Province for many years and the bulletins of various prefecture-level cities (prefectures) when collecting data. The compilation subjects are different, the year is different, and there are certain differences in the statistical caliber. It is difficult to comprehensively analyze the Changbai Mountain area. Conduct an overall analysis.
- When selecting input–output indicators, considering the availability and reliability of data, the selection of indicators has certain limitations. The selected index data may have errors, which may cause slight deviations in the results of the model calculation, but it does not affect the conclusion and reference value. In future research, the comprehensiveness of the research needs to be improved.
- Due to limited ability and time, only the more important influencing factors were analyzed emphatically, and problems and countermeasures were put forward. There are also many general or secondary factors that have not been thoroughly analyzed. It needs to be further improved in future research.

5. Conclusions and recommendations

5.1. Conclusions

Based on the DEA-Malmquist index model, the water resource utilization efficiency in Changbai Mountain from 2009 to 2018 was measured, and the conclusions were as follows:

- The utilization efficiency of Changbai Mountain water resources in 2009–2018 was generally low. The mean value of comprehensive efficiency is only 0.772, the mean value of pure technical efficiency is 0.853, and the scale efficiency is 0.891. From the average point of view, there is still a large room for improvement in the water resource utilization efficiency in the Changbai Mountains during this period.

- In the past 10 y, Tonghua City, Tonghua County, Baishan City, Fusong County, Changbai County, Hunchun City, Tyumen City and Halong City have achieved both pure technical efficiency and scale efficiency in Changbai Mountain area. While other regions failed to reach DEA effectively. The comprehensive efficiency of Liuhe County, Meihekou City and Wangqing County is below 0.5. In other regions, the overall efficiency is between 0.5 and 1 due to the low pure technical efficiency. From the decomposition of comprehensive efficiency, the main reason is that the pure technical efficiency is too low, resulting in low comprehensive efficiency. In the past 10 y, the fluctuation of comprehensive efficiency showed three times of increase and decrease before and after, and during this research period, the change of scale efficiency was not large, and it was mainly affected by pure technical efficiency.
- The change of technical efficiency is mainly affected by the change of pure technical efficiency, and the change trajectory of the two is basically the same. The fluctuation of scale efficiency is relatively flat, indicating that the scale of water resources utilization in Changbai Mountain is relatively stable. However, due to the large fluctuation of technology, it has a great impact on the utilization efficiency of water resources in the Changbai Mountains.

The research method of this paper has a certain macroscopic character, and the research on the microscopic factors such as human activities is relatively lacking. China is in the process of industrialization, and the macro-control by the government that dominates the economy is effective. Therefore, the DEA-Malmquist index model is suitable for the macroscopic research in this paper. In the future, it can be used for further research by improving the model or considering new indicators and models.

5.2. Recommendations

- By adjusting the industrial structure, rationally allocate the water resources of different industries, so as to realize the sustainable utilization of regional water resources. The primary industry in Changbai Mountain area should develop in the direction of low water consumption and high output value. On the basis of giving priority to ensuring regional agricultural and ecological water use, guide the remaining water resources to industries with less water consumption, high economic benefits, high added value and comparative advantages. For example, with the help of the Changbai Mountain landscape and Korean culture with regional characteristics, increase publicity and moderately develop characteristic tourism industry. While driving economic development, it also reduces water consumption.
- There are various types of groundwater and abundant water in Changbai Mountain, but the geographical distribution of groundwater resources is very uneven. The population and cultivated land in the Changbai Mountains are mainly concentrated in the inter-mountain valley basins. The groundwater resources in populated areas are relatively scarce, and some areas will still experience water shortages. In areas with sparse population distribution, groundwater resources are often more abundant. Therefore, it is necessary to formulate and implement the water resources allocation plan in Changbai Mountain area, realize the optimal allocation of water resources, and build an efficient, flexible and strict water resources management system. Build a market mechanism for water resources in the Changbai Mountains region, firmly promote the reform of water prices, and increase the motivation to protect water resources through market-based operations, so as to ensure the sustainable use of water resources.
- Establish a water resource investigation database and evaluation system in Changbai Mountains, form a complete data system and systematic and scientific evaluation methods, carry out periodic water resources investigations, and understand the dynamic changes of water resources at the first time, so as to provide resources for the Changbai Mountains area. Contribute to the coordinated development of economy and ecology.

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