Quantification of industrial wastewater discharge from the major cities in Sichuan province, China

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Abstract
In this study, we used spatial autocorrelation, Environmental Kuznets Curve (EKC), and Logarithmic Mean Divisia Index model to study the spatial characteristics and driving factors of industrial wastewater discharge in Sichuan province (2003–2018). We showed that the amount of industrial wastewater discharge in Sichuan province for the period was reduced from 116,580 to 42,064.96 million tons as observed from the Moran index ranging from -0.310 to 0.302. We identified that the EKC type of Sichuan province was monotonically decreasing and six types of the EKC (monotonically decreasing, monotonically increasing, U, N, inverted U, and inverted N, shape) in 18 major cities. The technical effect (from -0.0964 to -8.8912) can reduce the discharge of industrial wastewater, while the economy effect (0.2948–5.882), structure effect (0.0892–4.5183), and population effect (from -0.0059 to 0.2873) can promote the industrial wastewater discharge. Our findings suggest that industrial wastewater discharge was reduced and changed from non-significant dissociation to non-significant agglomeration to non-significant dissociation during the study period. Furthermore, technical management upgrade is the primary driver in Sichuan province to reduce industrial wastewater discharge during this period.

Keywords Spatial autocorrelation · Environmental Kuznets Curve · Logarithmic Mean Divisia Index · Driving factors · Technical effect · Structure effect · Economic development effect · Population effect

Introduction
The continuous global industrialization and urbanization have led to large amounts of industrial wastewater in urban areas worldwide (Dutta et al. 2021). For instance, industrial water discharge was 44 million cubic meters every day in India in 2014 (Ranade and Bhandari 2014). It will pollute the surface water and groundwater, and endanger human health when a large amount of industrial wastewater is discharged into the environment (Owodunni and Ismail 2021), such as diarrhea, malaria, and schistosomiasis (Jabeen et al. 2015). Even unsafe drinking water causes 2.2 million deaths from diarrhea, 1.3 million from malaria and 160 million people are infected with schistosomiasis each year in the world (Jabeen et al. 2015). Given the complexity of processing technology and the high processing cost of industrial wastewater pollution (Jabeen et al. 2015), reducing industrial wastewater discharge is more important from a practical perspective than its treatment. Due to this, numerous governments worldwide have implemented various effective measures to reduce industrial wastewater discharge (Keiser and Shapiro 2019; Sun et al. 2021). For instance, the Clean

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Water Act was established by the USA to improve water quality in 1972 (Keiser and Shapiro 2019). The discharge of industrial wastewater was reduced by 45.6% in the industrial park of Tianjin’s economic development area of China as a result of the overall management model for optimization of water resources (Geng et al. 2007). Additionally, the National Drinking Water Act was established to prevent water pollution in Pakistan in 2009 (Jabeen et al. 2015).

Understanding the characteristics of industrial wastewater discharge is the foundation for reducing industrial wastewater discharge (Ma et al. 2020). In particular, spatial autocorrelation (including global and local spatial autocorrelation) was applied to explain the relationship between variables and spatial distribution (Geng et al. 2014), such as the previous study used spatial autocorrelation to explore the water resources utilization and its temporal and spatial characteristics in various areas of Turkey from 2004 to 2014 (Emrehan et al. 2018). Additionally, the Environmental Kuznets Curve (EKC) was widely utilized to determine the relationship between environmental pollution and economic development (Ma et al. 2020; Murshed et al. 2021; Pérez-Suárez and López-Menéndez 2015), such as carbon dioxide (CO₂) (Pérez-Suárez and López-Menéndez 2015), PM2.5 (Zhang et al. 2019a), and sulfur dioxide (SO₂) (Ding et al. 2019). Moreover, the EKC is thought to have six types of correlations between environmental pollution and industrial wastewater discharge such as monotonically increasing, monotonically decreasing, N shape, inverted N shape, U shape, and inverted U shape (Abid 2015; Ajmi et al. 2015; Azam and Khan 2016; Liu et al. 2015; Ma et al. 2020; Zhou and Sun 2013). In general, spatial autocorrelation and the EKC can be used to study the relationship between industrial wastewater discharge and the economy, but they cannot explain the factors that affect industrial wastewater discharge (Guan et al. 2008; Xu et al. 2014; Zhuang et al. 2018). To better understand the drivers of industrial wastewater discharge, the Logarithmic Mean Divisia Index (LMDI) model was applied by researchers to study effects on industrial wastewater from the technical, population, economic, and industrial perspectives (Cansino et al. 2015; Chen et al. 2019; Emrehan et al. 2018; Geng et al. 2007; González et al. 2014; Jeong and Kim 2013; Mao et al. 2021; Román et al. 2018; Zhang and Wu 2015). For instance, some previous studies reported that technical effect is the main factor to reduce the discharge of industrial wastewater (Chen et al. 2016, 2019; Ma et al. 2020), and other studies believe that economic effect and urbanization effect will promote the discharge of industrial wastewater (Chen et al. 2016).

At the present stage, a large number of studies have been carried out on the discharge characteristics of industrial wastewater (Chen et al. 2016, 2019), driving factors (Chen et al. 2016, 2019), and its relationship with the urbanization process (Chen et al. 2016, 2019; Zhang et al. 2019b). However, most of these studies reveal the differences at the provincial scale (Chen et al. 2016; Ilyas et al. 2019) or regional scale (Chen et al. 2019), such as Pakistan (Román et al. 2018), China (Chen et al. 2016), and the Yangtze River Economic Zone (China) (Chen et al. 2019). However, the refined urban management, which with accurate positioning as the business goal and the application of precise management means to manage the city, requires precise management measures based on the reality of each city (Zhang et al. 2019b), while previous large-scale research results have been unable to meet this demand. As the first and only province in western China with a GDP higher than the national average (Ma et al. 2020), Sichuan is home to more than 83.67 million people (People’s Government of Sichuan Province 2021a). Therefore, accurate analysis of the spatial and temporal patterns and influencing factors of industrial wastewater in major cities in Sichuan province has a high reference value for other provinces in China and other developing countries in the world.

To this end, our study explored the spatial characteristics and driving factors of industrial wastewater discharge in Sichuan province by using spatial autocorrelation, EKC, and the LMDI model. We hypothesized that the industrial wastewater discharge showed a scattered distribution characteristic and technical effect is the driving factors in reducing industrial wastewater discharge from 2003 to 2018 in Sichuan province. The objectives were as follows: (1) to study the discharge characteristics of industrial wastewater in 18 major cities of Sichuan province (2003–2018), (2) to examine the driving factors of industrial wastewater discharge in 18 major cities of Sichuan province, and (3) to propose tailored guidelines for environmental policy-making with regards to water quality based on our results.

Materials and methods

Data sources

There are 21 major cities in Sichuan province, but Liangshanzhou, Abazhou, and Ganzizhou were not considered due to insufficient data. We only analyzed the other 18 major cities including: Chengdu, Zigong, Panzhihua, Luzhou, Deyang, Mianyang, Guangyuan, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin, Guanghan, Dazhou, Yaan, Bazhong, and Ziyang. Moreover, according to the plan of Sichuan province, these 18 cities are divided into four economic zones, including: the Chengdu plain economic zone (ECD), Southern Sichuan economic zone (ESS), Northeast Sichuan economic zone (ENES), Panxi economic zone (EXP) (People’s Government of Sichuan Province 2016) (See Fig. 1 for details). We obtained the data of industrial wastewater discharge, population, gross domestic product (GDP), per
capita GDP, and industrial added value of Sichuan province from the 2004 to 2019 from the Sichuan Statistical Yearbook and the industrial wastewater discharge data of major cities from 2004 to 2019 from the China City Statistical Yearbook.

**Global spatial autocorrelation**

We adopted the global spatial autocorrelation method to study the spatial distribution characteristics of industrial wastewater discharge (Chen et al. 2016; Ma et al. 2020). There are five indicators of spatial autocorrelation: E (I) (the value of mathematical expectation), SD (the standard deviation), P(I) (the significance level), Z (the correlation between industrial wastewater and its location), and I (the Moran index) (Chen et al. 2016; Ma et al. 2020). A Moran index > 0 expresses a positive spatial correlation; the larger the value, the more prominent the agglomeration characteristics of the research subjects are (Ma et al. 2020; Chen et al. 2016, 2019). Moran index < 0 reflects a negative spatial correlation; the smaller the value, the more prominent is...
the discrete feature of the object in space (Ma et al. 2020; Pérez-Suárez and López-Menéndez 2015). A Moran index of 0 expresses a state of random distribution (Geng et al. 2014). Through the Geoda software, the analysis revealed that the industrial wastewater discharge of Sichuan province’s 18 major cities is spatial-positive or spatial-negative in space. The equation was expressed as follows (Eq. 1, Chen et al. 2016).

\[
I = \frac{n}{\sum \sum W_{ij} (X_i - X) (X_j - X)} \left( \sum \sum W_{ij} \right) \sum (X_i - X)^2
\]  

(1)

where \( n \) represents the number of study objects in this study, \( W_{ij} \) represents the proximity of element \( i \) and element \( j \) in the space, \( X_i \) represents the industrial wastewater discharge in city \( i \), \( X_j \) represents the industrial wastewater discharge in city \( j \), and \( X \) represents the average estimate of industrial wastewater emissions of each city.

**Environmental Kuznets curve**

Previous studies produced EKC with SPSS 19 software (Ma et al. 2020) and Python (Liu et al. 2020), while we used Origin 8 software (Origin Lab Northampton MA, USA) to explore the data and the relationship between industrial wastewater discharge and economic development in Sichuan province and 18 major cities to show the graphical results of EKC analysis. The expression can be established following a previous study (Fosten et al. 2021; Ma et al. 2020) by Eq. (2), (3), and (4) below:

\[
Y_{it} = \beta_0 + \beta_{1i} X_{it} + \epsilon_{it}
\]  

(2)

\[
Y_{it} = \beta_0 + \beta_{1i} X_{it} + \beta_{2i} X_{it}^2 + \epsilon_{it}
\]  

(3)

\[
Y_{it} = \beta_0 + \beta_{1i} X_{it} + \beta_{2i} X_{it}^2 + \beta_{3i} X_{it}^3 + \epsilon_{it}
\]  

(4)

\( Y_{it} \) represents the industrial wastewater discharge of a province or a city in the year \( t \); \( X_{it} \) is the GDP of a province or city in the year \( t \), \( \epsilon \) is an error term, \( \beta_0 \) is the intercept, and \( \beta_{1i}, \beta_{2i}, \) and \( \beta_{3i} \) are constant terms of the variables.

**Logarithmic Mean Divisia Index**

The factors that affect industrial wastewater discharge include technical, structural, economic, and population effects. We applied the LMDI method to analyze the changes in industrial wastewater discharge in 18 major cities in Sichuan province from 2003 to 2018. The equation was expressed as follows (Eq. 5, Ma et al. 2020).

\[
W^t = \sum_{i} W^t_i = \sum_{i} \frac{W^t_i - C_i^t}{G_i^t} \cdot \frac{C_i^t}{G_i^t} \cdot P_i^t
\]

\[
= \sum_{i} \left( W_{tec, i} \cdot W_{eco, i} \cdot W_{str, i} \cdot W_{pop, i} \right)
\]

(5)

where \( W^t_i \) represents the total industrial wastewater discharge in year \( t \); \( C_i \) represents the total amount of urban domestic sewage discharge of the city \( i \); \( G_i \) is the gross regional product and \( P_i \) represents the industrial wastewater discharge of the city \( i \) in the year \( t \).

According to the LMDI type of the total contribution decomposition equation, the contribution of each factor to the sewage discharge intensity is obtained (Ang 2005). The equation was expressed as follows (Eqs. 6, 7, 8, and 9).

\[
\Delta W_{tec,i} = \frac{W^t_i - W^{0}_i}{ln W^t_i - ln W^{0}_i} \cdot ln \left( \frac{W^t_{tec,i}}{W^{0}_{tec,i}} \right)
\]

(6)

\[
\Delta W_{str,i} = \frac{W^t_i - W^{0}_i}{ln W^t_i - ln W^{0}_i} \cdot ln \left( \frac{W^t_{str,i}}{W^{0}_{str,i}} \right)
\]

(7)

\[
\Delta W_{eco,i} = \frac{W^t_i - W^{0}_i}{ln W^t_i - ln W^{0}_i} \cdot ln \left( \frac{W^t_{eco,i}}{W^{0}_{eco,i}} \right)
\]

(8)

\[
\Delta W_{pop,i} = \frac{W^t_i - W^{0}_i}{ln W^t_i - ln W^{0}_i} \cdot ln \left( \frac{W^t_{pop,i}}{W^{0}_{pop,i}} \right)
\]

(9)

\( W^{0}_i \) represents the industrial wastewater discharge of the city \( i \) in the base year. \( \Delta W_{tec,i} \) represents the contribution of science and technology to industrial wastewater discharge, \( W_{tec,i}^{t} \) represents the ratio of industrial wastewater discharge and industrial added value in the \( t \)th year of the \( i \)th city, \( W^{0}_{tec,i} \) represents the ratio of the annual industrial wastewater discharge and industrial added value of the \( i \)th city of the base year. \( \Delta W_{str,i} \) represents the contribution value of the industrial structure to industrial wastewater, \( W_{str,i}^{t} \) represents the ratio of industrial added value to regional GDP of the \( i \)th city in year \( t \), \( W^{0}_{str,i} \) represents the ratio of industrial added value and regional GDP of the \( i \)th city of the base year. \( \Delta W_{eco,i} \) represents the contribution value of economic development to industrial wastewater discharge, \( W_{eco,i}^{t} \) represents the ratio of GDP of the \( i \)th city region to the total population of the \( i \)th city in the base year, \( W^{0}_{eco,i} \) represents the ratio of the regional GDP of the \( i \)th city in the \( t \)th year. \( \Delta W_{pop,i} \) is the contribution value of the total population to industrial wastewater discharge, \( W_{pop,i}^{t} \) represents the total population of the \( i \)th city in the \( t \)th year, and \( W^{0}_{pop,i} \) represents the total population of the \( i \)th city in the base year.
The contribution value of the technical, industrial structure, effect, and population effect on industrial wastewater discharge is greater than 0, indicating that their effects promote industrial wastewater discharge (Ma et al. 2020); On the contrary, the minus numbers indicated that their effects could reduce the discharge (Ma et al. 2020).

**Results**

**Spatio-temporal variation of industrial wastewater discharge**

The total amount of industrial wastewater discharged in Sichuan decreased from 116,580 million tons in 2003 to 42,064.96 million tons in 2018, and peaked at 118,130 million tons in 2005 (Fig. 2). The industrial wastewater discharge in the ECD and ENES exhibited a downward trend from 2003 to 2018 (Fig. 2). The industrial wastewater discharge in the Panzhihua exhibited a decreasing trend from 2003 to 2011 and an increasing trend from 2012 to 2018 (Fig. 2 and Table S1). The industrial wastewater discharge in the ESS has been fluctuating between 2003 and 2018 (Fig. 2). Chengdu, Zigong, Luzhou, Guangyuan, Suining, Neijiang, Leshan, Nanchong, Dazhou, Yaan, and Ziyang exhibited a decreasing trend in industrial wastewater discharge from 2003 to 2018 (Table S1). Deyang, Mianyang, Meishan, Yibin, Bazhong, and Guangan exhibited a positive trend first, further, shifting to a negative trend in 2003–2018 (Table S1).

**Analysis of global spatial autocorrelation of industrial wastewater discharge**

The Moran index of industrial wastewater discharge in Sichuan province ranged from -0.310 to 0.302 in 2003–2018 and did not pass the significance test (P > 0.05, Table 1). Specifically, the Moran index of industrial wastewater discharge of Sichuan Province varied between -0.115 to -0.253 and between -0.128 to -0.112 for 2003–2010 and 2015–2018 (negative), respectively. In comparison, the Moran index ranged from 0.200 to 0.108 from 2011–2014 (positive) (Table 1).

**Analysis of EKC of industrial wastewater discharge**

Our results showed different shapes of the EKC of the amount of industrial wastewater discharged as different levels of economic development. Furthermore, the economy of Sichuan province shows a monotonic decreasing shape (Fig. 3a and Table S3). Among the 18 major cities, the EKC of industrial wastewater discharge and economic growth of Suining, Neijiang and Meishan are monotonically decreasing (Fig. 3a and Table S3), in contrast, the Panzhihua is monotonically increasing (Fig. 3b and Table S3). Additionally, the EKC of industrial wastewater discharge and economic growth of Luzhou and Guangyuan are U shape (Fig. 3c and Table S3), then Ziyang, Mianyang, Dazhou, Yaan and Bazhong are N shape (Fig. 3d and Table S3). Moreover, the inverted U shape was found in the Zigong and Guangan (Fig. 3e and Table S3), while the inverted N shape was found in the Deyang, Leshan, Nanchong, Yibin (P = 0.656), and Chengdu (Fig. 3f and Table S3).

**Analysis of logarithmic mean Divisia index of industrial wastewater discharge**

The results showed that the contribution value of technological effect to industrial wastewater discharge is < 0, while the
The contribution value of structural effect and economic effect to industrial wastewater discharge is $> 0$ from 2003 to 2018 (Table 2). The contribution value of population effect to industrial wastewater discharge in Ziyang and Zigong is $< 0$, while for other 16 cities is $> 0$ (Table 2). Our results demonstrated that the technical effect had the highest contribution to the discharge of industrial wastewater (-0.0964 to -8.8912), followed by the economic effect (0.2948 to 5.8882), the structure effect (0.0892 to 4.5183), whereas the population effect (-0.0059 to 0.2873) had the least contribution to industrial wastewater discharge (Table 2). In general, the least value for the technical effect and the highest value for the structure effect, economic effect, and population effect are all in the Chengdu (Table 2).

**Discussion**

**Spatio-temporal characteristics of industrial wastewater discharge**

The amount of industrial wastewater discharged from Sichuan province has decreased from 116,580 million tons to 42,064.96 million tons from 2003 to 2018 (Table 1). This suggested that the water environment in Sichuan province is gradually changing, which can also be indirectly proved

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### Table 1 Global Moran’s I of industrial wastewater discharge at the Sichuan province in 2003–2018

| Year | Moran’s I | z value | E (I) | SD  | P    |
|------|-----------|---------|-------|-----|------|
| 2003 | -0.115    | -0.2219 | -0.0588 | 0.1954 | 0.481 |
| 2004 | -0.113    | -0.2176 | -0.0588 | 0.1847 | 0.500 |
| 2005 | -0.113    | -0.2222 | -0.0588 | 0.1858 | 0.487 |
| 2006 | -0.154    | -0.3393 | -0.0588 | 0.2314 | 0.435 |
| 2007 | -0.224    | -0.6021 | -0.0588 | 0.2510 | 0.334 |
| 2008 | -0.310    | -0.8841 | -0.0588 | 0.2776 | 0.204 |
| 2009 | -0.134    | -0.3169 | -0.0588 | 0.2210 | 0.462 |
| 2010 | -0.253    | -0.6028 | -0.0588 | 0.3127 | 0.323 |
| 2011 | 0.200     | 0.9308  | -0.0588 | 0.2879 | 0.182 |
| 2012 | 0.161     | 0.7524  | -0.0588 | 0.3002 | 0.236 |
| 2013 | 0.302     | 1.3110  | -0.0588 | 0.2839 | 0.111 |
| 2014 | 0.108     | 0.5870  | -0.0588 | 0.2970 | 0.261 |
| 2015 | -0.128    | -0.2900 | -0.0588 | 0.2331 | 0.471 |
| 2016 | -0.159    | -0.4450 | -0.0588 | 0.2260 | 0.408 |
| 2017 | -0.137    | -0.2429 | -0.0588 | 0.2853 | 0.450 |
| 2018 | -0.112    | -0.1420 | -0.0588 | 0.2904 | 0.480 |

E (I) is the value of mathematical expectation, SD is the standard deviation, P(I) is the significance level, Z represents the correlation between industrial wastewater and its location, and I is the Moran index.

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Fig. 3  Classification of EKC curve of Sichuan province and major cities
by reducing chemical oxygen demand and ammonia nitrogen emissions from industrial wastewater during the same period (Table S2). The main driver of this decrease was seemingly the implementation of energy conservation, and emission reduction, which had been previously introduced by the Sichuan Provincial Government (Zhang et al. 2020). For example, China’s environmental protection policies and measures were scientifically combined with the actual situation of Sichuan Province (Department of Ecology and Environment of Sichuan Province 2020), polluting enterprises were transformed and upgraded, and the pollution control facilities were increased (People’s Government of Sichuan Province 2020). In other words, reducing industrial waste book emissions forces industrial enterprises to speed up industrial and technological upgrading (Department of Ecology and Environment of Sichuan Province 2020), but also provides a new development opportunity for the industrial wastewater treatment industry (Duttaa et al. 2021).

Our results further showed that the industrial wastewater discharge of ECD, ESS, and ENES was reduced by 70%, 59%, and 76%, respectively (Fig. 2). Most cities with high industrial wastewater discharge are concentrated in the ECD (Fig. 2), thus resonating with some previous studies (Zhou and Sun 2013). In particular, a previous study has reported that high industrial wastewater discharge areas are mainly characterized by relatively developing economies, large populations, and high industrialization (Zhou and Sun 2013). Therefore, it is necessary to properly control the population and adjust the industrial structure to reduce industrial wastewater discharge in cities with a high discharge of industrial wastewater. For example, industrial wastewater discharges can be reduced by reducing the proportion of the chemical industry in the overall industrial system because of its higher effluent discharges (Ghisetti and Quatraro 2017; Ma et al. 2020; The People’s Government of Sichuan Province 2021b). While the industrial wastewater discharge of Panzhihua increased by 73% (Fig. 2), it may be related to the policy of industrial development, which is expanding and strengthening steel, energy, electrometallurgy, chemical industry, vanadium and titanium, and other pillar industries, and extending the mechanical processing and manufacturing industry of Panzhihua in the same period (People’s Government of Panzhihua Municipal 2006). The Moran index was previously used to evaluate the spatial agglomeration characteristics of pollutant emissions (Ma et al. 2020). For instance, a previous study concluded that Turkey’s provincial water consumption changed from 0.1286 to -0.025 from 2004 to 2014, thus, suggesting that the distribution pattern of areas with high water consumption changed from agglomeration to dissociation (Chen et al. 2016). According to the previous study (Ma et al. 2020), our result of the Moran index (Table 1) suggested that the provincial industrial wastewater discharge of Sichuan Province has changed from non-significant dissociation (2003–2010) to non-significant agglomeration (2011–2014) to non-significant dissociation (2015–2018) during the study period. Therefore, each city should formulate corresponding emission reduction measures according to the specific situation of local industrial wastewater discharge (Emrehan et al. 2018). For example, the Asbestos Industrial Park in Sichuan province has implemented reasonable arrangements, timely disposal of waste materials and strengthening management and maintenance of wastewater treatment facilities (Department of Ecology and Environment of Sichuan Province 2017).

**Environmental Kuznets curve changes of major industrial cities**

As mentioned, the EKC can be utilized as an indicator for studying the relationship between environmental pollution and economic development (Pérez-Suárez and López-Menéndez 2015; Lu et al. 2020). Moreover, previous studies have found that the EKC showed six types of environmental pollution and economic development (Ajmi et al. 2015; Azam and Khan 2016; Bimonte and Stabile 2017; Liu et al. 2015). Based on this, we found that the EKC of total

### Table 2 Decomposition analysis results of industrial wastewater discharge in Sichuan Province, China (per one hundred million cubic meters)

| City     | tec   | str   | eco   | pop  |
|----------|-------|-------|-------|------|
| Chengdu  | -7.8912 | 4.5183 | 5.8882 | 0.2873 |
| Deyang   | -1.3758 | 1.1544 | 1.2421 | 0.0112 |
| Mianyang | -1.8055 | 1.5842 | 1.6963 | 0.0182 |
| Leshan   | -2.3969 | 1.2296 | 2.1003 | 0.0114 |
| Meishan  | -1.6219 | 0.9897 | 1.6528 | 0.0111 |
| Ziyang   | -1.1032 | 0.5471 | 0.7306 | -0.0059 |
| Suining  | -0.4771 | 0.3824 | 0.4472 | 0.0013 |
| Yaan     | -0.4969 | 0.3448 | 0.4550 | 0.0019 |
| Zigong   | -0.7653 | 0.5325 | 0.6454 | -0.0278 |
| Luzhou   | -2.8674 | 1.5107 | 2.0603 | 0.0481 |
| Neijiang | -1.2546 | 0.7535 | 0.9856 | 0.0015 |
| Yibin    | -2.1058 | 1.5442 | 2.2043 | 0.0466 |
| Guangyuan| -1.0779 | 0.5873 | 0.9051 | 0.0036 |
| Nanchong | -1.2175 | 0.8689 | 0.6970 | 0.0101 |
| Guang'an | -0.2689 | 0.2650 | 0.2948 | 0.0044 |
| Dazhou   | -0.7867 | 0.6188 | 0.6128 | 0.0168 |
| Bazhong  | -0.0964 | 0.0892 | 0.0849 | 0.0021 |
| Panzhihua| -0.5215 | 0.3087 | 0.5961 | 0.0099 |

tec represents the contribution value of science and technology to industrial wastewater discharge, str represents the contribution value of industrial structure to industrial wastewater discharge, eco represents the contribution value of economic development to industrial wastewater discharge, pop represents the contribution value of the total population to industrial wastewater discharge.
industrial wastewater discharge and economic growth in Sichuan Province is monotonically decreasing (Fig. 3a and Table S3). The EKC of industrial wastewater discharge and economic growth in the 18 major cities of Sichuan province has six types: monotonous decreasing shape, monotonically increasing shape, U shape, N shape, inverted U shape and inverted N shape (Fig. 3 and Table S3). The types of EKC are monotone decreasing type, inverted U and inverted N type, all of which indicate that industrial wastewater eventually presents a downward trend with the development of the economy (Zhou and Sun 2013). In turn, this emphasizes that the pollution caused by the discharge of industrial wastewater from these cities (Suining, Neijiang, Meishan, Zigong, Guangan, Deyang, Leshan, Nanchong, Yibin and Chengdu) (Fig. 3a, b, c and Table S3) have been improved to a certain extent. These cities can achieve the emission reduction of industrial wastewater as long as they continue to implement the policies and measures of industrial wastewater discharge management formulated at the present stage in the future development process (Chen et al. 2016; Ma et al. 2020). For example, the N shape city, Neijiang (Fig. 3a and Table S3), has accelerated the construction of sewage treatment plants and sewage treatment facilities and strengthened the supervision and management of enterprises’ sewage discharge through law enforcement, such as monitoring pollution sources by drones (Department of Ecology and Environment of Sichuan Province 2019).

However, the types of EKC are monotonically increasing, U and N types expressing that industrial wastewater discharge is increasing with economic growth (Mursheed et al. 2021). The monotonically increasing type city, Pazhihua (Fig. 3b and Table S3), need to start with improving industrial technology to reduce industrial wastewater discharge because their policy of industrial development which is expanding and strengthening steel, energy, electrometallurgy, chemical industry, vanadium and titanium, and other pillar industries (People’s Government of Panzhihua Municipal 2006). The types of EKC are U and N types expressing that industrial wastewater discharge is increasing with economic growth (Mursheed et al. 2021). This finding suggests that the pollution driven by the discharge of industrial wastewater from these cities is owing to effective measures to improve the pollution promptly (Sun et al. 2021). Thus far, these cities need to formulate relevant policies to control water pollution and achieve green development in accordance with environmental changes (The People’s Government of Sichuan Province 2021b). For example, Luzhou, one of the U shape (Fig. 3c and Table S3), was implemented energy saving and consumption reduction measures in coal and electric power industries, controlled the growth of industries with high pollution and high energy consumption, eliminated backward equipment and technology, and developed modern service industries with low energy consumption and low pollution to reduce industrial wastewater discharge (Bureau of Ecology and Environment of Luzhou 2009).

**Analysis of driving factors of industrial wastewater discharge in major cities**

A previous study has concluded that population, economy, and urbanization levels were the main drivers of industrial wastewater pollution (Zhang et al. 2020). Moreover, many studies have analyzed the drivers of industrial wastewater using LMDI (Geng et al. 2007, 2014; Ma et al. 2020). For example, some studies have found, by using LMDI, that economic or technical effects are the main factors influencing the industrial wastewater discharge of Chinese provinces (Chen et al. 2016; Geng et al. 2014). The same result has been reported for industrial wastewater discharge in the Yangtze River Economic Zone from 2002 to 2015 (Chen et al. 2019). Meanwhile, our results indicated that technical effect is the main factor in reducing industrial wastewater discharge in 18 major cities in Sichuan province (from -0.0964 to -7.8912) (Table 2). Although previous studies have shown that technical effects have a limited impact on the reduction of industrial wastewater discharge (Ma et al. 2020), Sichuan province still needs to import foreign advanced wastewater treatment in the future (Chen et al. 2016), which based on our result (Table 2). Previous study pointed out that physical treatment technologies (such as adsorption, gravity separation, and so on), chemical treatment technologies (such as coagulation and flocculation, oxidation and reduction and so on), biological treatment technologies (activated sludge or biofilm) and wastewater reuse technology should be adapted (Mao et al. 2021; Sathaiah and Chandrasekaran 2020). As an economical, environmentally friendly and most promising treatment technology, biological treatment, purifying the sewage through microorganisms (Mao et al. 2021). Additionally, the Shuangliu County of Chengdu has implemented classification and screening for enterprises, standardized the enterprise wastewater detection system, and invested funds to build 22 wastewater treatment stations, with an annual sewage treatment capacity of 2310.45 million tons (Chengdu Municipal Ecology and Environment Bureau 2008).

The industrial structure effect (from 0.0892 to 4.5183), economic effect (from 0.2948 to 5.8882), and population effect (from -0.0059 to 0.2873) will increase the discharge of industrial wastewater according to the current study (Table 2). Enterprises need to transform from an industrial economy to a service economy (Geng et al. 2014; Ma et al. 2020) since previous studies have shown the adjustment structure of the industry (Lu et al. 2020; Zhang et al. 2021). For example, the development of new energy and
new material industry in Luzhou city can reduce the discharge of industrial wastewater and promote the economic development of Luzhou city (Department of Ecology and Environment of Sichuan Province 2021). As the economic effect can also promote the discharge of industrial wastewater, we need measures to reduce the discharge of industrial wastewater, including increasing investment in sewage treatment facilities for encouraging technical innovation, and continuous amelioration of sewage treatment equipment to ensure economic development and reduce the discharge of industrial wastewater (Chen et al. 2016). The results further indicate that the population effect of most cities can also promote the discharge of industrial wastewater (Table 2). Therefore, enterprises must frequently carry out activities broadening the knowledge about scientific and industrial aspects of wastewater. This will help promote wastewater treatment knowledge among residents and reward those who report the illegal discharge of industrial wastewater (Ma et al. 2020; Chen et al. 2019).

Limitations

Firstly, there are only 18 cities in this study (Fig. 1), the sample numbers is relative small, meanwhile, the P-value of the Moran index results is only less than 0.1 (Table 1), resulting in the low reliability of this result. Further studies should be conducted on a large sample and refined scale for similar questions. Moreover, a previous study showed the EKC of Chengdu of the GDP per capita and the amount of industrial wastewater per capita discharge as an inverted U shape from 1997 to 2018 (Liu et al. 2020), while the inverted N shape from 2003 to 2018 in this study (Fig. 3f and Table S3). Moreover, the same results from multiple approaches can ensure they are highly reliable; further study is needed to analyze our finds with multiple additional approaches.

Conclusions

This study uses spatial autocorrelation, EKC, and LMDI models to analyze the spatio-temporal characteristics and influencing factors of industrial wastewater discharge in 18 major cities (four major economic zones) in Sichuan Province (China) in 2003–2018. Our results showed that industrial wastewater discharge and the Moran index decreased from 116,580 million tons to 42,064.96 million tons and from -0.310 to 0.302, respectively. The EKC curve of Sichuan’s industrial wastewater discharge and economy is monotonically decreasing. The EKC of industrial wastewater discharge and economic development in major cities are monotonically decreasing (Sichuan province, Suining, Neijiang and Meishan), monotonically decreasing (Panzhihua), U shape (Luzhou and Guangyuan), N shape (Ziyang, Mianyang, Duzhou, Yaan and Bazhong) inverted U shape (Zigong and Guangan), and inverted N shape (Deyang, Leshan, Nanchong, Yibin, and Chengdu). During the study period, technical effects were the major contributors of the discharge (from -0.0964 to -8.8912), followed by economic effects (from 0.2948 to 5.8882), industrial structure effects (from 0.0892 to 4.5183), and population effects (from -0.0059 to 0.2873). These results suggest that from 2003 to 2018, the total amount of industrial wastewater discharge in Sichuan province exhibited a decreasing trend and changed from non-significant dissociation to non-significant agglomeration to non-significant dissociation during the study period. In contrast, the technical effect upgrade played a significant role in reducing industrial wastewater discharge. Moreover, the reduction chemical and biological treatment technology for emission reduction were widely used in the steel, energy, electrometallurgy, chemical, and other industries, and strengthening enterprise sewage discharge monitoring with automated monitoring technology are all effective measurements for urban management.

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